**Assessment of Spatial Temporal Patterns of Nutrient Dynamics in Batapady Mangrove Ecosystem, Southwest India**

**Abstract:** This study examines the seasonal and spatial variability of nutrient concentrations in the Batapady mangrove ecosystem (Dakshina Kannada, India), based on monthly surface water sampling from five stations between October 2023 to June 2024. Four key nutrients ammonia-nitrogen (NH₃-N), nitrite-nitrogen (NO₂-N), nitrate-nitrogen (NO₃-N), and phosphate-phosphorus (PO₄-P) were measured alongside environmental parameters including salinity, pH, dissolved oxygen (DO), biological oxygen demand (BOD), and temperature. NH₃-N and PO₄-P exhibited peaks during the summer (NH₃-N85.15 µg-at/l at S1), while NO₃-N concentrations were highest during early post-monsoon. Nutrient levels and BOD, DO, and salinity were found to be significantly correlated by Spearman correlation analysis, which shows that nutrient release and retention are influenced by hydrological fluctuations and redox conditions. Spatial differences between stations reflected anthropogenic activities and variable flushing. Our findings demonstrate the vulnerability of small, fragmented mangrove stands to nutrient surges and underscore the need for targeted management interventions. Incorporating these monitoring insights into long-term nutrient management will help safeguard mangrove health and ensure estuarine water quality under growing human pressure.

**Keywords**: Mangrove, Nutrient variability, Tropical estuary, Batapady, Mangalore.

**1. Introduction**

Mangrove ecosystems provide vital services like shoreline stabilization, nutrient retention, carbon sequestration, and habitat provisioning. They are found along tropical and subtropical coasts and serve as ecological buffers between terrestrial and marine systems (Alongi, 2014; Friess *et al.*, 2016). Characterized by halophytic tree species like *Avicennia, Rhizophora, and Sonneratia*, mangroves thrive in dynamic intertidal environments through adaptations such as salt exclusion, aerial roots, and viviparous reproduction (Kathiresan & Bingham, 2001). Through microbial processes~~,~~ sediment adsorption, and plant uptake, mangrove sediments are essential for controlling nutrient dynamics (Alongi, 2002; Kristensen *et al.*, 2008). Nutrients (especially nitrogen and phosphorus) in the mangrove system are important regulators of carbon cycling and mangrove productivity (Wang *et al.,* 2021). While phosphorus is frequently immobilized under reducing conditions by binding with metal oxides, nitrogen compounds are primarily transformed and eliminated through coupled nitrification–denitrification and anaerobic ammonium oxidation (anammox) (Bouillon *et al.*, 2008; Chen *et al.*, 2010). However, depending on the season and degree of disturbance, mangrove systems can be both sources and sinks of nutrients due to remobilization that can happen during resuspension or changes in redox potential (Kristensen *et al.*, 2008).

These natural processes can be overpowered by anthropogenic nutrient enrichment from aquaculture, sewage discharge, and agriculture, which can also change nutrient ratios and upset the biogeochemical balance (Lee *et al.*, 2014). It has been demonstrated that too much phosphorus and nitrogen can cause eutrophication in nearby waters, change the structure of microbial communities, and decrease mangrove biodiversity (Bouillon *et al.*, 2008; Chen *et al.*, 2010). Due to limited hydrological flushing, small or fragmented mangrove patches are especially vulnerable to these impacts (Saravanakumar *et al.*, 2008). Many smaller mangrove systems in the Indian subcontinent are still not well-monitored, particularly those on the southwest coast. In these systems, water exchange and nutrient transport are significantly impacted by tropical monsoon cycles. Typically, monsoon-driven runoff leads to higher nutrient concentrations and lower salinity, while the dry season encourages concentration through evaporation (Kristensen *et al.*, 2008). However, there is still a lack of localized data from mangroves in southwest India despite these established trends.

In this context, the Batapady mangrove ecosystem, with its limited areal extent and exposure to agricultural and domestic inputs, presents a unique case for evaluating localized nutrient dynamics. However, no prior long-term nutrient assessment has been conducted in this system. This study addresses that gap by exploring with the objective, how do nutrient concentrations vary seasonally and spatially across stations within the Batapady mangrove region.

