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Original Article

Unveiling hydro-edaphic dynamics of the Manakudy Estuary: implications for ecosystem health

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Abstract
The present study investigated the seasonal variations of physicochemical and sediment parameters in the Manakudy Estuary, a critical tropical estuarine ecosystem in India. Key water quality variables encompassing basic physicochemical properties, oxygen dynamics, inorganic carbon, major ions, primary productivity, and nutrient regimes were analysed, as these collectively regulate estuarine biogeochemical processes and biological functioning. These parameters are essential as they collectively influence the chemical and biological environment of the estuary. Seasonal samples were collected from three selected sites across the estuary over a one-year period from March 2024 to February 2025, covering four seasons with triplicate sampling at each site. Descriptive statistics i.e., mean ± standard error (SE) were calculated based on replicate samples at each site and season to evaluate spatial and temporal variability. ANOVA revealed significant effects of season on several physicochemical and soil parameters (p<0.001), indicating pronounced spatio-temporal heterogeneity in the ecological conditions of the Manakudy Estuary. Such variability reflects shifts in nutrient availability, oxygen balance, and productivity patterns, providing clear insights into the ecological condition and ecosystem health of the Manakudy Estuary and its vulnerability to environmental stressors.

Keywords: Manakudy Estuary; physicochemical parameters; primary productivity; sediment characteristics; spatio-temporal variation

1 | INTRODUCTION

An estuary is a semi-enclosed coastal water body with a free connection to the open sea and partial dilution by freshwater from terrestrial drainage (Pritchard 1967). Seasonal variations in river discharge, tides, and freshwater create fluctuations in salinity and physicochemical characteristics, driving ecological processes within estuarine ecosystems. Hydrobiological and geochemical studies are essential to understand the water quality, nutrient dynamics, and ecological productivity in aquatic communities (Krishna *et al*. 2011; Anitha Kumari *et al*. 2023). Estuaries contain complex physical, chemical, and biological processes that regulate aquatic life distribution. Environmental variables like salinity (Marais 1982; Whitfield 1999; Sreekanth *et al*. 2017), temperature (Peterson and Ross 1991; Jaureguizar *et al*. 2004), turbidity (Blaber and Blaber 1980), and depth (Hyndes *et al*. 1999) regulate fish assemblage structure. Hydrochemical parameters including dissolved oxygen (DO), pH, total dissolved solids (TDS), alkalinity, hardness, and heavy metals influence estuarine biota (Anitha Kumari *et al*. 2023). Sediments serve as sinks and sources for macronutrients like nitrogen and phosphorus, which may cause eutrophication in excess (Gulfem *et al*. 2010). Organic carbon levels indicate benthic productivity in aquatic systems (Sharma and Farooq 2018).

The deterioration of estuarine water quality due to anthropogenic pressures, such as pollution, habitat alteration, and overexploitation, has led to major declines in biodiversity and fish assemblage health (Duque *et al*. 2020). Given their ecological and economic significance, estuaries warrant continuous monitoring to assess environmental fluctuations, nutrient enrichment, and overall ecosystem resilience.

India's extensive coastline, spanning approximately 11,098.81 km (Ministry of Ports, Shipping and Waterways 2025), supports 1.44 – 2.6 million hectares of estuarine and backwater ecosystems, harbouring rich biological diversity (Nair *et al*. 1983). The 53 major estuaries of the country, including the Ganges–Hooghly, Godavari, Krishna, and Cauvery systems sustain vital fisheries of Hilsa, mullets, prawns, and crabs (Jhingran 1991; Ranjan and Yadava 2021). In Tamil Nadu, estuarine wetlands such as Pichavaram, Muthupet, Vellar, and Manakudy collectively account for approximately 56,000 ha (De 2011), serving as key habitats for ichthyofauna (Mogalekar *et al*. 2018).

The Manakudy Estuary, the second largest in Kanyakumari district, covers an area of about 150 ha and is situated approximately 8 km northwest of Cape Comorin in Tamil Nadu (Pearl and Fenreji 2010). This tropical sandbar-built estuary is formed at the confluence of the River Pazhayar and the Arabian Sea and encompasses a mosaic of habitats, including mangroves, mudflats, tidal pools, and seagrass beds (Ajithamol *et al*. 2014). Mangroves enhance nutrient cycling through detrital input, supporting high biological productivity. The estuary has a semi-arid climate influenced by both monsoons, with average annual rainfall of 800 mm and mean temperature of 27.97 °C (Ajithamol *et al*. 2014). Several studies have examined the hydrochemical and sediment characteristics, focusing on physicochemical parameters and nutrient status (Kannappan and Karthikeyan 2013; Ajithamol *et al*. 2014; Ramamurthy and Abhinand 2016; Hency and Kavitha 2021; Muthusamy *et al*. 2021). While earlier studies have provided valuable baseline information on the Manakudy Estuary, they largely focused on a limited set of physicochemical variables such as temperature, salinity, and nutrients. Most lacked an integrated evaluation linking comprehensive physicochemical parameters, including oxygen dynamics, productivity metrics, and sediment characteristics, with biological components, thereby restricting a holistic understanding of ecosystem functioning and health. Moreover, the substantial temporal gap since the last detailed assessment underscores the need for updated investigations to evaluate present environmental conditions and ongoing ecological dynamics in the Manakudy Estuary. Hence, the present study aims to quantify seasonal and spatial variations in physicochemical and sediment characteristics of the Manakudy Estuary and to evaluate their implications for ecosystem health using integrated environmental indicators.

2 | METHODOLOGY

2.1 Description of the study area

The Manakudy Estuary, the second largest estuary in the Kanyakumari district, encompasses an area of approximately 150 ha and is located approximately 8 km northwest of Cape Comorin in Tamil Nadu. Three sampling sites were selected within the Manakudy Estuary for the present investigation: near the freshwater inflow (S1: 8°6′27.91″N, 77°28′52.76″E), within the mid-mangrove region (S2: 8°5′59.76″N, 77°29′2.36″E), and near the estuarine mouth (S3: 8°5′32.04″N, 77°29′8.01″E) (Figure 1).

2.2 Sampling and analysis of water quality parameters

Water samples were collected in 1 litre polypropylene bottles from the selected sampling stations during the morning hours between 6 to 9 AM. The air and water temperature, TDS, EC, pH, and salinity were recorded on the spot using a handheld Electrode Method (Flyouth multifunctional water quality tester). Transparency was measured using a Secchi disc. The initial dissolved oxygen was also recorded immediately for further calculation using Winkler's iodometric method (Adoni 1985). The collected water samples were taken to the laboratory for further analysis using standard methods. The water quality parameters, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total alkalinity, total hardness, free carbon dioxide (CO_2), nitrite – nitrogen, nitrate – nitrogen, ammonia, and phosphate concentrations, were analysed by APHA (2012) method.

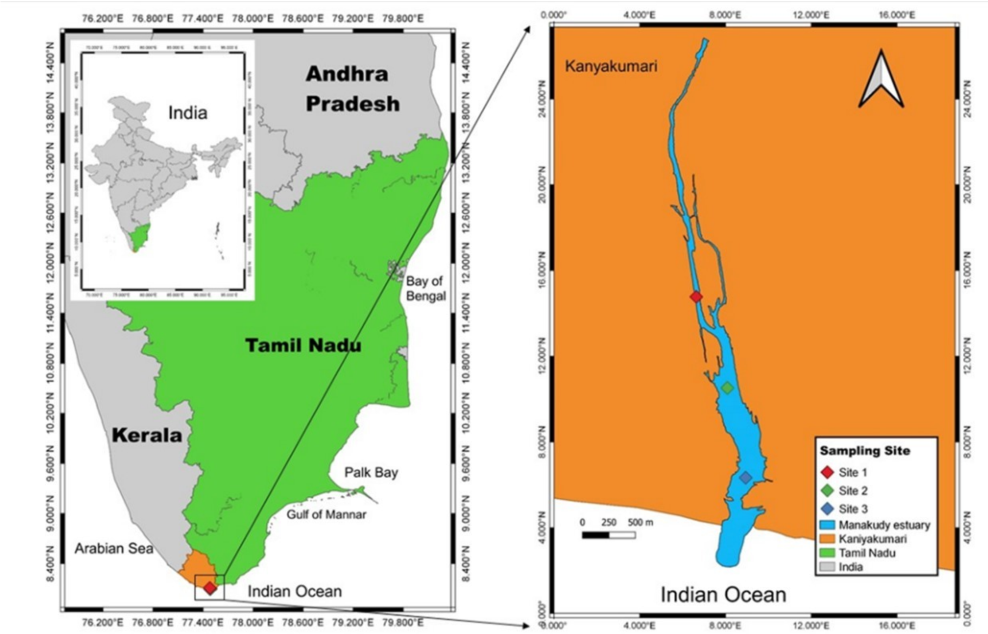


FIGURE 1 Map showing Study Area in the Manakudy Estuary, India.

