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Spatial Dynamics of Pollution in a Tropical Lagoon Ecosystem and Its Social-Ecological Impacts

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Abstract Tropical lagoon ecosystems constituting lagoons with fringe mangroves are continually polluted with effluents from different sources. This study assessed the spatial variation of selected physicochemical parameters (pH, nitrates, phosphates, and conductivity) in water and sediments from the Chilaw lagoon and its fringe mangroves located on the North-Western coast of Sri Lanka. Interviews were also conducted with local communities (including fishermen) on the social-ecological impacts of pollution in the lagoon ecosystem. Physicochemical analysis was conducted following the APHA standard methods. Statistically significant differences at 95% confidence interval were observed for levels of physicochemical parameters in water and sediment samples, with a horizontal (i.e. length-wise) and vertical (i.e. depth-wise) pollution stratification in the lagoon. Latitude had significant effects on the levels of physicochemical parameters recorded in surface water samples. High levels of pH ($pH > 9$) recorded in water samples were evidenced by the observation of algal blooms and limited fish catch in the lagoon over the years. Local people report a novel impact of effluent pollution on mangroves, where redworms feed on mangrove leaves. The study, therefore, calls for immediate control of effluent pollution from shrimp farming and other point sources.

Keywords Tropical lagoons · Fringe mangroves · Effluents · Social-ecological impacts · Sri Lanka

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1 Introduction

Lagoon ecosystems are formed in areas with small tidal ranges, like a shallow basin near the shore,

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which progressively experiences erosion, allowing the ocean to find its way in between the barrier and the basin (Miththapala, 2013). They contribute to the general ecosystem productivity yield of coastal waters by harbouring diverse habitats such as benthic seagrasses, extensive mudflats, salt marshes, and mangroves, enabling several organisms extending from unicellular protozoans to dugongs, green turtles, roosting birds, etc., to thrive (Silva et al., 2013; Thompson and Rog, 2019; Sievers et al., 2019). They provide a variety of socio-ecological services such as finfish and shellfish production, storm surge protection, tourism, anchorage, and salt production among others of immense value to the society (Silva et al., 2013; Zu Ermgassen et al., 2021).

The shallow nature and the high-water retention time of tropical lagoons make them highly vulnerable to the over-enrichment of nutrients (pollution) from different sources (Miththapala, 2013). A typical example is the Chilaw lagoon which is located on the North-Western coast of Sri Lanka. Being a shallow lagoon with an average depth of 1.5 m and a high water retention time, it has been reported to receive increased levels of wastewater and solid waste from different sources. Some of the reported sources include shrimp farms, the Chilaw market, fishing activities on landing sites, and local settlements (Asian Development Bank (ADB) and IUCN 2002; Leslie, 2011). The expansion of shrimp farming, since its introduction in the Pambala-Chilaw lagoon complex (indicated as P-CLC hereafter) during the early 1980s, has resulted in increased deforestation of mangroves (Dahdouh-Guebas et al., 2002), causing an unrestricted movement of pollutants into the Chilaw lagoon.

Shrimp farms located around the Chilaw lagoon and its fringe mangroves are known to release effluents containing dissolved nutrients, noxious chemicals, vitamins, growth enhancers, medicines, and sometimes supplementary fresh food materials including thrash fish, mollusc meat or egg (the uneaten balance of these supplementary feeds also contribute to the quality of effluents), microorganisms, shrimp excrements, and unconsumed food pellets, into the ecosystem (ADB and IUCN, 2002; Corea, 2019). The Chilaw market is also reported to release effluents containing organic waste such as fish and food waste through waterways into the Chilaw lagoon (Leslie, 2011). Fishermen have also joined in dumping fish waste at landing sites, finding their way back into the lagoon. Furthermore, settlements located close to the Chilaw lagoon are known to release wastewater via pipelines directly into the Chilaw lagoon (ADB and IUCN, 2002).

