

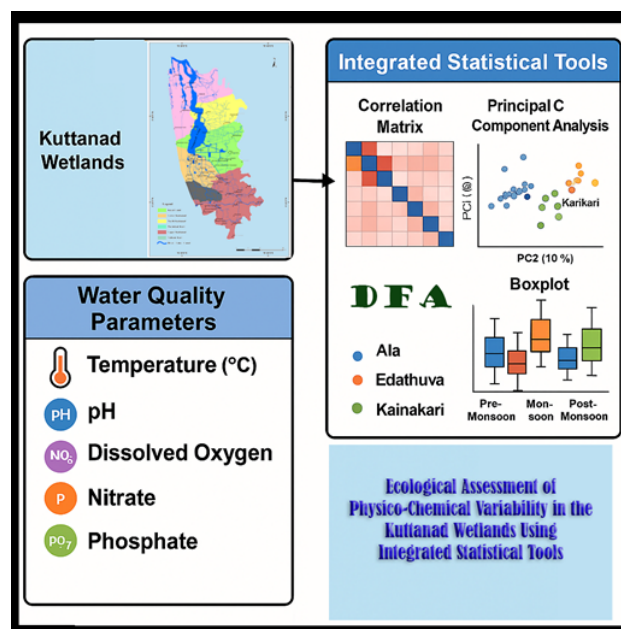
Ecological Assessment of Physico-Chemical Variability in the Kuttanad Wetlands Using Integrated Statistical Tools

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Abstract: The current research work examines the spatial and seasonal variability of physico-chemical water quality parameters in the Kuttanad wetlands of Kerala, India, using integrated univariate and multivariate statistical methods. Seasonal sampling was conducted from 24 sites within three ecologically distinct panchayats in Kuttanad wetland such as Ala, Edathuva and Kainakari, during pre-monsoon, monsoon and post-monsoon seasons. Important water quality parameters including temperature, pH, dissolved oxygen (DO), nitrate, and phosphate were analysed. Descriptive statistics exposed significant seasonal fluctuations in nitrate and phosphate particularly monsoonal nitrate variation in Ala panchayat and persistent phosphate enrichment in Kainakari panchayat. Boxplot analysis highlighted location-based extremes and seasonal trends, while correlation analysis demonstrated strong inverse associations between nitrate and phosphate, and negative relationships between DO and both phosphate and pH. Two-way ANOVA indicated significant spatial influence on nitrate concentrations, with no significant seasonal effects. Principal Component Analysis (PCA) captured over 80% of the total variance in the first two components, distinguishing sites based on nutrient loading and oxygen-pH gradients. PCA separated Kainakari due to its phosphate enrichment and alkaline character, while Ala showed strong monsoonal nitrate variability. Discriminant Function Analysis (DFA) further confirmed distinct water quality clusters among the panchayats, with LD1 accounting for 99.5% of variance. These findings point out the spatial dominance over temporal variability in nutrient dynamics and the utility of integrated statistical tools for wetland water quality analysis. The study offers a healthy framework for future ecological monitoring and management strategies of all wetlands particularly the Ramsar wetlands of Kerala.

Keywords: Kuttanad wetlands, nutrient dynamics, Principal Component Analysis, Discriminant Function Analysis, seasonal variation.



1. Introduction

Wetlands are among the most productive and ecologically significant ecosystems on Earth, offering a wide range of ecosystem services including water purification, nutrient cycling, carbon sequestration, flood regulation and biodiversity support (Mitsch & Gosselink, 2015; Ramsar STRP, 2025). In tropical regions, monsoon-mediated wetlands are particularly sensitive to seasonal hydrological fluctuations, which strongly influence nutrient transport, sedimentation and ecological processes (Wetzel, 2001). The Kuttanad wetland region in Kerala, spread across the districts of Alappuzha, Kottayam, and Pathanamthitta, comprises a mosaic of rivers, canals, floodplains and lakes exemplifies such a dynamic and sensitive monsoonal wetland. Designated as a Ramsar Site in 2002, it is renowned for its unique below-sea-level paddy cultivation system (padasekharams), extensive backwater networks, and biodiversity-rich aquatic habitats (Ramsar, 2023; Thomas et al., 2021). Seasonal floods and monsoon rains traditionally replenish nutrients and sediments, maintaining ecological functioning. However, recent decades have witnessed steady

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deterioration of water quality driven by intensified farming, unregulated waste disposal, and nutrient-rich agricultural runoff (Venukumar et al., 2024; Asha et al., 2016; SWAK, 2022; Sinha et al., 2022). These pressures threaten the wetland's ecological resilience, underscoring the urgent need for systematic monitoring and sustainable management interventions.

The present study focuses on three representative panchayats such as Ala, Edathuva, and Kainakari, located in the upper, middle, and lower stretches of Kuttanad, respectively. These sites were selected to represent a gradient in land use intensity, hydrological connectivity and nutrient exposure. Ala is characterized by extensive paddy cultivation and canal systems directly influenced by monsoonal inflows. Edathuva serves as a transitional zone with moderate agricultural activity and more stable hydrology. Kainakari is a low-lying backwater-dominated region, exhibits persistent nutrient enrichment and sediment accumulation due to restricted drainage and intensive land use (Prasad & Ramesh, 2019; SWAK, 2022). This spatial framework allows for assessing how local land use and hydrology shape water quality dynamics within the wetland.