**2. Materials and Methods**

**2.1 Study Area**

The study was conducted in the Batapady mangrove ecosystem, located in the Mangaluru taluk of Dakshina Kannada district, Karnataka, India (12°55′–13°05′ N; 74°50′–75°00′ E). This estuarine fringe ecosystem is influenced by two rivulets Talapady and Uchila which transport freshwater and nutrients from upstream agricultural and semi-urban catchments. Five surface water sampling stations (S1 to S5) were selected to represent spatial heterogeneity in mangrove vegetation density, salinity gradients, and proximity to anthropogenic inputs (Fig. 1; Table 1).

**Table 1.** *Coordinates of the sampling locations (Chaturvedi,2024)*

|  |  |  |
| --- | --- | --- |
| **Station no.** | **Latitude** | **Longitude** |
| 1 | 120 45’52’’ N | 740 51’59’’ E |
| 2 | 120 45’41’’ N | 740 51’52’’ E |
| 3 | 120 45’45’’ N | 740 51’57’’ E |
| 4 | 120 45’33’’ N | 740 51’58’’ E |
| 5 | 120 45’37’’ N | 740 51’11’’ E |



**Figure 1.** *Sampling Locations of Batapady Mangroves, Mangaluru (Chaturvedi,2024).*

**2.2 Sampling Design**

Water samples were collected monthly from October 2023 to June 2024, covering post-monsoon, summer, pre-monsoon, and early monsoon transitional periods. All samples were collected during high tide and daylight hours to minimize tidal and diel variability. At each station, surface water (0–30 cm depth) was collected using pre-cleaned high-density polyethylene bottles. Physical parameters (e.g., pH, temperature, salinity, DO) were measured immediately, while samples for laboratory analysis were preserved and processed within 24 hours.

**2.3 Measured Parameters and Analytical Procedures**

The study measured a suite of physico-chemical and nutrient parameters that are critical for evaluating estuarine nutrient dynamics. These included environmental parameters such as Water temperature (°C), pH, Dissolved oxygen (DO; mg/L), Biological oxygen demand (BOD; mg/L), Salinity (ppt), Alkalinity (mg/L) and nutrients like Ammonia-nitrogen (NH₃-N; µg-at/L), Nitrite-nitrogen (NO₂-N; µg-at/L), Nitrate-nitrogen (NO₃-N; µg-at/L), Phosphate-phosphorus (PO₄-P; µg-at/L).

All field measurements and laboratory analyses were conducted following protocols outlined in the *Standard Methods for the Examination of Water and Wastewater* (APHA, 2017). In situ parameters, including water temperature and pH, were recorded immediately upon collection using a mercury thermometer and calibrated digital pH meter, respectively. Dissolved oxygen and BOD were measured using the Winkler titrimetric method, with BOD samples incubated at 20 °C for five days in the dark. Salinity was assessed using a handheld optical refractometer and reported in parts per thousand (ppt). Alkalinity was determined by acid titration, using phenolphthalein and methyl orange indicators to differentiate between total and carbonate fractions. Nutrient analyses were performed using colorimetric spectrophotometric methods. Ammonia-nitrogen (NH₃-N) by phenol-hypochlorite method with absorbance measured at 640 nm, Nitrate-nitrogen (NO₃-N) by cadmium column reduction followed by diazotization with sulphanilamide and N-1-naphthylethylenediamine dihydrochloride (NNED), absorbance at 543 nm, Nitrite-nitrogen (NO₂-N) by direct diazotization with sulphanilamide and NNED, absorbance at 543 nm and Phosphate-phosphorus (PO₄-P) by ascorbic acid method using ammonium molybdate and antimony potassium tartrate reagents, absorbance at 885 nm.

All spectrophotometric readings were taken using a UV-Visible spectrophotometer (Model: *Systronics Visiscan 167*). Reagent blanks, standard calibration curves, and replicate samples were included for quality assurance and control. All nutrient concentrations were later converted to micromoles per liter (µg-at/L) for standardization and comparability.

**2.5 Data Analysis**

Microsoft Excel 2016 was used to compile and preprocess the raw data. While station-wise median and interquartile ranges (IQR) were used to analyze spatial variability, monthly nutrient trends were analyzed by averaging concentrations across all five stations. To visualize distributional patterns, boxplots were created using the R package.