2.3 Primary productivity

The primary productivity of estuarine water was estimated using the light and dark bottle method of Gaarder and Gran (1927). Water samples were collected from a depth of 0 – 20 cm and gently transferred into three 300 ml BOD bottles (initial, light, and dark), ensuring minimal disturbance. The initial bottles were immediately fixed and analyzed for dissolved oxygen using Winkler's iodometric method, while the light and dark bottles were suspended at the sampling depth with bamboo poles and incubated in situ for 2 hours. This incubation period was selected as a compromise between allowing measurable oxygen changes and minimising changes due to bottle effects or diel variation. At the end of the incubation period, both bottles were retrieved, fixed immediately, and their dissolved oxygen content was determined. The measured oxygen changes were then standardised to per-hour rates in the productivity calculations.

$$\text{GPP (mg C/ m}^3\text{/hr)} = \frac{(LD-DB)\times 1000\times 0.375}{(1.2\times t)}$$

Where
LB = DO concentration in the light bottle
DB = DO concentration in the Dark Bottle
IB = DO concentration in the Initial Bottle
t = exposure time in hour

2.4 Sampling and analysis of soil quality parameters

Sediment samples from the Manakudy Estuary were collected using an Ekman grab sampler at a depth of approximately 1–3 m. At each site and season, three grab samples were collected and either composited or treated as independent replicates for laboratory analysis. Upon collection, the samples were immediately placed in sterile polythene bags, tagged, and transported to the laboratory for analysis. In the laboratory, the sediments were air-dried at room temperature to remove excess moisture while preserving their natural properties. The dried samples were gently disaggregated using a mortar and pestle and subsequently sieved through a 2-mm mesh to obtain a fine, homogeneous fraction suitable for further analysis. Soil pH and electrical conductivity (EC) were determined using standard meters, whereas organic carbon content was estimated using the Walkley–Black method (Walkley and Black 1934). Soil moisture content was determined gravimetrically using a standardised subsample mass of 20 g to ensure uniform drying and minimise variability. Samples were oven-dried at 105±5°C for 24 h until a constant weight was reached. Moisture was expressed as a percentage of the dry weight, calculated from the mass loss during the drying process following FAO (2023) protocols. Soil texture was determined using the Jar Test method and classified with the USDA Soil Texture Triangle (Wang and Feddema 2020).

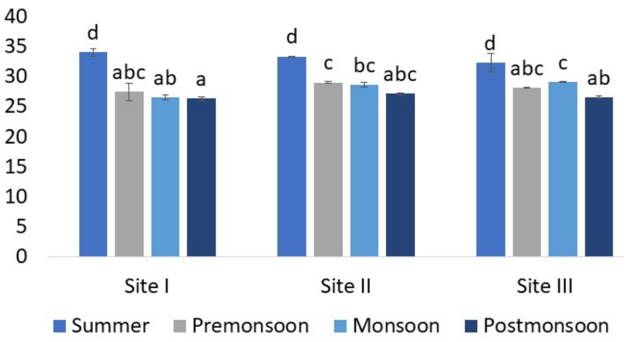
2.5 Data analysis

The sampling was conducted seasonally such as post-monsoon (January–March), summer (April–June), pre-monsoon (July–September) and monsoon (October–December) (Pillai *et al*. 2014) for a period of one year from March 2024 to February 2025, with triplicate samples taken for each parameter at each site during every season. Analysis of variance (ANOVA) was performed to determine the significance of seasonal variations in water and sediment quality parameters. Statistical analyses were carried out using SPSS v22 with a significance level set at $p<0.001$.

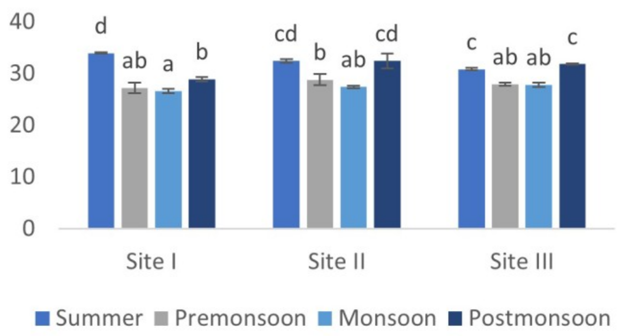
3 | RESULTS

The physicochemical characteristics of estuarine water, such as temperature, salinity, pH, electrical conductivity (EC), total dissolved solids (TDS), transparency, dissolved oxygen (DO), BOD, COD, free carbon, alkalinity, hardness, primary productivity (GPP, NPP), and nutrients (phosphate, ammonia, nitrite, nitrate), play a critical role in regulating estuarine chemical and biological processes. Seasonal surface water samples from the three selected sites of the Manakudy Estuary were collected from March 2024 to February 2025. Descriptive statistics (Mean±SE) were computed for all water and soil parameters to evaluate temporal and spatial variability. Spatio–temporal variations in air, water and soil quality parameters of the Manakudy Estuary across sampling sites and seasons are presented in Figure 2a–2x. To assess the effects of both season and site, as well as their potential interactions, a two-way ANOVA was performed with a significance level of $p<0.05$. This approach enabled independent evaluation of the main effects (season and site) and their interaction, which provides a more robust analysis. The results revealed significant seasonal and spatial variations across parameters (Table 1), with detailed ANOVA outcomes presented in Table 2.

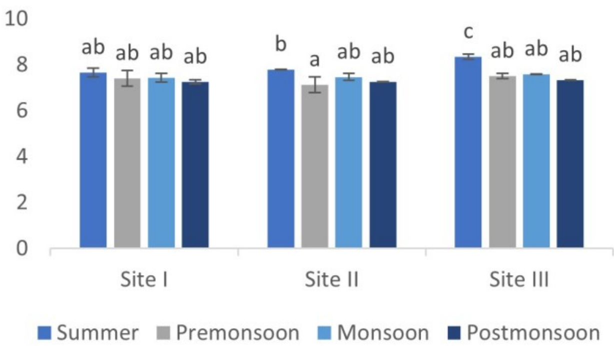
FIGURE 2 Spatio–temporal variations in physico–chemical properties of the Manakudy Estuary (a–x)



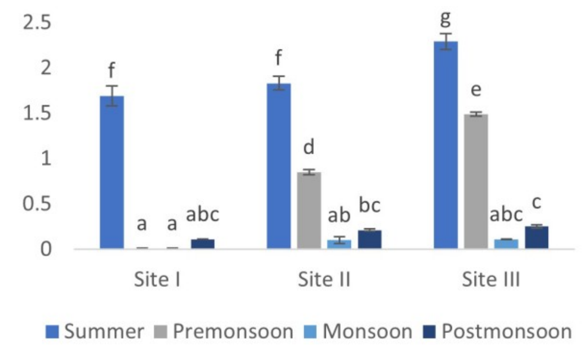
(a) Air temperature (°C)



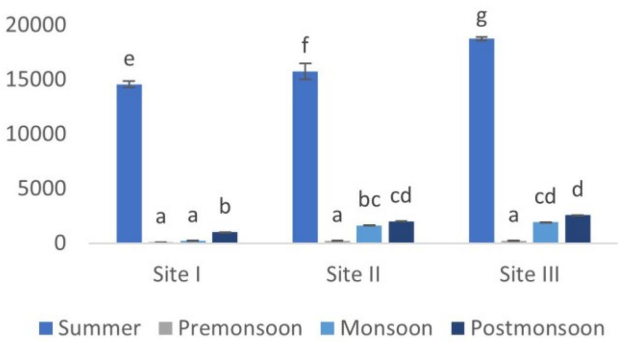
(b) Water temperature (°C)



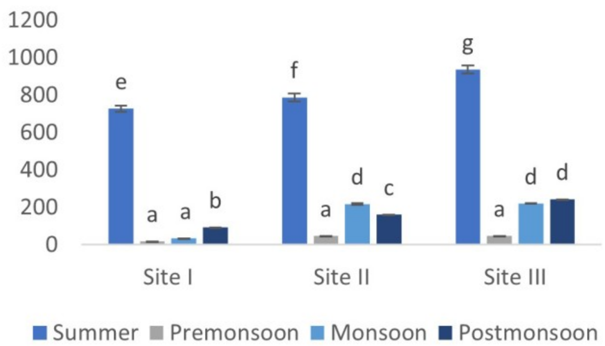
(c) pH



(d) Salinity (%)

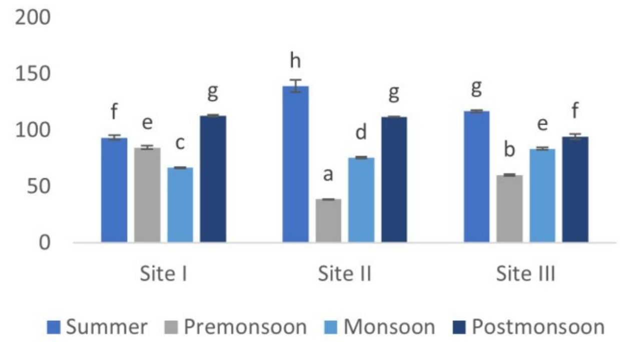


(e) TDS (ppm)