Despite the ecological importance of Kuttanad, few studies have systematically examined wetland-specific seasonal patterns in water quality using integrated statistical approaches. This study addresses that gap by applying descriptive statistics, correlation analysis, Principal Component Analysis (PCA), Discriminant Function Analysis (DFA), and boxplot visualization to evaluate key water quality parameters as temperature, pH, dissolved oxygen, nitrate, and phosphate, across seasons in Ala, Edathuva, and Kainakari. By integrating spatial and seasonal variability with multivariate tools, this work aims to generate insights into nutrient dynamics and ecological gradients that can inform adaptive monitoring and targeted management strategies for the Kuttanad wetland ecosystem (Jolliffe & Cadima, 2016; Legendre & Legendre, 2012; Manly & Alberto, 2016; Venukumar et al., 2024).

2. Materials and Methods

A. Study Area and Sampling Procedure

The present study was conducted in the Kuttanad wetland system of Alappuzha district, Kerala, encompassing three representative panchayats namely Ala, Edathuva, and Kainakari, selected based on their contrasting hydro-ecological settings and land-use patterns Fig. 1 depicts the location map of the study area, which was generated using the ArcGIS mapping tool to accurately represent the geographical context and sampling sites.

Water samples were collected seasonally (pre-monsoon, monsoon and post-monsoon) from pre-determined open water

bodies within each panchayat during the year 2022 and 2023. Water sampling was conducted across 24 sites, (eight locations from each panchayat) dispersed among the three panchayats in the Kuttanad wetlands (Table 1). These sites were selected to represent varied aquatic environments, including canals, backwaters and waterlogged agricultural zones, thereby addressing the spatial heterogeneity of the wetland ecosystem.

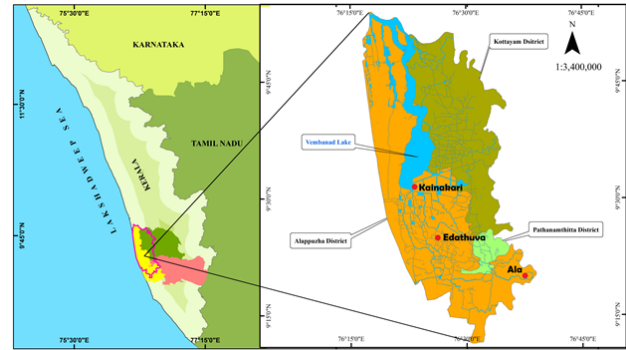


Fig. 1. Location map of study area

B. Analytical Methods

From each sampling site, surface water samples were collected in pre-cleaned polyethylene bottles for laboratory analysis. Measurements of temperature, pH, and dissolved oxygen were recorded using calibrated portable multiparameter. Nitrate and phosphate concentrations were performed using standard colorimetric methods following APHA (2017) guidelines.

Descriptive statistics, including mean, standard deviations and standard errors, were computed to summarize trends using Excel. A correlation matrix was generated to explore relationships between parameters and identify statistically significant associations among physico-chemical variables. Two-way Analysis of Variance (ANOVA) was performed to evaluate the effects of panchayat (location), season, and their interaction on nitrate concentrations across the study sites. Statistical analysis was carried out using windows based PAST 4.3 and to interpret the spatial and seasonal changes in water quality.

Principal Component Analysis (PCA) was applied on z-score standardized data to reduce dimensionality and extract key components governing water quality variation. Additionally, boxplot analysis was employed to visualize seasonal variability and detect extreme values across the three panchayats (Jolliffe & Cadima, 2016; Legendre & Legendre, 2012). Discriminant Function Analysis (DFA) was conducted using the Linear Discriminant Analysis (LDA) algorithm, wherein the categorical variable (panchayat) served as the grouping factor.

Table 1
Sampling locations across the three panchayat

No.	Kainakari Panchayat	Edathuva Panchayat	Ala Panchayat
W1	Ayiraveli	108 Chira	Pennukkara
W2	Ilankavu	Kattumbhagam	Mullavelikkadavu
W3	Kainakari	Edathuva Boat Jetty	Ala East
W4	Guveinda Church	Chakkidikkadavu	Ala South
W5	Chakkankari	Mankottachira	Ala West
W6	Kuttamangalam	Kozhippakkalam	Ala Main Canal
W7	Meenampally Vattakayal	Thayamkari South	Neduvaramcodu
W8	Chennankari	Kankayathodu Palam	Ala Junction

and the continuous physico-chemical parameters as the independent variables. Wilks' Lambda and associated F-statistics were used to test the significance of the discrimination (Manly & Alberto, 2016).

3. Results

A. Seasonal and Spatial Distribution of Physico-Chemical Parameters

The seasonal and spatial variations in physico-chemical

water quality parameters across the three panchayats such as Ala, Edathuva, and Kainakari are summarized in the following tables (Table 2 to table 10). These results provide baseline insights into temperature, pH, dissolved oxygen, nitrate, phosphate, and other key indicators measured during pre-monsoon, monsoon, and post-monsoon seasons.

Table 2
Average value of physico-chemical quality of water during pre-monsoon season in Kainakari panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	28.9	29.0	29.2*	29.0	29.0	29.1	28.7*	28.9
pH	6.16	6.47	6.47	6.34	6.52	6.45	6.53	6.38
Conductivity (µs/cm)	59	33	65	42	44	21	39	63
Turbidity (NTU)	5.5	7.5	4.7	6.7	4.8	6.1	4.3	5.8
Salinity (%)	0.063	0.087	0.076	0.113	0.101	0.810	0.111	0.105
DO (Mg/L)	5.85	5.95	5.90	5.85	6.30	5.72	6.15	5.42
CO2 (Mg/L)	10.0	12.5	12.5	15.0	10.0	12.5	10.0	12.5
Acidity (Mg/L)	12.5	12.5	15.0	12.5	15.0	25.0	25.0	15.0
Alkalinity (Mg/L)	15	20	20	15	20	20	15	15
NO3 (Mg/L)	0.026	0.024	0.026	0.025	0.025	0.044	0.019	0.030
PO4 (Mg/L)	0.180	0.171	0.175	0.178	0.161	0.145	0.201	0.195
Ca (Mg/L)	3.21	4.81	4.81	3.21	9.01	4.92	8.96	5.38
Mg (Mg/L)	6.03	2.35	4.54	2.51	4.51	2.58	4.62	4.10
Hardness (Mg/L)	10	8	10	6	14	8	14	10
Chloride (Mg/L)	35.11	48.36	42.13	62.55	56.34	44.88	61.96	58.34
Na (Mg/L)	6.9	6.4	5.4	7.5	5.6	5.2	7.3	6.0
K (Mg/L)	1.6	2.1	1.7	2.5	2.1	2.8	1.9	2.9