Using R version 4.3.1 and the Hmisc package, pairwise Spearman's rank correlation was calculated to investigate the impact of environmental factors on nutrient concentrations. Because of non-normal distributions and possible non-linear relationships, this non-parametric approach was chosen. Heatmaps created with the corrplot package were used to display correlation matrices. Every statistical test was carried out with a significance level of p < 0.05.

**3. Results**

**3.1 Environmental Parameters**

Environmental conditions across the Batapady mangrove system exhibited substantial spatiotemporal variation during the study period. Water temperature ranged from 24.85°C to 32.55°C, with a mean of 28.93°C, reflecting typical seasonal warming in tropical estuarine settings. The pH values remained moderately stable, fluctuating between 6.7 and 8.1, indicating slightly acidic to mildly alkaline conditions consistent with estuarine mixing zones. Dissolved oxygen (DO) levels varied markedly between 2.75 and 9.02 mg/L, pointing to occasional hypoxic events, potentially linked to high biological demand or restricted water exchange. BOD ranged from 0.81 to 6.75 mg/L, suggesting considerable variability in the organic load and microbial respiration across locations and seasons. Salinity exhibited strong seasonal influence, ranging from 1.2 to 17.85 PSU, shaped by monsoonal freshwater inflow and tidal intrusion. Alkalinity values varied widely from 17 to 160 mg/L, reflecting differential buffering capacity likely driven by geogenic inputs and sediment–water interactions.

To avoid excessive detail, monthly or station-wise trends for each parameter are not presented here. Instead, the summary statistics (Table 2) offer a consolidated snapshot of the physicochemical background during the sampling period. A detailed correlation analysis involving these variables is presented in Section 3.3 to explore their relationship with nutrient dynamics.

**Table 2.** *Range and average of all parameters across the stations during the study period.*

|  |  |  |
| --- | --- | --- |
| **Parameters** | **Range (Min-Max)** | **Average** |
| Water Temperature (ºC) | (24.85-32.55) | 28.93 |
| pH | (6.7-8.1) | 7.42 |
| Dissolved Oxygen (mg/l) | (2.75-9.02) | 6.05 |
| Biological Oxygen Demand (mg/l) | (0.81-6.75) | 3.32 |
| Salinity (PSU) | (1.2-17.85) | 4.69 |
| Alkalinity (mg/l) | (17-160) | 69.87 |

**3.2 Temporal Variation in Nutrient Concentrations**

Nutrient concentrations in the Batapady mangrove ecosystem exhibited distinct temporal fluctuations across the study period from October 2023 to June 2024, reflecting seasonal pulses, hydrological inputs, and biogeochemical processes.

**3.2.1 Ammonia-Nitrogen (NH₃-N)**

Ammonia concentrations exhibited substantial temporal variation across stations. The highest value, 85.15 µg-at/l, was recorded at Station S1 in December. All stations showed elevated concentrations in December and January, followed by a steady decline from February through April. A secondary increase was observed in May and June, with values reaching up to 33.45 µg-at/l at S5 in May. Figure 2 illustrates the monthly distribution of NH₃-N across stations.

**3.2.2 Nitrite-Nitrogen (NO₂-N)**

Nitrite concentrations were generally low across stations throughout the study period, with most values remaining below 1 µg-at/l. However, two prominent peaks were recorded. The highest concentration, 29.24 µg-at/l, occurred at Station S1 in April, while a similar spike of 28.54 µg-at/l was observed at the same station in October. Moderate increases were also noted at S2 and S3 during April. Figure 3 presents the monthly distribution of NO₂-N across stations.

**3.2.3 Nitrate-Nitrogen (NO₃-N)**

Nitrate concentrations varied markedly over the study period, with higher values observed in October and April. The maximum recorded concentration was 17.54 µg-at/l at Station S3 in April. From November to February, nitrate levels remained consistently low, generally below 1 µg-at/l across all stations. A moderate increase was noted from March onward, particularly in Stations S1–S3. These fluctuations were more pronounced at upstream and midstream locations. Monthly patterns are depicted in Figure 4.

**3.2.4 Phosphate-Phosphorus (PO₄-P)**

Phosphate levels remained low during most of the study period, except for a pronounced peak in January 2024, when concentrations exceeded 27 µg-at/l across all stations. The maximum was recorded at Station S4 (28.84 µg-at/l). After January, PO₄-P levels declined rapidly but exhibited minor increases in May and June, particularly at S5 (3.15 µg-at/l) and S3 (3.84 µg-at/l). (Figure 5 – Monthly variation of PO₄-P.).