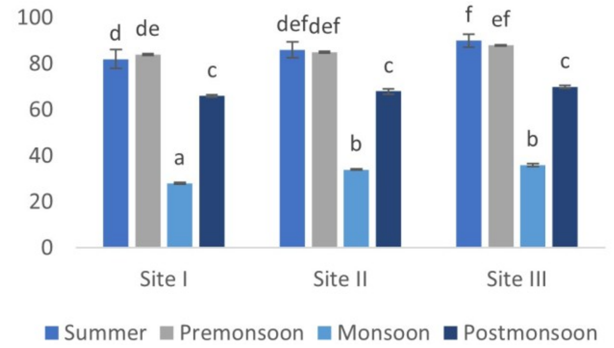


(f) EC (ds/m)

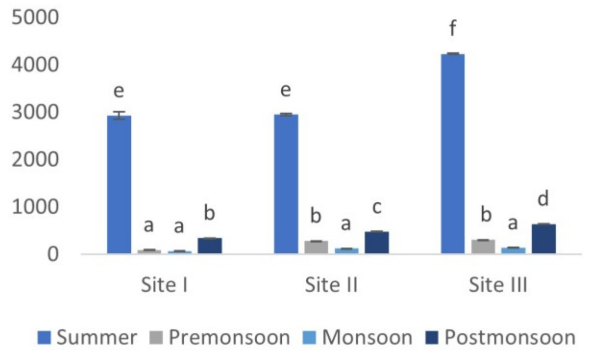
FIGURE 2 Continued.



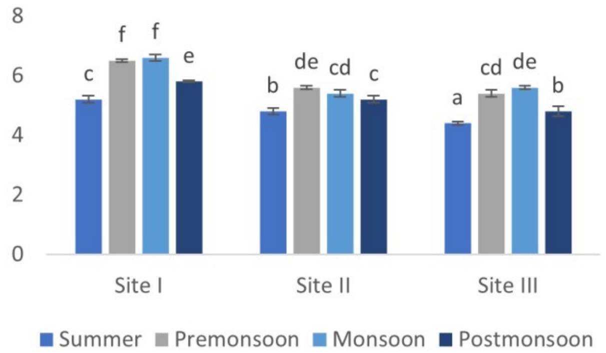
(g) Transparency (cm)



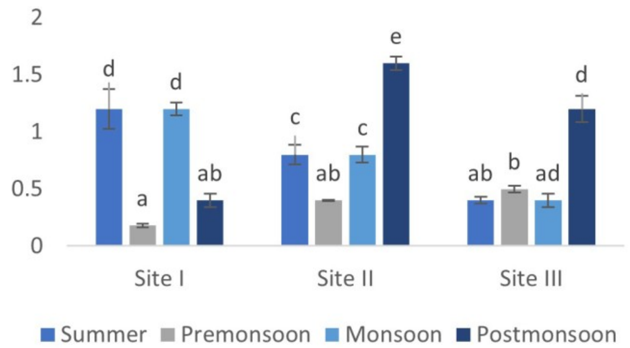
(h) Alkalinity (mg/L)



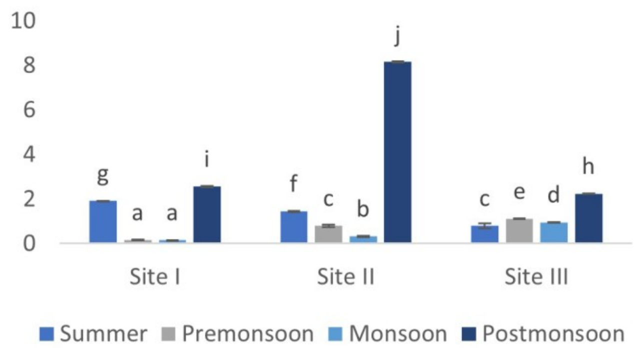
(i) Hardness (mg/L)



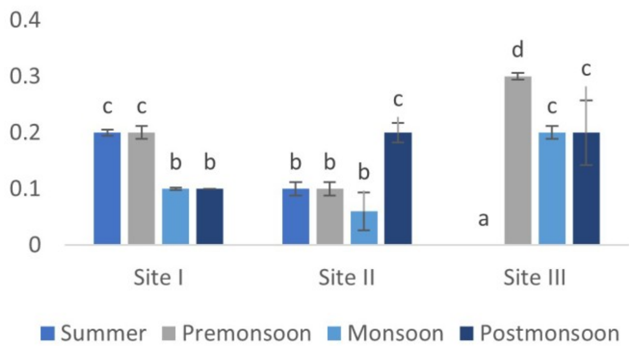
(j) Dissolved oxygen (mg/L)



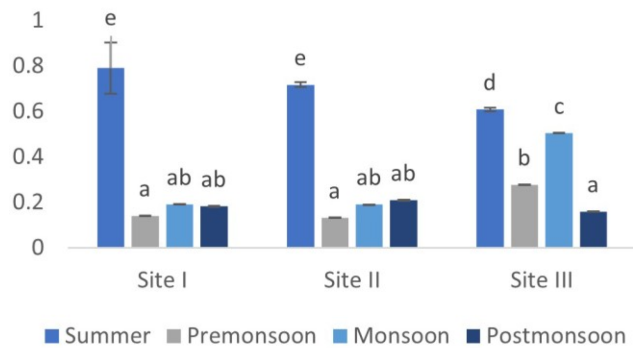
(k) BOD (mg/L)



(l) COD (mg/L)

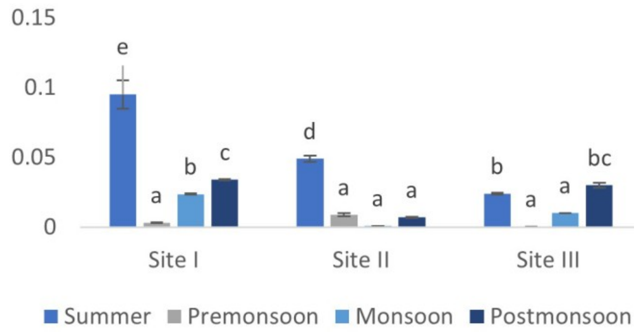


(m) Free carbon dioxide (mg/L)

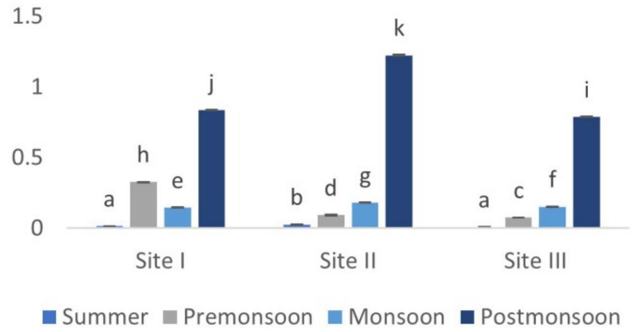


(n) Phosphate (mg/L)

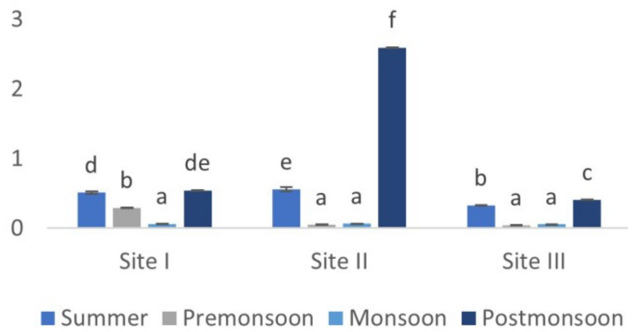
FIGURE 2 Continued.