Table 3
Average value of physico-chemical quality of water during monsoon season in Kainakari panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	27.6	27.9	27.9	28.1	27.4	28.9	28.6	28.4
pH	6.40	6.38	6.45	7.27	6.53	7.03	6.43	6.57
Conductivity (µs/cm)	27	42	40	36	35	24	50	61
Turbidity (NTU)	3.9	6.2	13.2	5.4	7.8	4.4	3.4	7.2
Salinity	0.051	0.054	0.047	0.076	0.077	0.092	0.087	0.699
DO (Mg/L)	6.4	5.9	5.5	6.8	6.1	6.1	5.5	5.4
CO2 (Mg/L)	12.5	10.0	15.0	15.0	17.5	15.0	15.0	12.5
Acidity (Mg/L)	15.0	12.5	12.5	15.0	15.0	15.0	12.5	15.0
Alkalinity (Mg/L)	20	25	15	20	15	25	15	35
NO3 (Mg/L)	0.024	0.022	0.147	0.040	0.099	0.015	0.068	0.115
PO4 (Mg/L)	0.130	0.127	0.134	0.137	0.134	0.130	0.135	0.136
Ca (Mg/L)	7.41	8.21	6.01	7.91	3.21	9.81	6.21	6.41
Mg (Mg/L)	5.28	4.96	3.26	4.32	1.99	3.32	1.07	3.28
Hardness (Mg/L)	14	14	10	12	6	14	8	10
Chloride (Mg/L)	28.16	30.33	26.41	42.18	39.66	51.13	48.21	38.71
Na (Mg/L)	6.1	5.3	9.5	9.1	5.3	6.8	6.4	5.5
K (Mg/L)	1.3	1.4	1.4	0.9	2.3	1.8	1.8	0.9

Table 4
Average value of physico-chemical quality of water during post-monsoon season in Kainakari panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	28.0	28.1	28.5	28.5	28.5	29.5	29.7	27.9
pH	6.52	8.15	6.44	7.38	7.11	6.52	6.32	6.25
Conductivity (µs/cm)	49	55	63	69	59	63	62	48
Turbidity (NTU)	2.5	5.2	8.4	2.7	3.2	2.8	2.3	5.8
Salinity	0.641	0.090	0.101	0.121	0.126	0.129	0.098	0.156
DO (Mg/L)	5.0	4.7	5.3	6.7	4.8	5.4	5.0	4.6
CO2 (Mg/L)	11.0	8.8	13.2	8.8	11.0	11.0	8.8	13.2
Acidity (Mg/L)	12.5	10.0	12.5	7.5	12.5	17.5	17.5	17.5
Alkalinity (Mg/L)	45	45	30	25	45	20	35	35
NO3 (Mg/L)	0.027	0.026	0.028	0.021	0.028	0.029	0.031	0.039
PO4 (Mg/L)	0.155	0.148	0.154	0.151	0.148	0.134	0.143	0.152
Ca (Mg/L)	8.08	26.83	11.80	5.80	19.62	6.80	8.41	9.21
Mg (Mg/L)	5.21	18.51	6.33	6.81	7.92	5.43	6.97	8.22
Hardness (Mg/L)	14	42	18	12	28	12	16	18
Chloride (Mg/L)	35.50	49.86	56.17	67.13	69.82	71.66	54.69	86.38
Na (Mg/L)	4.2	4.5	4.4	5.1	4.8	6.4	10.3	4.0
K (Mg/L)	0.9	0.9	0.9	1.5	1.6	1.8	1.3	0.9

Table 5
Average value of physico-chemical quality of water during pre-monsoon season in edathuva panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	27.9	28.1	28.0	28.0	28.5	28.2	28.8	27.9
pH	6.05	6.28	6.66	6.44	5.64	5.82	6.16	6.13
Conductivity (µs/cm)	62	55	138	225	188	32	67	170
Turbidity (NTU)	4.6	2.9	8.5	13.2	15.5	12.6	9.8	17.4
Salinity	0.028	0.035	0.033	0.020	0.048	0.020	0.025	0.025
DO (Mg/L)	6.2	7.5	5.8	6.7	6.2	5.5	7.1	7.3
CO2 (Mg/L)	22.0	70.4	30.8	22.0	26.4	22.0	30.8	22.0
Acidity (Mg/L)	15	35	60	40	25	25	35	25
Alkalinity (Mg/L)	60	50	60	60	40	50	40	40
NO3 (Mg/L)	5.244	5.338	4.397	4.844	12.017	4.844	4.750	9.054
PO4 (Mg/L)	0.018	0.019	0.014	0.002	0.013	0.002	0.001	0.004
Ca (Mg/L)	6.40	5.61	14.80	5.61	6.61	3.20	6.80	4.00
Mg (Mg/L)	4.46	5.01	6.03	2.11	5.51	3.94	4.02	3.23
Hardness (Mg/L)	12	12	22	8	12	8	12	8
Chloride (Mg/L)	15.62	19.88	18.46	11.36	26.96	11.36	14.29	14.20
Na (Mg/L)	12.8	9.5	8.2	10.6	8.8	9.2	12.0	11.2
K (Mg/L)	2.1	3.9	1.5	4.2	2.6	3.1	4.5	4.8