Overall, NH₃-N and PO₄-P exhibited clear seasonal pulses likely linked to organic matter breakdown and sediment interactions, while NO₃-N and NO₂-N reflected shorter-term events such as runoff and microbial transformations.

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| **Fig. 2** Monthly variation of Ammonia-Nitrogen (µg-at.NH3-N/l) at the selected stations of Batapady mangroves | **Fig.3** Monthly variation Nitrite-Nitrogen (µg-at.NO2-N/l) at the selected stations of Batapady mangroves |
|  |  |
| **Fig.4** Monthly variation Nitrate-Nitrogen (µg-at.NO3-N/l) at the selected stations of Batapady mangroves | **Fig.5** Monthly variation Phosphate-Phosphorus (µg-at.PO4-P/l) at the selected stations of Batapady mangroves |

**3.3 Spatial Variation of Nutrients**

Boxplot analysis revealed clear spatial differences in nutrient concentrations across the five sampling stations (S1–S5) over the study period (Figs. 6–9), Table 2.

**Table 3**. Nutrient Statistics by Station (Oct 2023 – Jun 2024)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Nutrient** | **Station** | **Median (µg-at/l)** | **IQR** | **Nutrient** | **Station** | **Median (µg-at/l)** | **IQR** |
| **NH₃-N** | S1 | 13.18 | 22.48 | **NO₂-N** | S1 | 1.75 | 2.20 |
|  | S2 | 18.85 | 16.70 |  | S2 | 1.25 | 2.25 |
|  | S3 | 17.30 | 14.99 |  | S3 | 0.74 | 1.14 |
|  | S4 | 11.23 | 19.69 |  | S4 | 0.75 | 1.78 |
|  | S5 | 17.15 | 21.03 |  | S5 | 0.91 | 1.78 |
| **NO₃-N** | S1 | 2.20 | 1.98 | **PO₄-P** | S1 | 1.75 | 1.86 |
|  | S2 | 2.08 | 4.27 |  | S2 | 1.98 | 1.75 |
|  | S3 | 1.75 | 3.68 |  | S3 | 1.05 | 1.47 |
|  | S4 | 0.63 | 0.85 |  | S4 | 1.01 | 1.54 |
|  | S5 | 0.75 | 1.81 |  | S5 | 0.89 | 1.63 |

**3.3.1 Ammonia-Nitrogen (NH₃-N)**

Ammonia concentrations were elevated at Stations S2, S5, and S3, with the highest median observed at S2 (18.85 µg-at/l, IQR: 16.70), followed by S5 (17.15 µg-at/l, IQR: 21.03) and S3 (17.30 µg-at/l, IQR: 14.99). S1 exhibited a comparatively lower median (13.18 µg-at/l) but the widest interquartile range (IQR: 22.48), indicating greater temporal variability. S4 had the lowest median (11.23 µg-at/l, IQR: 19.69), possibly reflecting reduced anthropogenic inputs or more stable hydrodynamic conditions (Fig. 6 – NH₃-N Boxplot).

**3.3.2 Nitrite-Nitrogen (NO₂-N)**

Nitrite concentrations were highest at S1 (Median: 1.75 µg-at/l, IQR: 2.20) and S2 (1.25 µg-at/l, IQR: 2.25), likely reflecting active nitrification or recent organic matter degradation near these stations. Intermediate values were observed at S4 and S5 (Medians: 0.75 and 0.91 µg-at/l, respectively), both with IQRs around 1.78 µg-at/l, indicating relatively consistent nitrite levels in the mid- and downstream estuarine zones (Fig. 7 – NO₂-N Boxplot).

**3.3.3 Nitrate-Nitrogen (NO₃-N)**

Nitrate concentrations were generally low throughout the study area, with median values ranging from 0.63 µg-at/l at S4 to 2.20 µg-at/l at S1. Stations S2 and S3 exhibited the highest variability (IQRs: 4.27 and 3.68 µg-at/l, respectively), suggesting episodic inputs potentially linked to runoff, tidal mixing, or local microbial transformations (Fig. 8 – NO₃-N Boxplot).