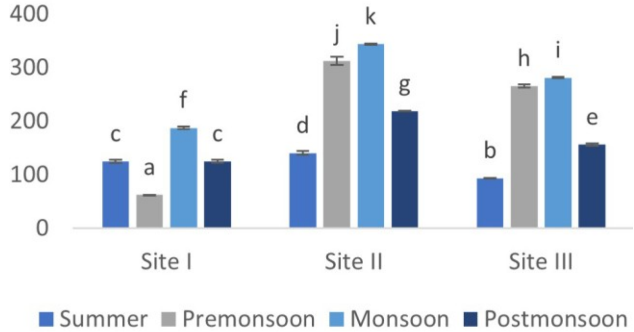
(o) Ammonia (mg/L)



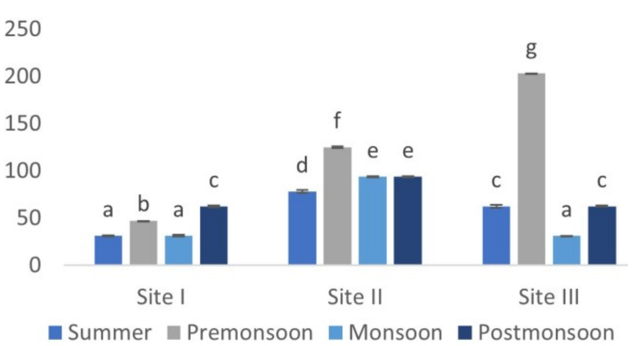
(p) Nitrite (mg/L)



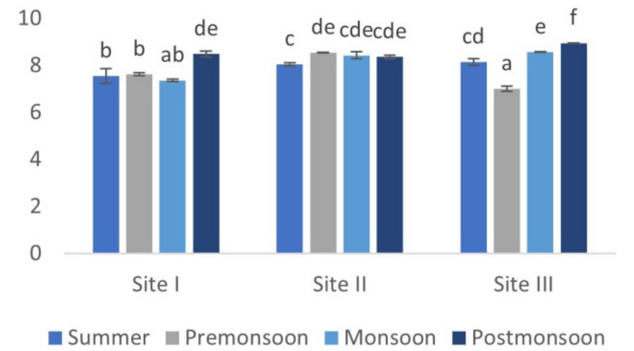
(q) Nitrate (mg/L)



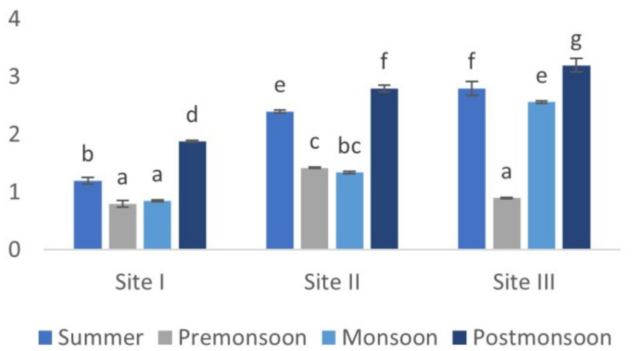
(r) GPP (mg C/m^3/h)



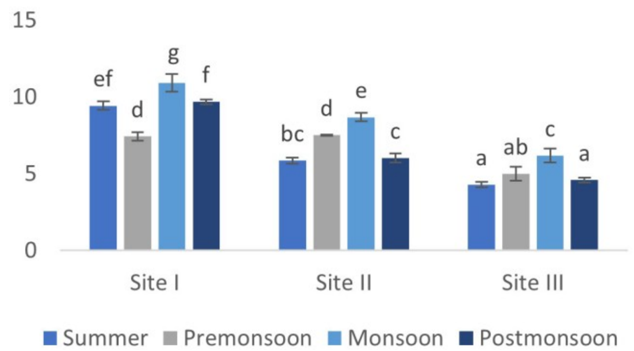
(s) NPP (mg C/m^3/h)



(t) Soil pH

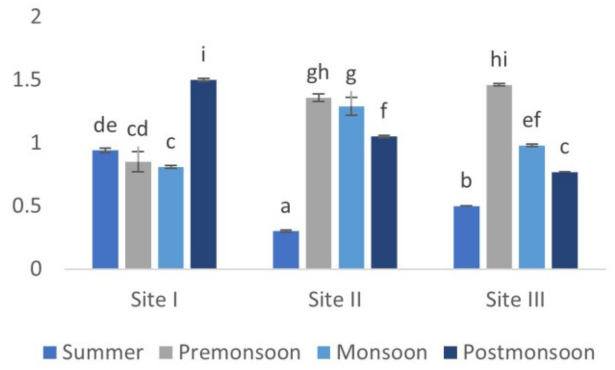


(u) Soil EC (ds/m)

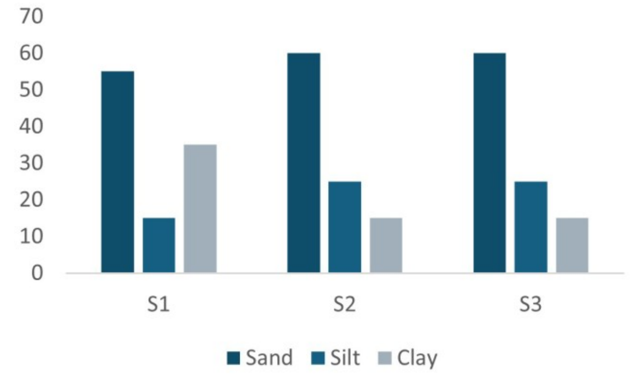


(v) Soil moisture (%)

FIGURE 2 Continued.



(w) Soil organic carbon (%)



(x) Soil texture (%)

TABLE 1 Analysis of physicochemical parameters of air, water and soil of the Manakudy Estuary, India.

Parameters	Summer			Pre-monsoon			Monsoon			Post-monsoon		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
Air temperature (°C)	34.1 ± 0.58	33.4 ± 0.12	32.4 ± 1.56	27.5 ± 1.44	29.1 ± 0.12	28.2 ± 0.12	26.6 ± 0.40	28.7 ± 0.40	29.2 ± 0.12	26.4 ± 0.35	27.2 ± 0.12	26.6 ± 0.23
Water temperature (°C)	33.9 ± 0.11	32.4 ± 0.35	30.8 ± 0.23	27.2 ± 1.03	28.8 ± 1.03	27.9 ± 0.28	26.6 ± 0.46	27.4 ± 0.23	27.8 ± 0.40	28.9 ± 0.40	32.4 ± 1.38	31.8 ± 0.17
pH	7.66 ± 0.19	7.79 ± 0.02	8.35 ± 0.11	7.4 ± 0.34	7.13 ± 0.34	7.5 ± 0.11	7.43 ± 0.19	7.46 ± 0.15	7.59 ± 0.01	7.25 ± 0.08	7.26 ± 0.01	7.33 ± 0.02
Salinity (%)	1.69 ± 0.10	1.83 ± 0.07	2.29 ± 0.08	0.01 ± 0.00	0.85 ± 0.02	1.49 ± 0.02	0.01 ± 0.00	0.10 ± 0.03	0.11 ± 0.00	0.11 ± 0.00	0.21 ± 0.01	0.25 ± 0.01
TDS (ppm)	14560 ± 323.31	15740 ± 735. 05	18740 ± 138.56	96 ± 0.57	234 ± 1.73	236 ± 3.46	217 ± 2.88	1634 ± 3.46	1914 ± 8.08	1004 ± 2.33	2000 ± 1.73	2560 ± 1.73
EC (ds/m)	728 ± 16.16	787 ± 21.36	937 ± 21.36	18.6 ± 0.17	46.5 ± 0.86	46.9 ± 0.11	33.9 ± 0.34	219.5 ± 4.90	219.5 ± 1.44	92.4 ± 0.47	161.1 ± 0.17	242.9 ± 0.11
Transparency (cm)	93.35 ± 1.93	139 ± 5.45	116.7 ± 0.98	84.5 ± 1.44	38.7 ± 0.17	60.2 ± 0.69	66.7 ± 0.51	75.5 ± 0.86	83.5 ± 0.86	112.75 ± 0.74	111.75 ± 0.14	94.25 ± 2.45
Alkalinity (mg/L)	82 ± 4.04	86 ± 3.46	90 ± 2.88	84 ± 0.28	85 ± 0.28	88 ± 0.28	28 ± 0.40	34 ± 0.28	36 ± 0.57	66 ± 0.60	68 ± 1.15	70 ± 0.69
Hardness (mg/L $CaCO_3$)	2930 ± 75.05	2950 ± 28.86	4230 ± 11.54	92 ± 2.30	282 ± 1.15	308 ± 1.15	70 ± 0.69	126 ± 2.30	140 ± 1.73	342 ± 1.15	480 ± 1.73	642 ± 2.88
DO (mg/L)	5.2 ± 0.11	4.8 ± 0.11	4.4 ± 0.05	6.5 ± 0.05	5.6 ± 0.05	5.4 ± 0.11	6.6 ± 0.11	5.4 ± 0.11	5.6 ± 0.05	5.8 ± 0.02	5.2 ± 0.11	4.8 ± 0.17
BOD (mg/L)	1.2 ± 0.17	0.8 ± 0.08	0.4 ± 0.02	0.18 ± 0.01	0.4 ± 0.00	0.5 ± 0.02	1.2 ± 0.05	0.8 ± 0.06	0.4 ± 0.05	0.4 ± 0.05	1.6 ± 0.05	1.2 ± 0.11
COD (mg/L)	1.92 ± 0.00	1.44 ± 0.02	0.8 ± 0.11	0.16 ± 0.00	0.8 ± 0.05	1.12 ± 0.02	0.16 ± 0.00	0.32 ± 0.01	0.96 ± 0.00	2.56 ± 0.01	8.16 ± 0.02	2.24 ± 0.01
Free CO_2 (mg/L)	0.2 ± 0.00	0.1 ± 0.01	0	0.2 ± 0.01	0.1 ± 0.01	0.3 ± 0.00	0.1 ± 0.00	0.06 ± 0.03	0.2 ± 0.01	0.1 ± 0.00	0.2 ± 0.01	0.2 ± 0.05
Phosphate (mg/L)	0.79 ± 0.11	0.72 ± 0.00	0.60 ± 0.00	0.14 ± 0.00	0.13 ± 0.00	0.28 ± 0.00	0.19 ± 0.00	0.19 ± 0.00	0.50 ± 0.00	0.18 ± 0.00	0.20 ± 0.00	0.16 ± 2.59
Ammonia (mg/L)	0.09 ± 0.01	0.049 ± 0.00	0.02 ± 0.00	0.003 ± 0.00	0.008 ± 0.00	0.0004 ± 0.00	0.02 ± 0.00	0.0009 ± 0.00	0.01 ± 0.00	0.03 ± 0.00	0.007 ± 0.00	0.03 ± 0.00
Nitrite (mg/L)	0.01 ± 0.00	0.03 ± 0.00	0.009 ± 0.00	0.32 ± 0.00	0.09 ± 0.00	0.08 ± 0.00	0.15 ± 0.00	0.18 ± 0.00	0.15 ± 0.00	0.84 ± 0.00	1.22 ± 0.00	0.79 ± 0.00
Nitrate (mg/L)	0.51 ± 0.01	0.56 ± 0.03	0.33 ± 0.00	0.29 ± 0.00	0.05 ± 0.00	0.05 ± 0.01	0.06 ± 0.00	0.07 ± 0.00	0.06 ± 00	0.55 ± 0.00	2.59 ± 0.00	0.40 ± 0.00