Table 6
Average value of physico-chemical quality of water during monsoon season in edathuva panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	28.1	28.0	28.2	28.8	28.6	27.9	28.3	27.7
pH	6.59	6.55	6.72	6.52	6.41	6.36	6.41	6.61
Conductivity (µs/cm)	58	177	207	243	40	362	810	230
Turbidity (NTU)	11.2	6.1	5.2	3.5	10.6	9.8	3.4	15.3
Salinity	0.033	0.089	0.077	0.108	0.026	0.187	0.556	0.072
DO (Mg/L)	6.1	5.9	5.5	6.2	6.7	6.2	5.6	5.6
CO2 (Mg/L)	17.6	13.5	17.6	22	17.6	13.5	17.6	35
Acidity (Mg/L)	20	15	15	15	15	20	20	30
Alkalinity (Mg/L)	40	20	60	40	40	30	40	100
NO3 (Mg/L)	9.666	5.291	4.492	4.633	5.997	4.609	4.256	7.573
PO4 (Mg/L)	0.018	0.019	0.016	0.008	0.001	0.003	0.019	0.016
Ca (Mg/L)	3.2	3.2	9.61	4.0	2.40	7.21	12.82	15.23
Mg (Mg/L)	0.974	2.436	7.309	4.872	0.487	4.385	19.0	6.822
Hardness (Mg/L)	12	18	46	30	8	36	110	66
Chloride (Mg/L)	18.46	49.70	42.60	59.69	14.20	103.66	308.14	39.76
Na (Mg/L)	6.5	7.6	9.5	5.9	8.2	7.9	9.8	10.0
K (Mg/L)	3.8	2.1	3.2	2.5	3.5	1.9	3.4	4.1

Table 7
Average value of physico-chemical quality of water during post-monsoon season in edathuva panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	27.8	28.1	27.9	28.1	28.0	27.6	28.0	28.0
pH	5.79	5.81	5.97	5.98	6.11	6.02	6.91	5.58
Conductivity (µs/cm)	82	127	45	44	43	228	166	93
Turbidity (NTU)	10.5	2.1	8.2	7.6	6.6	8.4	9.1	2.1
Salinity (%)	0.049	0.028	0.028	0.031	0.056	0.064	0.027	0.033
DO (Mg/L)	6.9	6.3	6.8	5.8	7.0	6.8	6.5	5.9
CO2 (Mg/L)	13.2	17.6	13.2	13.2	13.2	13.2	17.6	22
Acidity (Mg/L)	20	25	40	60	35	15	35	30
Alkalinity (Mg/L)	20	30	35	30	20	30	40	20
NO3 (Mg/L)	6.326	5.703	5.550	5.291	5.408	5.985	5.726	4.132
PO4 (Mg/L)	0.026	0.028	0.031	0.029	0.033	0.022	0.028	0.014
Ca (Mg/L)	13.21	14.81	6.44	12.44	6.44	14.08	20.61	48.9
Mg (Mg/L)	2.94	6.92	2.97	2.97	2.97	9.89	11.84	36.7
Hardness (Mg/L)	16	24	10	16	10	26	38	96
Chloride (Mg/L)	19.94	28.40	15.62	14.20	12.78	59.64	31.24	66.7
Na (Mg/L)	8.3	12.6	11.5	11.7	10.8	13.4	15.6	14.9
K (Mg/L)	1.3	3.8	3.2	4.5	2.6	9.3	9.5	9.2

Table 8
Average value of physico-chemical quality of water during pre-monsoon season in Ala panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	27.9	28.2	28.5	28.3	29.0	29.1	27.8	28.4
pH	6.26	6.41	6.42	6.49	6.95	6.71	6.55	6.03
Conductivity (µs/cm)	127	69	249	70	116	81	63	36
Turbidity (NTU)	10.6	11.9	6.8	13.6	12.1	14.6	52	9.5
Salinity (%)	0.049	0.028	0.028	0.031	0.056	0.064	0.027	0.033
DO (Mg/L)	5.8	7.1	7.0	6.2	6.7	6.5	6.7	5.5
CO2 (Mg/L)	26.4	22.0	22.0	22.0	39.6	22.0	12.5	26.4
Acidity (Mg/L)	40	25	30	30	40	25	25	30
Alkalinity (Mg/L)	50	40	40	50	80	30	30	30
NO3 (Mg/L)	4.515	8.795	8.254	6.185	4.915	6.796	5.331	5.221
PO4 (Mg/L)	0.021	0.006	0.011	0.011	0.039	0.022	0.015	0.056
Ca (Mg/L)	10.41	8.41	7.21	8.00	18.81	5.61	7.57	6.80
Mg (Mg/L)	9.22	4.27	1.01	2.48	9.36	1.05	3.21	4.03
Hardness (Mg/L)	16	14	10	12	44	8	12	12
Chloride (Mg/L)	26.96	15.62	15.62	17.04	31.24	35.50	14.8	18.48
Na (Mg/L)	9.5	15.3	11.9	13.6	10.2	11.3	10.3	14.1
K (Mg/L)	2.9	6.2	2.4	3.5	1.9	3.4	4.2	2.9