**3.3.4 Phosphate-Phosphorus (PO₄-P)**

Phosphate concentrations varied across stations, with the highest median recorded at S2 (1.98 µg-at/l, IQR: 1.75), followed by S1 (1.75 µg-at/l, IQR: 1.86). S3 had a lower median of 1.05 µg-at/l and a moderate interquartile range (1.47 µg-at/l). Concentrations were lowest at S5 (Median: 0.89 µg-at/l), suggesting localized differences in phosphorus sources or uptake. The relatively narrow IQRs across sites point to stable phosphate conditions during the sampling period (Fig. 9 – PO₄-P Boxplot).

These spatial differences across all the nutrient concentrations reflect distinct physicochemical profiles among sampling sites and indicate that nutrient levels were not homogeneously distributed across the mangrove system, which is evident by the sampling site’s locations in the Batapady Mangrove Ecosystem.

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| --- | --- |
|  |  |
| **Fig. 6.** Boxplot showing spatial variation in ammonia-nitrogen (NH₃-N) concentrations across Stations S1–S5 in Batapady mangroves (Oct 2023 – Jun 2024). | **Fig. 7.** Boxplot showing spatial variation in nitrite-nitrogen (NO₂-N) concentrations across Stations S1–S5. |
|  |  |
| **Fig. 8.** Boxplot showing spatial variation in nitrate-nitrogen (NO₃-N) concentrations across Stations S1–S5. | **Fig. 9.** Boxplot showing spatial variation in phosphate-phosphorus (PO₄-P) concentrations across Stations S1–S5. |

**3.4. Correlation Analysis of Nutrients and Environmental Variables**

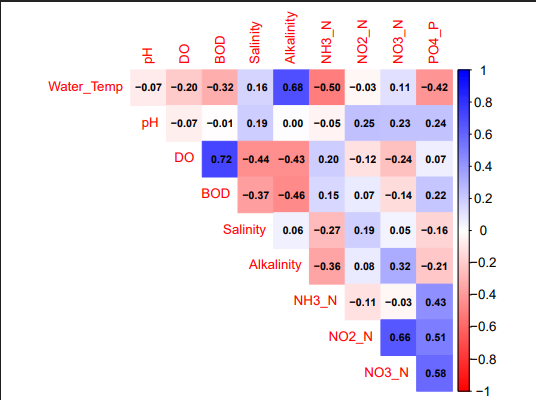
To investigate the environmental controls on nutrient dynamics in the Batapady mangrove system, a Spearman rank correlation was conducted between four nutrient species (NH₃-N, NO₂-N, NO₃-N, PO₄-P) and selected physico-chemical parameters across 45 observations (five stations; October 2023 to June 2024). The resulting correlation coefficients (ρ) and significance levels are presented in Table 4, with a heatmap visualization in Figure 10 for better visualisation of the correlation pairs. Ammonia (NH₃-N) showed a significant negative correlation with water temperature (ρ = –0.50, *p* < 0.001) and alkalinity (ρ = –0.36, *p* = 0.016), with a weaker inverse relationship to salinity (ρ = –0.27, *p* = 0.074). These patterns suggest enhanced ammonia accumulation under cooler, less buffered, and potentially lower salinity conditions. Weak positive correlations with DO (ρ = 0.20) and BOD (ρ = 0.15) were not statistically significant. Nitrite (NO₂-N) was significantly correlated with nitrate (ρ = 0.66, *p* < 0.001) and phosphate (ρ = 0.51, *p* < 0.001), highlighting their potential co-mobilization or shared biogeochemical pathways. NO₂-N also exhibited moderate but non-significant correlations with pH (ρ = 0.25) and salinity (ρ = 0.19). Nitrate (NO₃-N) concentrations were positively associated with phosphate (ρ = 0.58, *p* < 0.001) and alkalinity (ρ = 0.32, *p* = 0.029), reflecting possible terrestrial or sedimentary inputs enriched in both nitrogen and phosphorus. A weak inverse correlation with DO (ρ = –0.24) and a modest positive trend with pH (ρ = 0.23) were also noted, though not statistically significant. Phosphate (PO₄-P) was negatively correlated with water temperature (ρ = –0.42, *p* = 0.004) and weakly with alkalinity (ρ = –0.21), while maintaining strong positive correlations with NO₃-N and NO₂-N, reinforcing its coupling with nitrogen transformations under varying redox and hydrological regimes.