TABLE 1 Continued.

GPP (mg C/m³/h)	125 ± 2.89	140.62 ± 3.24	93.75 ± 0.29	62.5 ± 0.06	312.5 ± 7.22	265.62 ± 3.24	187.5 ± 2.60	343.75 ± 0.72	281.25 ± 1.01	125 ± 2.89	218.75 ± 0.14	156.25 ± 2.60
NPP (mg C/m³/h)	31.25 ± 0.72	78.12 ± 1.80	62.5 ± 1.44	46.88 ± 0.22	125 ± 1.15	203.125 ± 0.01	31.25 ± 0.01	93.75 ± 0.72	31.25 ± 0.08	62.5 ± 0.87	93.75 ± 0.52	62.5 ± 0.58
Soil pH	7.54 ± 0.31	8.05 ± 0.05	8.14 ± 0.13	7.62 ± 0.06	8.54 ± 0.01	7 ± 0.11	7.36 ± 0.05	8.42 ± 0.15	8.56 ± 0.01	8.48 ± 0.13	8.36 ± 0.08	8.94 ± 0.01
Soil EC (ds/m)	1.2 ± 0.05	2.4 ± 0.02	2.8 ± 0.12	0.8 ± 0.05	1.42 ± 0.01	0.9 ± 0.01	0.85 ± 0.01	1.34 ± 0.01	2.56 ± 0.02	1.88 ± 0.01	2.8 ± 0.05	3.2 ± 0.11
Soil moisture (%)	9.44 ± 0.28	5.86 ± 0.20	4.3 ± 0.17	7.43 ± 0.28	7.52 ± 0.04	5.00 ± 0.46	10.62 ± 0.56	8.69 ± 0.28	6.18 ± 0.45	9.69 ± 0.16	6.03 ± 0.30	4.59 ± 0.16
Organic carbon (%)	0.94 ± 0.02	0.3 ± 0.01	0.5 ± 0.00	0.85 ± 0.08	1.36 ± 0.03	1.46 ± 0.01	0.81 ± 0.01	1.29 ± 0.07	0.98 ± 0.01	1.5 ± 0.01	1.05 ± 0.01	0.77 ± 0.00
Soil texture	Sandy clay	Sandy loam	Sandy loam	Sandy clay	Sandy loam	Sandy loam	Sandy clay	Sandy loam	Sandy loam	Sandy clay	Sandy loam	Sandy loam

S1, Site 1 (towards freshwater influx); S2, Site 2 (mid-mangrove area); S3 (towards the mouth of the estuary)

TABLE 2 ANOVA results showing temporal effects on physicochemical parameters in the Manakudy Estuary, India.

Parameters	*df*	*F*	*p*
Air temperature	3, 30	16.628	<0.001*
Water temperature	3, 30	15.194	<0.001*
pH	3, 30	3.333	<0.007*
Salinity	3, 30	303.541	<0.001*
TDS	3, 30	874.548	<0.001*
EC	3, 30	1074.096	<0.001*
Transparency	3, 30	203.794	<0.001*
Alkalinity	3, 30	157.723	<0.001*
Hardness	3, 30	3776.495	<0.001*
DO	3, 30	41.023	<0.001*
BOD	3, 30	34.001	<0.001*
COD	3, 30	3027.735	<0.001*
Free CO_2	3, 30	15.162	<0.001*
Phosphate	3, 30	55.590	<0.001*
Ammonia	3, 30	79.675	<0.001*
Nitrite	3, 30	33257.098	<0.001*
Nitrate	3, 30	3526.847	<0.001*
GPP	3, 30	945.678	<0.001*
NPP	3, 30	2862.908	<0.001*
Soil pH	3, 30	21.686	<0.001*
Soil EC	3, 30	221.481	<0.001*
Soil moisture	3, 30	44.845	<0.001*
Organic carbon	3, 30	138.905	<0.001*

*Significant at 99.9% level of significance (p<0.001); df, degree of freedom; F, *F*-test statistic for regression analysis; p, *p*-value

4 | DISCUSSION

4.1 Water quality parameters

Temperature is a crucial regulator of aquatic metabolism, influencing species distribution and physiological processes (Galib *et al.* 2018; Parvez *et al.* 2023; Khatun *et al.* 2024). In the Manakudy Estuary, air temperature ranged from 26.4±0.35°C (post-monsoon, S1) to 34.1±0.58°C (summer, S1), consistent with Kannappan and Karthikeyan (2013) and Ramamurthy and Abhinand (2016), who reported similar seasonal trends linked to solar intensity and tidal mixing. Comparable fluctuations were recorded in Cochin (Thasneem *et al*. 2018), Arasalar (Raju *et al*. 2017), and Adimalathura (Kumary *et al*. 2007), reflecting regional climatic and hydrological influences on temperature dynamics. Water temperature ranged from 26.6±0.46°C (monsoon, S1) to 33.9±0.11°C (summer, S1), aligning with previous reports of 24±1.4 – 31.0±1.5°C (Kannappan and Karthikeyan 2013) and 27.4±2.06 – 33.4±2.56°C (Ramamurthy and Abhinand 2016). Similar seasonal variations were noted in Cochin (25.0–34.0°C; Nandan and Geetha 2018), Arasalar (25.0–31.5°C; Raju *et al*. 2017), and Kodungallur–Azhikode (23.9±0.5°C in July to 31.3±0.8°C in March; Jayachandran *et al*. 2012). Higher summer temperatures reported for Narmada (29–30°C) and Mahi (28–30°C) estuaries, compared to Sabarmati (27–30°C), were attributed to industrial effluent discharge (Deshkar *et al*. 2012). Overall, temperature fluctuations in the Manakudy Estuary reflect typical tropical estuarine responses to seasonal and anthropogenic factors.

pH reflects the acidity or alkalinity of water and indicates water quality. In the Manakudy Estuary, pH ranged from 7.13±0.34 at S2 during pre-monsoon to 8.35±0.11 at S3 in summer, showing alkaline conditions suitable for estuarine biota. Higher summer pH resulted from increased photosynthetic CO_2 uptake and evaporation, while lower pre-monsoon values reflected riverine input. These align with previous reports of 7.5±0.56 – 8.4±0.73 (Kannappan and Karthikeyan 2013), 7.6±1.26 – 8.7±2.16 (Ramamurthy and Abhinand 2016), and 7.7–8.7 (Muthusamy *et al*. 2021). Similar patterns were observed in Cochin Estuary (7.07–7.47) (Nandan and Geetha 2018), Karamana River Estuary (6.98–7.63) (Shanmugasundharam *et al*. 2023), Arasalar Estuary (7.1–8.2) (Raju *et al*. 2017), and Thoothukudi mangroves (8.18–8.47) (Ramesh *et al*. 2023). Lower pH occurred during monsoon in Kodungallur–Azhikode Estuary (6.9±0.2) due to freshwater inflow (Jayachandran *et al*. 2012). Manakudy Estuary maintains stable, slightly alkaline pH year-round, supporting nutrient cycling and estuarine organisms.