Table 9
Average value of physico-chemical quality of water during monsoon season in Ala panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	28.2	28.7	27.8	27.5	27.4	28.0	28.5	27.8
pH	5.36	6.03	5.92	6.16	6.41	6.72	6.33	5.52
Conductivity (µs/cm)	41	57	34	46	82	55	94	84
Turbidity (NTU)	12.7	6.2	12.7	9.3	12.7	10.5	10.5	13.0
Salinity (%)	0.026	0.023	0.027	0.026	0.024	0.046	0.031	0.023
DO (Mg/L)	6.1	6.7	6.5	6.0	6.2	6.0	6.3	5.9
CO2 (Mg/L)	35	22	22	13.5	13.5	35	35	22
Acidity (Mg/L)	35	30	30	15	15	15	30	30
Alkalinity (Mg/L)	30	60	50	40	50	40	50	50
NO3 (Mg/L)	4.774	4.727	5.821	9.877	10.27	3.501	5.597	16.462
PO4 (Mg/L)	0.006	0.024	0.024	0.011	0.018	0.013	0.011	0.0149
Ca (Mg/L)	4.80	9.0	5.06	4.90	9.812	8.445	8.01	5.61
Mg (Mg/L)	4.01	4.949	5.391	5.01	6.321	4.581	11.949	5.487
Hardness (Mg/L)	10	18	12	10	18	16	28	16
Chloride (Mg/L)	14.20	12.78	15.13	14.20	13.49	25.5	17.09	12.78
Na (Mg/L)	8.1	6.8	11.3	7.6	10.5	5.5	9.3	8.2
K (Mg/L)	2.9	2.6	3.1	2.8	5.2	1.9	3.9	1.5

Table 10
Average value of physico-chemical quality of water during post-monsoon season in Ala panchayat

Parameters	W1	W2	W3	W4	W5	W6	W7	W8
Temperature (0C)	28.5	28.7	28.9	27.5	28.1	27.8	27.8	28.7
pH	5.83	5.85	5.54	5.90	5.99	6.05	6.01	5.91
Conductivity (µs/cm)	57	100	337	101	80	51	165	102
Turbidity (NTU)	3.5	8.2	11.1	7.8	5.8	4.3	13.2	5.7
Salinity (%)	0.031	0.059	0.059	0.043	0.036	0.036	0.033	0.062
DO (Mg/L)	5.9	6.7	6.5	5.5	6.0	5.9	7.1	6.5
CO2 (Mg/L)	26.4	17.6	26.4	13.2	30.8	13.2	22.0	13.2
Acidity (Mg/L)	15	20	20	20	20	10	20	10
Alkalinity (Mg/L)	20	50	120	60	60	30	110	30
NO3 (Mg/L)	7.219	6.185	5.103	4.538	5.714	6.608	4.209	10.018
PO4 (Mg/L)	0.022	0.022	0.028	0.018	0.034	0.094	0.056	0.016
Ca (Mg/L)	4.41	14.08	7.27	13.26	12.404	6.44	18.825	12.85
Mg (Mg/L)	2.487	3.94	4.25	8.87	6.41	4.46	8.28	5.01
Hardness (Mg/L)	8	18	12	28	20	12	48	18
Chloride (Mg/L)	17.04	32.66	32.66	24.14	19.88	9.94	18.46	34.08
Na (Mg/L)	9.5	12.8	10.3	9.8	15.2	15.6	8.1	13.5
K (Mg/L)	3.9	3.5	5.2	4.1	4.6	6.2	2.0	4.3

The seasonal analysis of physico-chemical water quality parameters of three panchayats shows distinct spatial and temporal variations. Temperature varied from 27.4°C to 29.7°C, with slightly lower values during the monsoon and higher during pre and post-monsoon periods. The lowest values of pH recorded in Ala during the monsoon and the highest in Kainakari during post-monsoon. Electrical conductivity (EC) showed highest values in Edathuva during monsoon. Turbidity levels showed maximum during the monsoon and pre-monsoon

seasons, particularly in Ala.

Dissolved oxygen (DO) ranged between 4.6 and 7.3 mg/L, with higher values during the monsoon, where as Carbon dioxide level was notably elevated during the pre-monsoon at Edathuva (up to 70.4 mg/L). Water from Ala panchayat exhibited high acidity (up to 60 mg/L) during pre-monsoon, while Edathuva had comparatively higher alkalinity during the monsoon and post-monsoon seasons. Nitrate concentrations were highest in Edathuva (up to 12.017 mg/L) and Phosphate

Table 11
Transposed matrix of seasonal water quality parameters across three panchayats

	Ala Panchayat			Edathuva Panchayat			Kainakari Panchayat		
Season	Monsoon	Post-Monsoon	Pre-Monsoon	Monsoon	Post-Monsoon	Pre-Monsoon	Monsoon	Post-Monsoon	Pre-Monsoon
Temp_mean	27.98	28.25	28.4	28.2	27.93	28.17	28.1	28.58	28.97
Temp_std	0.458	0.518	0.465	0.362	0.168	0.319	0.507	0.67	0.148
Temp_sem	0.161	0.183	0.164	0.128	0.059	0.112	0.179	0.237	0.052
pH_mean	6.056	5.885	6.477	6.521	6.021	6.147	6.632	6.836	6.415
pH_std	0.454	0.159	0.277	0.121	0.395	0.325	0.331	0.661	0.121
pH_sem	0.16	0.056	0.098	0.043	0.139	0.114	0.117	0.233	0.042
DO_mean	6.212	6.262	6.437	5.975	6.5	6.537	5.962	5.187	5.892
DO_std	0.274	0.523	0.565	0.406	0.459	0.726	0.489	0.67	0.265
DO_sem	0.097	0.185	0.199	0.143	0.162	0.257	0.173	0.237	0.093
NO ₃ _mean	7.628	6.199	6.251	5.814	5.515	6.311	0.066	0.028	0.027
NO ₃ _std	4.327	1.849	1.58	1.899	0.647	2.74	0.04	0.005	0.007
NO ₃ _sem	1.529	0.653	0.558	0.671	0.228	0.968	0.017	0.001	0.002
PO ₄ _mean	0.015	0.036	0.022	0.012	0.026	0.009	0.132	0.148	0.175
PO ₄ _std	0.006	0.026	0.016	0.007	0.005	0.0076	0.003	0.006	0.017
PO ₄ _sem	0.002	0.009	0.005	0.002	0.002	0.002	0.001	0.002	0.006

mean: average concentration calculated from multiple samples; std: standard deviation; sem: standard error of the mean.

concentrations remained low across sites, with values mostly below 0.2 mg/L.