Among physico-chemical variables, DO and BOD exhibited a strong positive correlation (ρ = 0.72, *p* < 0.001), contrary to typical expectations and likely reflecting the simultaneous influence of primary productivity. DO was also inversely correlated with salinity (ρ = –0.44, *p* = 0.003) and alkalinity (ρ = –0.43, *p* = 0.003), suggesting that oxygen dynamics are tightly linked to estuarine mixing and buffering capacity. Water temperature showed a strong positive association with alkalinity (ρ = 0.68, *p* < 0.001), while BOD declined with increasing salinity (ρ = –0.37, *p* = 0.012) and alkalinity (ρ = –0.46, *p* = 0.002), likely indicating enhanced organic matter decomposition in fresher, less buffered zones. Together, these correlations reveal a complex interplay between nutrient cycling and hydrological-chemical gradients in this subtropical estuarine environment. Full correlation values are listed in Table 4.

**Table 4.** Spearman correlation coefficients (ρ) and corresponding *p*-values among physico-chemical and nutrient parameters (n = 45).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Water Temp | pH | DO | BOD | Salinity | Alkalinity | NH₃-N | NO₂-N | NO₃-N | PO₄-P |
| Water Temp | 1.00 (–) | –0.07 (0.637) | –0.20 (0.186) | **–0.32 (*p*=0.035)** | 0.16 (0.282) | **0.68 (*p*<0.001)** | **–0.50 (*p*<0.001)** | –0.03 (0.830) | 0.11 (0.456) | **–0.42 (*p*=0.004)** |
| pH | ... | 1.00 (–) | –0.07 (0.650) | –0.01 (0.951) | 0.19 (0.203) | 0.00 (0.980) | –0.05 (0.753) | 0.25 (0.099) | 0.23 (0.124) | 0.24 (0.115) |
| DO | ... | ... | 1.00 (–) | **0.72 (*p*<0.001)** | **–0.44 (*p*=0.003)** | **–0.43 (*p*=0.003)** | 0.20 (0.188) | –0.12 (0.446) | –0.24 (0.111) | 0.07 (0.669) |
| BOD | ... | ... | ... | 1.00 (–) | **–0.37 (*p*=0.012)** | **–0.46 (*p*=0.002)** | 0.15 (0.322) | 0.07 (0.641) | –0.14 (0.363) | 0.22 (0.146) |
| Salinity | ... | ... | ... | ... | 1.00 (–) | 0.06 (0.717) | –0.27 (0.074) | 0.19 (0.216) | 0.05 (0.765) | –0.16 (0.285) |
| Alkalinity | ... | ... | ... | ... | ... | 1.00 (–) | **–0.36 (*p*=0.016)** | 0.08 (0.604) | **0.32 (*p*=0.029)** | –0.21 (0.164) |
| NH₃-N | ... | ... | ... | ... | ... | ... | 1.00 (–) | –0.11 (0.457) | –0.03 (0.839) | **0.43 (*p*=0.003)** |
| NO₂-N | ... | ... | ... | ... | ... | ... | ... | 1.00 (–) | **0.66 (*p*<0.001)** | **0.51 (*p*<0.001)** |
| NO₃-N | ... | ... | ... | ... | ... | ... | ... | ... | 1.00 (–) | **0.58 (*p*<0.001)** |
| PO₄-P | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1.00 (–) |

Note: Statistically significant correlations (*p* < 0.05) are highlighted in bold.



**Figure 10.** Spearman correlation matrix (ρ) showing pairwise relationships among nutrients and physico-chemical parameters.

**4. Discussion**

**4.1 Temporal Dynamics and Seasonal Patterns**

The nutrient concentrations in the Batapady mangrove ecosystem displayed marked seasonality, consistent with broader patterns observed across South Asian estuarine systems. Elevated post-monsoonal concentrations of NH₃-N, particularly the peak of 85.15 µg-at/l at Station S1 in December, align with trends observed by Rahaman *et al.* (2014), who reported rising ammonia levels from post-monsoon to winter in the Rupsha-Passur system. They further highlighted a negative relationship between ammonia and temperature, a trend corroborated by the present study’s significant inverse correlation (ρ = –0.50, p < 0.001). In contrast, NO₃-N and NO₂-N concentrations in Batapady peaked during October and April, reflecting shorter-term events such as freshwater inputs or organic matter degradation. While the highest recorded NO₃-N level (17.54 µg-at/l) aligned temporally with a spike in NO₂-N, the co-mobilization of these nitrogen species, shown by their strong positive correlation (ρ = 0.66, p < 0.001), supports findings from Rao *et al.* (2018), who observed monsoonal spikes in nitrate, attributing them to high runoff. However, studies such as Gogoi *et al.* (2019) and Rahaman *et al.* (2014) report different seasonal tendencies or a lack of consistent patterns, suggesting that local hydrology and land-use pressure significantly mediate nitrogen dynamics.