Salinity is a key ecological parameter in estuarine systems, influencing osmoregulation and survival of aquatic organisms. In the Manakudy Estuary, salinity ranged from 0.01±0.00% at S1 during pre-monsoon to 2.29±0.08% at S3 during summer. Seasonal variability was evident, with lowest values during high freshwater inflow and highest in summer due to evaporation and seawater intrusion. Earlier studies reported 0.75±2.1 – 2.8±3.1% (Kannappan and Karthikeyan 2013), 2.38±1.44 – 2.91±1.25% (Ramamurthy and Abhinand 2016), and 0.29–1.61% (Sheela and Kumar 2014). Salinity fluctuations govern nutrient availability and primary productivity, driving adaptations in resident species. Similar patterns were observed in neighbouring estuaries, with salinity ranging from 0.001–3.4% in Cochin (Nandan and Geetha 2018); 0.54±5.8% during monsoon to 2.16±4.8% post-monsoon in Kodungallur–Azhikode (Jayachandran *et al*. 2012); and 0.01–3.2% in Tapti estuaries (Kumar *et al*. 2009). Thoothukudi mangroves recorded 3.0–3.6% (Ramesh *et al*. 2023), while Ennore Creek ranged from 2.3–2.8% during 2018–19 to 23–27.5% during 2022–23 (Vardhanapu 2024). Manakudy Estuary shows typical seasonal salinity patterns, with summer concentration and monsoon dilution shaping ecosystem functioning.

Total dissolved solids (TDS), indicative of salinity and overall estuarine health, ranged from 96±0.57 mg L^{-1} at S1 (pre-monsoon) to 18,740±138.56 mg L^{-1} at S3 (summer) in the Manakudy Estuary, markedly higher than earlier values of 854±1.21 – 910±1.12 mg L^{-1} (Ramamurthy and Abhinand 2016) and 2800–3900 mg L^{-1} (Sheela and Kumar 2014). Elevated summer TDS reflects evaporation and seawater intrusion, while monsoon minima result from freshwater dilution. Similar seasonal trends were reported in other estuaries such as, 0.01 – 323 mg L^{-1} in Cochin (Nandan and Geetha 2018), 61.4 – 7301.5 mg L^{-1} and 87.8 – 12,651 mg L^{-1} in Mahanadi (Sundaray *et al*. 2006, 2009 respectively), 1310 – 1620 mg L^{-1} (2018–19) and 1500 – 1627 mg L^{-1} (2022–23) in Ennore Creek (Vardhanapu 2024), and 130 – 17,500 mg L^{-1} in the Karamana river estuary (Shanmugasundharam *et al*. 2023).

Electrical conductivity (EC), which reflects the ionic content of water and is closely associated with salinity and dissolved solids, ranged from 18.6 ± 0.17 dS m^{-1} at S1 during pre-monsoon to 937 ± 21.36 dS m^{-1} at S3 in summer in the Manakudy Estuary. These values substantially exceeded earlier reports of 2.83 – 3.44 dS m^{-1} (Sheela and Kumar 2014) and 288 ± 5.14 – 392 ± 6.17 dS m^{-1} (Ramamurthy and Abhinand 2016). Elevated EC during summer likely results from strong evaporation, tidal influx, and seawater intrusion, whereas lower monsoon values reflect dilution from freshwater inflow. Similar seasonal patterns have been documented in other Indian estuaries, with EC ranging from 22.37 – 34.10 dS m^{-1} in the Cochin Estuary (Nandan and Geetha 2018), 0.1248 – 26.748 dS m^{-1} during the pre-monsoon period of the Mahanadi riverine estuary (Sundaray *et al*. 2009), and 0.1655 – 22.535 dS m^{-1} from monsoon to pre-monsoon in the Mahanadi river–estuarine system (Sundaray et al. 2006). These comparisons indicate that while EC variability is typical of estuarine systems, the Manakudy Estuary exhibits exceptionally high summer levels, reflecting pronounced ionic concentration effects.

Transparency, measured using a Secchi disc, indicates light penetration and inversely correlates with turbidity (Wetzel 2001). In the Manakudy Estuary, transparency ranged from 38.7 ± 0.17 cm at S2 during pre-monsoon to 139 ± 5.45 cm at S2 in summer. The observed higher transparency during summer corresponded with lower turbidity, suggesting reduced sediment inflow, efficient tidal flushing, and seasonal variation in catchment runoff. Previous reports documented turbidity levels of 48 ± 8.3 – 327 ± 14.5 NTU (Kannappan and Karthikeyan 2013), 1.1 – 2.31 NTU (Sheela and Kumar 2014), and 5.25 ± 3.08 – 7.87 ± 2.87 NTU (Ramamurthy and Abhinand 2016), indicating comparatively clearer waters in the present study. Similar seasonal patterns have been reported in neighbouring estuaries, with Cochin showing higher transparency during post- and pre-monsoon (90 ± 0.15 cm and 81 ± 0.15 cm) and lower values during monsoon due to increased runoff and reduced solar radiation (Patil and Anil 2011; Jayachandran *et al*. 2012; Bijoy Nandan *et al*. 2014; Nandan and Geetha 2018). The Kodungallur–Azhikode Estuary exhibited 80 ± 0.3 – 110 ± 0.5 cm (Jayachandran *et al*. 2012), while Adimalathura recorded 9 – 108 cm (Kumary *et al*. 2007). These findings confirm that the Manakudy Estuary displays typical estuarine transparency fluctuations, primarily influenced by riverine input, tidal mixing, and sediment load.

Alkalinity, indicating the buffering capacity of water derived mainly from carbonates, bicarbonates, phosphates, nitrates, borates, silicates, and hydroxyl ions, stabilizes pH and supports aquatic productivity (Saluja and Jain 1998). In the Manakudy Estuary, values ranged from 28 ± 0.40 mg L^{-1} at S1 (monsoon) to 90 ± 2.88 mg L^{-1} at S3 (summer), showing spatial and seasonal variation. Monsoon minima reflected freshwater dilution, while summer maxima resulted from reduced discharge, evaporation, and seawater intrusion. Higher levels compared to earlier reports (15.9 – 26.1 mg L^{-1}; Ramamurthy and Abhinand 2016) indicate enhanced buffering from organic decomposition, tidal mixing, and dissolved carbonates. Similar trends occurred in Cochin (20.05 – 40.22 mg L^{-1}; Nandan and Geetha 2018), Kodungallur–Azhikode (24.4 – 43.7 mg L^{-1}; Jayachandran *et al*. 2012), Mahanadi (21.0 – 193.0 mg L^{-1}; Sundaray *et al*. 2009), Thoothukudi mangroves (20.91 – 24.66 mg L^{-1}; Ramesh *et al*. 2023), and Tapti Estuary (76 – 224 mg L^{-1}; Kumar *et al*. 2009), confirming moderate to high alkalinity in Manakudy under strong tidal influence.

Water hardness, determined mainly by calcium and magnesium salts such as bicarbonates and carbonates for temporary hardness, and sulphates, chlorides, or other minerals for permanent hardness, affects water chemistry and quality (Jiwyam and Chareontesprasit 2001). In the Manakudy Estuary, hardness ranged from 70 ± 0.69 mg L^{-1} at S1 (monsoon) to 4230 ± 11.54 mg L^{-1} at S3 (summer), showing clear spatial and seasonal variation. Low monsoon values reflect freshwater dilution, while elevated summer concentrations result from reduced river discharge, evaporation, and salt accumulation. These levels exceed earlier reports of 1050 –1210 mg L^{-1} (Ramamurthy and Abhinand 2016), indicating stronger seawater intrusion, mineral leaching, and possible anthropogenic inputs. Seasonal hardness variation is also reported in Cochin (61 – 3233.85 mg L^{-1}; Nandan and Geetha 2018), Kodungallur–Azhikode (490.2 – 1294 mg L^{-1}; Jayachandran *et al*. 2012), Mahanadi (34.36 – 3437.51 mg L^{-1}; Sundaray *et al*. 2009), and Karamana (36 – 6000 mg L^{-1}; Shanmugasundharam *et al*. 2023) estuaries.

Dissolved oxygen (DO), a key indicator of estuarine health, ranged from 4.4 ± 0.05 mg L^{-1} at S3 in summer to 6.5 ± 0.05 mg L^{-1} at S1 during pre-monsoon in the Manakudy Estuary, reflecting moderately oxygenated conditions (Devi *et al*. 2017). Lower summer values result from higher temperatures reducing solubility, while monsoon peaks are driven by freshwater inflow, aeration, tidal mixing, and phytoplankton photosynthesis. Occasional reductions occur due to respiration and organic matter decomposition. Comparable DO levels are reported in Cochin (5.87 – 6.42 mg L^{-1}; Nandan and Geetha 2018), Kodungallur–Azhikode (4.7 – 5.9 mg L^{-1}; Jayachandran *et al*. 2012), Arasalar (5.0 – 10.3 mg L^{-1}; Raju *et al*. 2017), Mahanadi (3.40 – 8.13 mg L^{-1}; Sundaray *et al*. 2006), Thoothukudi mangroves (3.88 – 5.12 mg L^{-1}; Ramesh *et al*. 2023), Ennore Creek (3.0 – 5.3 mg L^{-1}; Vardhanapu 2024), Adimalathura (3.30 – 6.05 mg L^{-1}; Kumary *et al*. 2007), and Tapti (2.1 – 8.5 mg L^{-1}; Kumar *et al*. 2009). Overall, moderate DO of the Manakudy Estuary supports diverse aquatic life, though summer lows may stress sensitive species.