Concentrations of Calcium and magnesium were generally higher in Edathuva and Ala, particularly during the post-monsoon season. Chloride value exhibited spatial variability, with Edathuva recording the highest concentration (308.14 mg/L) during monsoon. Sodium and potassium concentrations remained moderate but showed site-specific peaks during certain seasons.

B. Seasonal and Spatial Descriptive Trends

The statistical trends of water quality parameters revealed that the temperature showed minimal seasonal fluctuation, with the highest values recorded during the pre-monsoon period, particularly in Kainakari (Table 11). pH ranged from slightly acidic to neutral, with Kainakari exhibiting more alkaline conditions in the post-monsoon season. Dissolved oxygen (DO) levels remained generally favourable across sites, with Ala showing higher concentrations, especially in the pre-monsoon period, indicating better water aeration. Nitrate levels were highest in Ala during the monsoon, while Kainakari consistently exhibited low nitrate concentrations. Phosphate values were elevated in Kainakari, especially during pre-monsoon, suggesting nutrient enrichment. The results indicate that Ala is more prone to monsoonal nitrate influx, Edathuva maintains moderate and stable water chemistry, and Kainakari is characterized by higher phosphate concentrations and slightly alkaline conditions.

C. Seasonal Trend Analysis/Boxplot Analysis

The boxplots-based analysis for Kainakari Panchayat clearly depict seasonal variation of important physico-chemical parameters. Temperature showed a marginal decline during the monsoon compared to pre and post-monsoon periods. pH values were significantly higher during the post-monsoon representing reduced acidity. Dissolved oxygen (DO) highest during the monsoon reflecting enhanced aeration. Nitrate concentrations showed a sharp increase during the monsoon due to nutrient influx from surface runoff. Phosphate levels remained comparatively stable but showed slight seasonal peaks (Fig. 2).

Seasonal Trends in Water Quality Parameters - Kainakari Panchayat

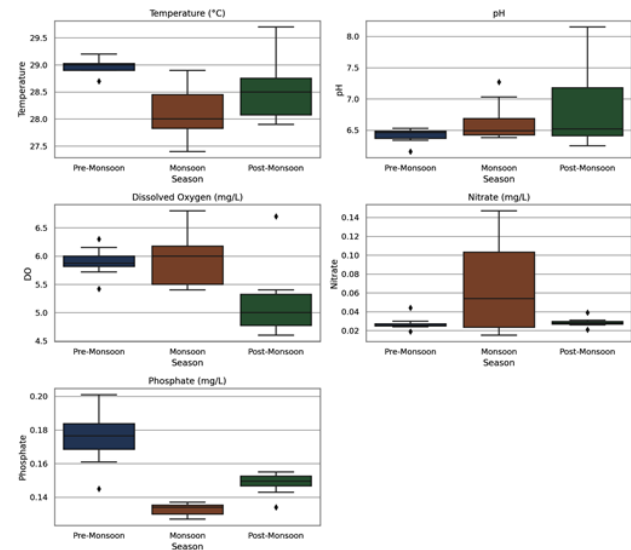


Fig. 2. Seasonal trends in the water quality parameters of Kainakari panchayat

Seasonal Trends in Water Quality Parameters - Edathuva Panchayat

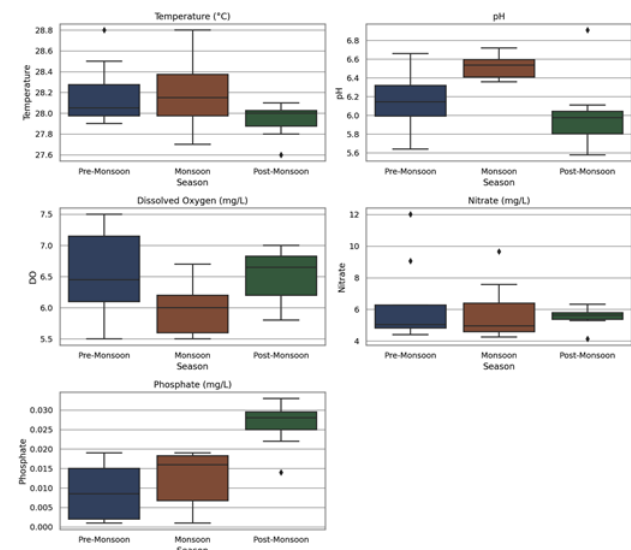


Fig. 3. Seasonal trends in the water quality parameters of Edathuva panchayat

The seasonal boxplots for Edathuva show noticeable fluctuations across parameters. Temperature remained relatively stable across seasons, pH values showed a slight increase during the monsoon indicating improved buffering. DO showed increased value in the post-monsoon season due to dilution effects and enhanced aeration. Nitrate concentrations were highest during the pre-monsoon and monsoon periods suggesting substantial nutrient runoff especially from agricultural zones. Phosphate levels remained low, with minor seasonal variations (Fig. 3).