For phosphate, a distinct seasonal pulse was recorded in January 2024 (>27 µg-at/l), potentially driven by desorption processes or sedimentary release, as postulated by Srinivasan *et al.* (2013), who observed elevated PO₄–P post-monsoon due to sediment desorption under increased salinity. This is supported by the negative correlation between phosphate and water temperature (ρ = –0.42, p = 0.004) observed in this study, suggesting a linkage with cooler, saltier, and possibly more reducing post-monsoonal conditions enhancing phosphorus remobilization.

**4.2 Spatial Heterogeneity in Nutrient Distribution**

Spatial patterns in nutrient concentrations revealed clearly heterogeneous zones across the Batapady estuary. Median NH₃-N values were highest at S2 and S3, potentially indicating anthropogenic sources or localized organic matter loading, consistent with upstream anthropogenic hotspots seen in Coringa and Bhitarkanika estuaries (Bala Krishna Prasad, 2011). S1, however, showed the largest variability in NH₃-N, pointing to fluctuating input conditions or dynamic internal processing. Elevated NO₂-N at S1 mirrored temporal trends and suggests site-specific microbial activity such as nitrification. Comparable hotspots were identified by Gogoi *et al.* (2019) in eutrophied regions characterized by high particulate inputs. The higher interquartile ranges of NO₃-N observed at S2 and S3 may similarly reflect episodic terrestrial inputs or fluctuations in residence time and hydrological connectivity (Rao *et al.*, 2018).

Among stations, PO₄-P was highest at S2 and S1 and lowest at S5. These gradients may reflect lateral groundwater seepage, sediment interactions, or varying exposure to upstream fluxes. Findings are consistent with sediment-driven PO₄ fluxes observed by Rao *et al.* (2018), who reported phosphate additions from both groundwater discharge and organic matter degradation concentrated in the upper estuarine reaches.

**4.3 Environmental Controls on Nutrient Dynamics**

The correlation analysis revealed complex interactions among nutrients and environmental drivers. NH₃-N showed significant inverse relationships with temperature and alkalinity, consistent with controlled lability under thermal and buffering gradients. The significant positive associations observed among NO₂-N, NO₃-N, and PO₄-P highlight tightly coupled redox dynamics and microbial transformation pathways, a pattern emphasized in studies that describe nitrate-phosphate synergy via denitrification and mineralization (Rao *et al.*, 2018; Srinivasan *et al.*, 2013). Dissolved oxygen demonstrated atypical positive correlation with BOD (ρ = 0.72), potentially reflecting co-increasing productivity and microbial respiration. This pattern has been described in seasonal blooms influenced by simultaneous photosynthetic oxygenation and biomass decay (Bala Krishna Prasad, 2011). Meanwhile, inverse DO-salinity and BOD-salinity relationships support the view that freshwater influx especially from land-based runoff or groundwater discharge delivers organic-rich, oxygen-demanding inputs, further shaping the system’s trophic status (Rao *et al.*, 2018).

**4.4 Influence of Hydrology and Anthropogenic Inputs**

Hydrological forcing especially monsoonal runoff and groundwater discharge emerges as a principal driver regulating seasonal nutrient flux and transformation. Elevated nitrate and phosphate during or immediately after the wet season signal upland contributions, as strongly demonstrated in the Gautami-Godavari estuary by Rao *et al.* (2018). However, the mid- to late-dry season phosphate spike in Batapady may also suggest enhanced pore water flux and mineralization under low flow and high residence time, paralleling findings in multiple Indian mangrove systems (Srinivasan *et al.*, 2013; Bala Krishna Prasad, 2011). While direct groundwater data were unavailable, the study's phosphate patterns and seasonal BOD-alkalinity trends align with similar dry season signatures attributed to subterranean discharge in Godavari mangroves (Rao *et al.*, 2018).