Biochemical oxygen demand (BOD) reflects oxygen consumed by microorganisms during organic matter decomposition and indicates organic pollution in aquatic systems. In the Manakudy Estuary, BOD ranged from 0.18 ± 0.01 mg L^{-1} at S1 during pre-monsoon to 1.6 ± 0.05 mg L^{-1}at S2 in post-monsoon, showing low organic load. The low values indicate efficient microbial decomposition and effective tidal dilution. Ramamurthy and Abhinand (2016) reported higher levels (8.8 – 14.2 mg L^{-1}) during their study period. Regional comparisons show Cochin recorded 1.89 – 3.15 mg L^{-1} (Nandan and Geetha 2018), Kodungallur–Azhikode 2.2 – 3.1 mg L^{-1} (Jayachandran *et al*. 2012), Mahanadi Estuary 0.38 – 6.27 mg L^{-1} (Sundaray *et al*. 2006), Thoothukudi mangroves 2.02 – 2.52 mg L^{-1} (Ramesh *et al*. 2023), and Ennore Creek 37.5 – 50.6 mg L^{-1} during 2018–19 and 23 – 49.6 mg L^{-1} during 2022–23 (Vardhanapu 2024). The low BOD levels in Manakudy indicate minimal organic stress, supporting healthier oxygen dynamics for estuarine biota.

Chemical oxygen demand (COD) reflects the oxidizable fraction of organic and inorganic matter in water and indicates pollution load. In the Manakudy Estuary, COD ranged from 0.16 ± 0.00 mg L^{-1} at S1 during pre-monsoon and monsoon to 8.16 ± 0.02 mg L^{-1} at S2 in post-monsoon, with peak values likely from enhanced terrestrial runoff after rainfall. Earlier studies showed higher COD levels, with Ramamurthy and Abhinand (2016) reporting 59.7 – 73.2 mg L^{-1}. Comparisons with other estuaries show regional variations: Thoothukudi mangroves 7.76 – 9.43 mg L^{-1} (Ramesh *et al*. 2023), and Ennore Creek 230 – 352 mg L^{-1} (2018–19) and 230 – 351 mg L^{-1} (2022–23) (Vardhanapu 2024). The low COD in Manakudy suggests reduced anthropogenic discharge and effective tidal flushing, indicating minimal organic stress and good conditions for estuarine biota.

In the present study, free carbon varied spatially and seasonally, from 0 mg L^{-1} at S3 in summer to 0.3 mg L^{-1} at S3 in pre-monsoon. The absence in summer likely reflects oxidation and greater organic carbon use under higher temperature and salinity, while pre-monsoon values suggest increased organic input and incomplete decomposition. Compared with Ramamurthy and Abhinand (2016), reporting 1.45 ± 2.14 mg L^{-1} in monsoon and 1.91 ± 2.45 mg L^{-1} in summer, this study shows lower concentrations, likely due to differences in organic loading, hydrodynamics, and freshwater inflow. CO_2 concentrations ranged from 5.3 ± 1.8 mg L^{-1} to 7.1 ± 2.1 mg L^{-1} in the Kodungallur–Azhikode Estuary (Jayachandran *et al*. 2012).

4.2 Nutrient concentrations

Phosphate is a vital nutrient regulating primary productivity in estuarine waters, though elevated levels can lead to eutrophication. In the Manakudy Estuary, concentrations ranged from 0.13 ± 0.00 mg L^{-1} (S2, pre-monsoon) to 0.79 ± 0.11 mg L^{-1} (S1, summer), with higher values during post-monsoon due to terrestrial runoff and organic matter decomposition. These values align with Kannappan and Karthikeyan (2013), reporting 0.023 ± 0.006 to 0.125 ± 0.025 mg L^{-1}, and Ramamurthy and Abhinand (2016), documenting 0.901 ± 0.84 mg L^{-1} in summer to 1.655 ± 0.15 mg L^{-1} in monsoon. Muthusamy *et al*. (2021) reported post-monsoon values of 1.6 to 11.5 mg L^{-1}. Nearby estuaries showed similar ranges such as, Cochin Estuary 0.185 ± 0.055 – 0.367 ± 0.055 mg L^{-1} (Nandan and Geetha 2018), Kodungallur–Azhikode Estuary 0.095 ± 0.123 mg L^{-1} (Jayachandran *et al*. 2012), Mahanadi system 0.11 – 18.63 mg L^{-1} (Sundaray *et al*. 2006), Arasalar Estuary 0.00029 – 0.00215 mg L^{-1} (Raju *et al*. 2017), Thoothukudi mangroves 0.00133 – 0.00224 mg L^{-1} (Ramesh *et al*. 2023), Adimalathura Estuary 0.020 – 0.086 mg L^{-1} (Kumary *et al*. 2007), and Tapti Estuary 0.015 – 0.473 mg L^{-1} (Kumar *et al*. 2009).

Ammonia, the main nitrogenous waste excreted by aquatic fauna, indicates nitrogen cycling efficiency in aquatic systems (Cao *et al*. 2007). In the Manakudy Estuary, ammonia ranged from 0.003 ± 0.00 mg L^{-1} (pre-monsoon, S1) to 0.09 ± 0.01 mg L^{-1} (summer, S1), reflecting minimal organic pollution. These values align with Kannappan and Karthikeyan (2013) (0.00051–0.00375 mg L^{-1}) but are far lower than those reported by Muthusamy *et al*. (2021) (7.3 mg L^{-1}) and Ramamurthy and Abhinand (2016) (5.8–7.3 mg L^{-1}). Seasonal peaks during summer and post-monsoon likely result from terrestrial runoff, organic decomposition, and limited dilution. Comparable levels were recorded in Cochin (0.0049–0.827 mg L^{-1}) (Nandan and Geetha 2018), Kodungallur–Azhikode (0.051–0.095 mg L^{-1}) (Jayachandran *et al*. 2012), Thoothukudi mangroves (0.00178–0.00269 mg L^{-1}) (Ramesh *et al*. 2023), and Ennore Creek (0.0141–0.0608 mg L^{-1}) (Vardhanapu 2024).

In the Manakudy Estuary, nitrite concentrations peaked during the post-monsoon season with 0.84 ± 0.00, 1.22 ± 0.00, and 0.79 ± 0.00 mg L^{-1} at S1, S2, and S3, respectively, indicating limited accumulation of intermediate nitrogen forms and a balanced nitrogen cycle. Seasonal peaks likely reflect enhanced microbial nitrification from organic matter input and runoff. Comparatively, lower nitrite levels were reported in Cochin (0.0060 – 0.0154 mg L^{-1}; Nandan and Geetha 2018), Kodungallur–Azhikode (0.018 mg L^{-1}; Jayachandran *et al*. 2012), Thoothukudi mangroves (0.00147 – 0.00206 mg L^{-1}; Ramesh *et al*. 2023), Ennore Creek (0.12 – 0.192 mg L^{-1}; Vardhanapu 2024), and Adimalathura (0.0024 – 0.0094 mg L^{-1}; Kumary *et al*. 2007). Overall, Manakudy exhibits moderately higher nitrite concentrations, suggesting active nitrogen transformation and efficient tidal flushing with minimal nitrogen accumulation.

Nitrate (NO_3^-), formed through bacterial nitrification and reduced to nitrogen via denitrification in anaerobic sediments (Furnas 1992), showed low concentrations in the Manakudy stuary, peaking post-monsoon at 0.55 ± 0.00, 2.59 ± 0.00, and 0.40 ± 0.00 mg L^{-1} at S1, S2, and S3, respectively. These values indicate limited nutrient enrichment, with post-monsoon peaks driven by freshwater inflow and runoff. Earlier reports from Manakudy recorded higher levels such as 9.1 – 17 mg L^{-1} (Ramamurthy and Abhinand 2016) and 85.5 mg L^{-1} (Muthusamy *et al*. 2021), while Kannappan and Karthikeyan (2013) found comparable low ranges (0.038 – 0.40 mg L^{-1}). Other Indian estuaries exhibit wide nitrate variability such as, Cochin (0.138 – 0.227 mg L^{-1}; Nandan and Geetha 2018), Kodungallur–Azhikode (0.24 – 1.18 mg L^{-1}; Jayachandran *et al*. 2012), Mahanadi (0.00049 – 3.73 mg L^{-1}; Sundaray *et al*. 2009), Arasalar (0.00049 – 0.00375 mg L^{-1}; Raju *et al*. 2017), Thoothukudi mangroves (0.00038 – 0.00067 mg L^{-1}; Ramesh *et al*. 2023), Ennore Creek (0.00007 – 0.000095 mg L^{-1}; Vardhanapu 2024), Karamana (2 – 65 mg L^{-1}; Shanmugasundharam *et al*. 2023), Adimalathura (0.0028 – 0.0168 mg L^{-1}; Kumary *et al*. 2007), and Tapti (0.05 – 0.16 mg L^{-1}; Kumar *et al*. 2009). Overall, nitrate levels in the Manakudy Estuary remain relatively low, indicating moderate nitrogen availability, efficient tidal flushing, and minimal eutrophication risk, with seasonal fluctuations governed by hydrological and catchment dynamics.