Seasonal boxplots in Ala Panchayat revealed marked variability in pH and turbidity related parameters. Temperature remained unchanging across seasons, pH dropped noticeably during the monsoon reflecting increased acidity possibly due to organic runoff. DO levels were comparatively lower during the post-monsoon. Nitrate concentrations peaked during the monsoon reflecting nutrient influx from catchment runoff. Phosphate concentration remained low with slight seasonal fluctuations (Fig. 4).

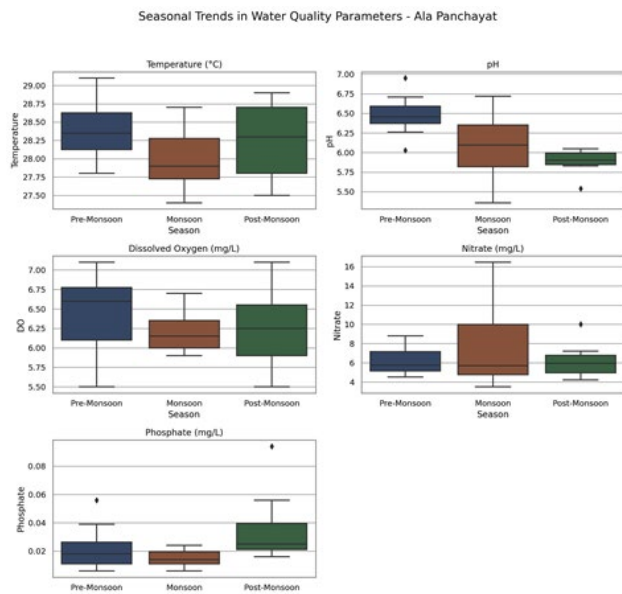


Fig. 4. Seasonal trends in the water quality parameters of Ala Panchayat

D. Correlation Matrix Interpretation

The correlation matrix (Fig. 5) summarizes the relationships among key physico-chemical parameters across all sites and seasons. Notable associations include a strong negative correlation between nitrate and phosphate concentrations, and moderate to strong inverse relationships between dissolved oxygen with both pH and phosphate. Temperature showed a positive correlation with phosphate and a negative correlation with nitrate.

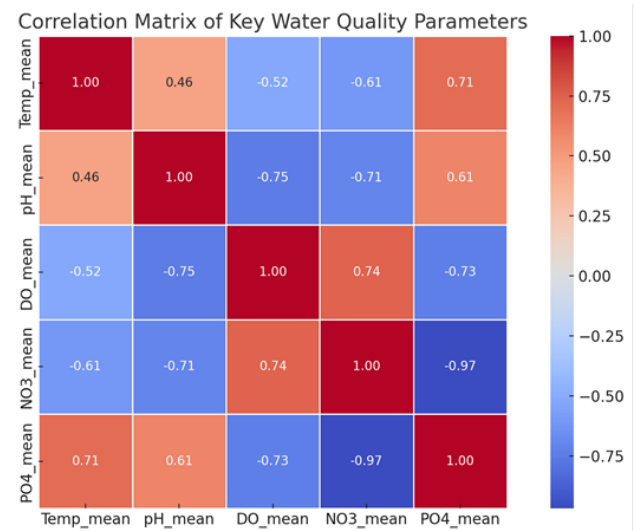


Fig. 5. Correlation matrix of key water quality parameters

E. Two-Way ANOVA Findings

The two-way ANOVA results revealed a statistically significant effect of panchayat (location) on nitrate concentrations ($F = 78.61$, $p < 0.0001$), while the effects of season and the interaction between panchayat and season were not significant (Table 12). This indicates that spatial variation plays a dominant role in influencing nitrate levels across the study area, whereas seasonal changes exert comparatively minimal influence.

F. Principal Component Analysis (PCA)

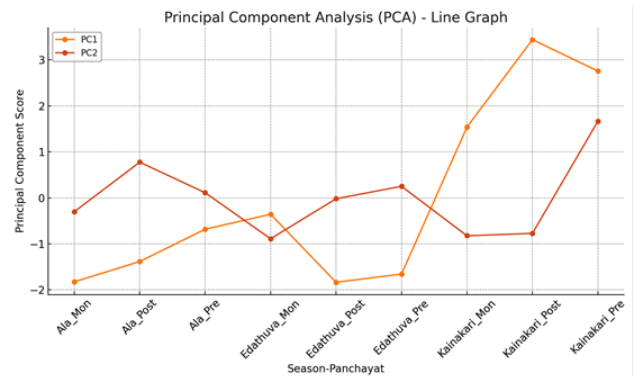


Fig. 6. PCA line graph showing the spatial and seasonal differentiation of water quality parameters across the three panchayats. Each point represents a season-specific water quality profile for a panchayat, and clustering patterns indicate similarity

G. Discriminant Function Analysis (DFA)

Discriminant Function Analysis (DFA) successfully differentiated the three panchayats based on five physico-chemical parameters. The first discriminant function (LD_1) explained 99.5% of the variance, clearly separating Kainakari from Ala and Edathuva. The DFA scatter plot (Fig. 7) illustrates distinct spatial clustering, with partial overlap between Ala and

Table 12
The two-way ANOVA effects of Panchayat (location), Season, and their interaction on nitrate concentrations across all sites

Source of Variation	Sum of Squares	df (degrees of freedom)	F-value
Panchayat	632.12	2	78.61
Season	4.16	2	0.52
Panchayat $\times$ Season	8.94	4	0.56
Residual	253.28	63	—

Edathuva, suggesting similar water quality influences in those regions.