Anthropogenic influences including likely sewage input, agricultural runoff, and possibly aquaculture may play a role in localized nutrient enrichment in the Batapady system. This is evident when comparing elevated solute levels at certain stations (e.g., S2 and S3) with patterns in other nutrient-impacted systems like Pichavaram or Rupsha-Passur (Rahaman *et al.*, 2014). Nutrient buildup due to reduced flushing and sediment trapping, especially during the dry season, further mirrors enclosure effects noted in previous studies of estuarine eutrophication (Gogoi *et al.*, 2019).

While the observed correlations provide insights into potential linkages among environmental variables and nutrient dynamics, they do not establish causation. Factors such as porewater fluxes, sediment redox potential, vegetation cover, and hydrological residence time may also play significant, unmeasured roles in shaping nutrient patterns.

**4.5 Implications for Management**

Given the seasonal nutrient build-up and spatial heterogeneity identified, it is essential to establish nutrient thresholds and loading sources for this ecosystem. Impacts of nutrient enrichment could lead to altered primary productivity and risk of eutrophication, as seen in comparable Indian estuarine systems undergoing anthropogenic alteration (Rao *et al.*, 2018; Bala Krishna Prasad, 2011).

**5. Conclusion**

This study provides a detailed temporal and spatial assessment of nutrient dynamics in the Batapady mangrove ecosystem over a nine-month period, revealing strong seasonal pulses and spatial heterogeneity in ammonia, nitrite, nitrate, and phosphate concentrations. Ammonia (NH₃-N) and phosphate (PO₄-P) peaked sharply during the post-monsoon and winter months, likely driven by organic matter mineralization under low-oxygen conditions and sediment–water interactions. In contrast, nitrate (NO₃-N) and nitrite (NO₂-N) showed episodic surges, reflecting short-term microbial processes and runoff-driven inputs.

Nutrient distributions differed considerably in space between stations, indicating varying exposure to vegetation density, hydrodynamic flushing, and human inputs. Higher nutrient concentrations were found in stations close to disturbed edges and rivulet inflows, whereas more interior vegetated stations demonstrated a larger buffering capacity. According to correlation analysis, nitrite and nitrate showed a positive correlation with pH and each other, indicating active nitrification pathways under particular environmental regimes, whereas ammonia and phosphate showed a negative correlation with temperature and alkalinity. The application of integrated R + D analysis, bolstered by mechanistic correlations and real-time environmental variables, emphasizes the importance of site-specific, high-resolution nutrient monitoring, particularly in small or fragmented mangrove systems that fall outside of national monitoring frameworks.

This study supports the necessity of integrating seasonal and spatial variability into nutrient management strategies from a management standpoint. Since nutrient loading is highest and buffering capacity is most at risk near freshwater inputs, conservation efforts should give priority to edge-zone mangroves. Furthermore, under increasing land-use pressures and climate variability, eutrophication or stoichiometric imbalance may have an impact on the long-term health of mangroves. To detect these conditions, nutrient ratios and correlation-based indicators provide useful early-warning tools. In order to identify early indicators of eutrophication and ecological degradation, these insights can help integrate small mangrove systems like Batapady into national estuarine health monitoring programs and inform threshold-based water quality guidelines.

**6. Limitations and Future Directions**

This study provides foundational insights into nutrient dynamics within the Batapady mangrove system, yet several limitations constrain broader interpretation. The nine-month sampling period excluded peak monsoon periods, potentially underestimating nutrient fluxes during critical runoff events. Surface water measurements limit understanding of vertical stratification and sediment-porewater interactions crucial for nutrient exchange processes. The absence of nutrient speciation analysis and stable isotope tracing precludes precise source apportionment of organic versus inorganic forms.

Future research should extend temporal coverage across multiple annual cycles and integrate sediment-water interface assessments. Incorporating microbial community profiling and stable isotope analysis would elucidate biogeochemical transformation pathways and anthropogenic signatures. Most critically, this study lacks quantitative flux measurements through river discharge, groundwater inputs, tidal exchange, and sediment transport, preventing comprehensive nutrient budget construction. Direct measurement of transport rates and loading dynamics is essential for accurate predictions of long-term ecosystem sustainability under varying land-use and climate scenarios.

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Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, manuscript.

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