4.3 Primary productivity

In the present study, Gross Primary Productivity (GPP) was highest at S2 during the monsoon season (343.75 ± 0.72 mg C m^{-3} h^{-1}) and lowest at S1 during the pre-monsoon season (62.5 ± 0.06 mg C m^{-3} h^{-1}). These seasonal variations reflect the influence of nutrient availability, light intensity, and hydrological conditions on primary production. Maharajan and Kumarasamy (2012) reported maximum GPP during the post-monsoon period (2318 mg C m^{-3} h^{-1}), highlighting similar seasonal trends where nutrient enrichment and hydrological inputs drive productivity. The elevated GPP observed in both studies during nutrient-rich periods underscores the strong dependence of estuarine primary production on seasonal environmental dynamics.

In the present study, Net Primary Productivity (NPP) was highest at S3 during the pre-monsoon season (203.125 ± 0.01 mg C m^{-3} h^{-1}). This aligns with the findings of Maharajan and Kumarasamy (2012), who reported peak NPP during the pre-monsoon period (1530 mg C m^{-3} h^{-1}), reflecting the balance between gross production and respiratory losses. The observed seasonal trend in the present study suggests that estuarine productivity is strongly influenced by environmental factors such as nutrient availability, light intensity, and hydrological conditions, as well as by ecosystem metabolic processes, which together regulate the net carbon assimilation across seasons.

4.4 Soil quality parameters

pH is a key parameter regulating chemical reactions in estuarine environments, influencing nutrient availability, microbial activity, and ecosystem health. In the present study, soil pH in the Manakudy Estuary ranged from 7.0 ± 0.11 (pre-monsoon at S3) to 8.94 ± 0.00 (post-monsoon at S3), indicating slightly acidic to moderately alkaline conditions. These values align with earlier reports where Hency and Kavitha (2021) documented an alkaline range of 8.06 –8.63. In Thoothukudi mangroves, pH values of 8.81 – 9.01 were reported (Ramesh *et al*. 2023), while lower values of 5.6 – 7.1 were observed in Thoothukudi mangrove forest (Keerthana *et al*. 2023). In the Kalpakkam coastal zone, pH ranged from 7.55 ± 1.1 in summer to 8.99 ± 1.1 during northeast monsoon (Pandion *et al*. 2023). Mangrove sediments of Kachchh showed values between 6.29 and 8.45 (Saravanakumar *et al*. 2008), while in the Sundarbans, pH varied from 6.47 ± 0.221 to 8.10 ± 0.391 (Ataullah *et al*. 2017). Seasonal pH changes are attributed to redox changes, freshwater inflow, and tidal mixing (Ramanathan 1997). The study confirms that Manakudy Estuary soil pH aligns with typical estuarine ranges.

Soil Electrical conductivity (EC) indicates salinity, affecting ion exchange, nutrient availability, and habitat suitability in estuarine systems. In the Manakudy Estuary, soil EC ranged from 0.8 ± 0.05 dS m^{-1} (pre-monsoon at S1) to 3.2 ± 0.11 dS m^{-1} (post-monsoon at S3), lower than previous reports where Hency and Kavitha (2021) recorded 2.83–9.14 dS m^{-1}. Comparisons with other systems show varying EC levels: Thoothukudi mangrove forest recorded 4.5-5.2 dS m^{-1} (Keerthana *et al*. 2023), Kalpakkam coastal zone showed 0.99-4.98 dS m^{-1} (Pandion *et al*. 2023), while Sundarbans exhibited higher levels of 4.84 ± 0.583 to 19.72 ± 5.695 dS m^{-1} (Ataullah *et al*. 2017). The moderate EC values in Manakudy Estuary indicate limited salinity stress, with seasonal increases post-monsoon reflecting tidal influx and reduced freshwater dilution.

Soil moisture regulates nutrient cycling, microbial activity, and vegetation growth, contributing to the stability of estuarine ecosystems. In the present study, soil moisture in the Manakudy Estuary ranged from 4.3 ± 0.17% (monsoon season at S3) to 10.62 ± 0.56% (monsoon season at S1). These values are lower than those reported for other estuarine systems, such as the Sundarbans of Bangladesh, where soil moisture ranged between 14.78 ± 3.65% and 33.27 ± 4.79% (Ataullah *et al*. 2017). The lower soil moisture in the Manakudy Estuary may be attributed to sandy sediment texture, higher evapotranspiration, and reduced freshwater retention compared to the clay-rich Sundarbans. These differences highlight the site-specific influence of geomorphology, vegetation cover, and hydrology on soil water retention capacity.

Soil organic carbon is vital for maintaining fertility, soil structure, and supporting microbial and plant productivity in estuarine environments. In the present investigation, organic carbon in the Manakudy Estuary ranged from 0.5 ± 0.00% (summer at S3) to 1.46 ± 0.01% (pre-monsoon at S3). Higher concentrations from this estuary were previously reported: 1.122 – 8.994% (Kumar and Sheela 2013) and 1.12 – 3.82% (Hency and Kavitha 2021). Other Indian mangrove systems showed varying values: 2.85 – 3.42% in Thoothukudi mangroves (Ramesh *et al*. 2023), 1.79 – 4.41% in Thoothukudi mangrove forest (Keerthana *et al*. 2023), and 0.29 – 2.56% in Kachchh, Gujarat (Saravanakumar *et al*. 2008). The Kalpakkam coastal zone showed 0.11% to 0.88% (Pandion *et al*. 2023), while Sundarbans, Bangladesh had 0.3168 ± 0.018% to 1.218 ± 0.215% (Ataullah *et al*. 2017). The present study indicates that Manakudy Estuary sediments contain low to moderate organic carbon compared to other South Asian estuarine ecosystems.

Sediment texture in the Manakudy Estuary showed spatial and seasonal variation. At S1, sediments were sandy (55% sand, 15% silt, 35% clay), while S2 and S3 had sandy loam textures (60% sand, 25% silt, 15% clay). Sand, silt, and clay averaged 54.81%, 44.50%, and 0.70%, indicating silty sand predominance, consistent with earlier observations (Hency and Kavitha 2021). Kumar and Sheela (2013) reported sand (76.23–91.7%), silt (6.29–22%), and clay (1.1–2.1%) proportions, with mud content between 8.3% and 23.77%. The present findings, with higher sand and lower clay content, reflect stronger tidal flushing during high-flow periods. Sediment composition varies across Indian estuarine ecosystems. In Kachchh-Gujarat mangroves, sand, clay, and silt ranged from 0.26–19.2%, 7.6–47%, and 47–87.4%, respectively (Saravanakumar *et al*. 2008), while in Thoothukudi mangrove forest, they ranged from 45.3–86.2%, 7.78–28.5%, and 6.0–26.2% (Keerthana *et al*. 2023).

The analysis revealed strong interrelationships among ionic, nutrient, and sediment parameters, indicating the combined influence of hydrology, tidal exchange, and anthropogenic inputs. Correlation and ANOVA confirmed significant ($p<0.05$) seasonal and spatial variations, demonstrating the estuary's sensitivity to environmental gradients. Compared with earlier studies, higher ionic and nutrient fluctuations suggest cumulative impacts of natural and human-induced factors. These findings highlight the need for continuous monitoring and integrated management to sustain the ecological health and productivity of the Manakudy Estuary.

5 | CONCLUSIONS

The present study provides a comprehensive assessment of the physicochemical parameters of the Manakudy Estuary, including primary productivity, and reveals pronounced seasonal and spatial variability characteristic of this tropical estuarine system. Variations in temperature, salinity, dissolved oxygen, nutrient concentrations, and sediment characteristics collectively regulate ecosystem health and productivity, reflecting the combined influence of natural processes and anthropogenic pressures. Elevated nitrite levels highlight the need for targeted control of land-based runoff and untreated effluent inputs, while seasonal increases in hardness and alkalinity emphasize the importance of managing freshwater inflow and groundwater interactions. In addition, site-specific salinity fluctuations underscore the need to maintain natural hydrological connectivity to sustain estuarine mixing and stability. Overall, the monsoon-driven heterogeneity of the Manakudy Estuary indicates a fragile metabolic balance, posing potential risks to its function as a fisheries nursery. These findings underscore the necessity for integrated, long-term monitoring that links physicochemical stressors with biological responses to support science-based management and enhance ecosystem resilience under ongoing climatic and environmental change.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

AUTHORS' CONTRIBUTION

Adyasha Sahu: Conceptualization, Data curation, Methodology, writing original draft, and editing. N. Jayakumar: Investigation, Supervision, Conceptualization, Validation. C. Sudhan: Software, Visualization, Formal analysis. R. Durairaja: Formal analysis, Supervision, Validation. P. Padmavathy and P. Velmurugan: Investigation and Formal analysis. Kamei Ringjonmeilu: Data curation, Conceptualization, Investigation. Sanjay Chandravanshi and Narsingh Kashyap: Formal analysis and Supervision.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available within the article.

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