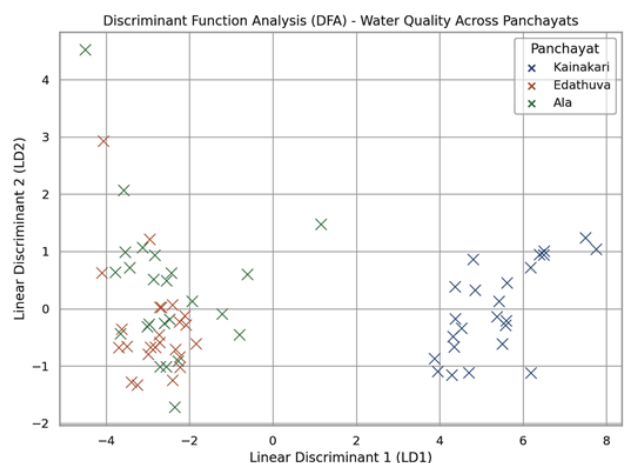


Fig. 7. Discriminant function analysis (DFA) Result showing water quality differentiation across panchayats

4. Discussions

Seasonal and spatial variations across Ala, Edathuva and Kainakari clearly reflect the combined influence of hydroclimatic drivers, land use intensity and internal wetland processes on water quality. Temperature showed only limited seasonal fluctuation, with slightly elevated pre-monsoon values at Kainakari, indicative of thermal retention in shallow wetland waters. pH exhibited spatial differentiation, with Ala experiencing lower monsoonal pH due to runoff and microbial respiration, while Kainakari remained mildly alkaline post-monsoon because of bicarbonate buffering and agricultural return flows. Elevated pre-monsoon phosphate and alkaline conditions in Kainakari highlight the contribution of domestic effluents and fertilizer leaching, consistent with recent studies identifying phosphate enrichment at river mouths and agricultural interfaces in the Vembanad-Kol wetland (Venukumar et al., 2024; SWAK, 2022; Yunus et al., 2020). These patterns mirror long-term trends of nutrient enrichment and hydrological alteration observed in tropical monsoon wetlands (Wetzel, 2001; Ramsar STRP, 2025).

Dissolved oxygen dynamics were strongly site-dependent: higher pre-monsoon DO at Ala suggests enhanced aeration, whereas post-monsoon declines in Kainakari correspond to increased oxygen demand following organic matter influx during the monsoon. Nutrient analysis revealed sensitivity to monsoonal nitrate pulses linked to runoff in Ala, relatively balanced nutrient state in Edathuva, and persistent phosphate enrichment due to waterlogging and sediment interactions in Kainakari. This aligns with broader evidence from Indian catchments where nitrate peaks during monsoon runoff while phosphate remains elevated in waterlogged zones with internal loading (Sinha et al., 2022; Venukumar et al., 2024). Correlation analysis demonstrated inverse nitrate-phosphate relationships and negative DO-phosphate/pH correlations, signatures characteristic of eutrophication and nutrient partitioning in monsoon-fed wetlands (SWAK, 2022; Wetzel,

2001). Two-way ANOVA confirmed that spatial heterogeneity rather than seasonality, dominates nitrate variability, reflecting differences in drainage, land use and fertilizer application across panchayats, consistent with monsoon-buffering effects observed in wetland soils (Sinha et al., 2022; Ramsar STRP, 2025).

Multivariate approaches provided strong diagnostic support for these patterns. PCA revealed clear nutrient gradients, separating Kainakari along phosphate-alkalinity axes and Ala along nitrate-runoff axes, while DFA highlighted distinct spatial clusters driven by phosphate enrichment and alkalinity at Kainakari. Such multivariate methods are increasingly recognized as essential for wetland assessment, offering integrated insight into land-use influences, hydrological dynamics, and internal nutrient cycling (Jolliffe & Cadima, 2016; Legendre & Legendre, 2012; Manly & Alberto, 2016). Applying these tools to the Kuttanad wetlands provides a robust basis for ecological monitoring and adaptive management, supporting regional strategies that emphasize targeted nutrient management, controlled drainage and continuous water-quality assessment to sustain the ecological integrity of this Ramsar site (SWAK, 2022; Ramsar STRP, 2025; Yunus et al., 2020).

5. Conclusions

This study elucidates distinct spatial and seasonal dynamics of key water quality parameters such as temperature, pH, dissolved oxygen, nitrate and phosphate across the Ala, Edathuva, and Kainakari panchayats of the Kuttanad wetlands. Seasonal analyses revealed that monsoonal nitrate enrichment in Ala primarily results from fertilizer runoff, while persistent phosphate accumulation and alkaline conditions in Kainakari, from sediment interactions and agricultural return flows, with Edathuva representing a transitional, relatively stable zone. Correlation analysis demonstrated strong inverse relationships between nitrate and phosphate and negative associations of dissolved oxygen with both pH and phosphate, indicating oxygen stress under eutrophic conditions. Multivariate approaches such as PCA effectively separated sites along nutrient and oxygen gradients, highlighting Kainakari's phosphate dominance and Ala's nitrate variability. These results underscore the utility of integrated statistical tools for identifying nutrient-driven ecological stressors and advocate for spatially differentiated nutrient management and continuous monitoring frameworks to sustain the ecological integrity of the Kuttanad wetland ecosystem.

Author Contribution Statement: Alexander T, as the sole author of this manuscript, was responsible for the conception and design of the study, field sampling, laboratory analysis, data processing, statistical analyses, interpretation of results, preparation of figures and tables, and drafting and revising the manuscript. The author has read and approved the final version of the manuscript and agrees to be accountable for all aspects of the work.

Data Availability Statement: The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. All raw data supporting the findings, including seasonal physico-chemical

parameters and statistical outputs (PCA, ANOVA, DFA), are maintained in institutional repositories and can be accessed with appropriate permissions.

Conflict of Interest: The author declares that there is no conflict of interest regarding the publication of this manuscript.

Funding declaration: The author declares that no funding or financial support was received from any agency, organization, or institution for the conduct of this research.

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