It has been demonstrated by ecologists that pollutants including allochthonous nutrients such as nitrates, phosphates, dissolved inorganic nitrogen, and phosphorus have strong consequences on interactions of species and dynamics in food webs. In theory, nutrient transfers can directly or indirectly influence all trophic levels of food webs of the Chilaw lagoon and its fringe mangroves, thereby initiating alterations in species composition and diversity (Serrano-Grijalva et al., 2011).

While some studies like that of Sun et al. (2020) have presented the ability of fringe mangroves to reduce the level of pollutants reaching coastal waters such as lagoons, the spatial variation of pollution in these lagoons and the degree to which local people are affected are not well established. Limited number of studies has reported on the socio-ecological impacts of lagoon and mangrove ecosystem pollution. Moreover, it has been introduced by Pickup and Tyrrell (2020) that in surface waters, higher concentrations of nutrients do occur at higher latitudes. Known to be only tested in larger surface waters of wider latitudes like the Atlantic Ocean (Pickup and Tyrrell 2020), the generality of this rule, however, has not been tested on surface waters such as lagoons which do have connectivity with the oceans.

This study, therefore, sought to achieve the following objectives:

i) To assess the spatial variation of selected physicochemical parameters (pH, conductivity, nitrates, and phosphates) in water and sediment samples of the Chilaw lagoon and its fringe mangroves.
ii) To test the generality of the rule that, in surface waters, higher concentrations of nutrients occur at higher latitudes using the selected physicochemical parameters measured in Chilaw lagoon surface water.
iii) To understand the social-ecological impacts of pollution in the Chilaw lagoon and its fringe mangroves.

2 Materials and Methods

2.1 Study Area

The P-CLC is located within the Chilaw Divisional Secretariat (DS) of the Puttalam district of Sri Lanka in the Indian Ocean. The landmarks defining the northern, western, eastern, and southern boundaries of the Chilaw DS are the Daduru Oya river, the seashore, the road between the Puttalam district and the Kurunegala district, and the long lying Kakkapalliya, respectively. The Chilaw DS consists of 49 Grama Niladhari divisions with a total population of 63,188 (Ministry of Home Affairs, 2021). The Chilaw DS is identified as one of the prominent regions in Sri Lanka where the local people are majorly involved in aquaculture inside and around the Chilaw lagoon (Ministry of Home Affairs, 2021).

The P-CLC extent is located within latitudes 7.518° and 7.542° and longitudes 79.824° and 79.821°. As found in the intermediate climate zone of Sri Lanka, the major land use/covers (indicated as LU/LCs hereafter) present in the P-CLC are mangroves, surface water bodies (lagoon, creeks, and dams), shrimp farms, coconut plantations, built area, and croplands/paddy fields. The mangrove community in the area has 17 true mangrove species and 13 mangrove associates (Jayatissa et al., 2002), and a vegetation distribution of the riverine or fringe type along the Chilaw lagoon and a complex of creeks, i.e., Marambettiya Ela, Bate Ela, Pol Ela, and Dutch Channel (Di Nitto et al., 2013).

Within the P-CLC is the Chilaw lagoon which has an area of about 630 ha. Unlike the many other lagoons in Sri Lanka which have rivers flowing directly into them, the only source of freshwater inflow into the Chilaw lagoon is floodwater from the Dedura Oya, Demure Oya, and surface runoff via Lunu Ela. The salinity ranges recorded for its head, middle, and mouth waters are 0–38, 0–38, and 0–40 ppm respectively (Leslie, 2011; Silva et al., 2013). Owing to the formation of high berms at the channel area (Thoduwawa channel) of the Chilaw lagoon, it is thus described as being gradually ephemeral (Silva et al., 2013). The southern entrance to the lagoon through the inlet at Thoduwawa is completely closed for a part of the year despite construction carried out in the early 1960s to prevent sand bar formation across the inlet (Cattermoul & Devendra, 2002).

The Chilaw lagoon and its fringe mangroves are fully surrounded by over 200 shrimp farms (Di Nitto et al., 2013), with other land-uses/covers such as coconut plantations, fishing landing sites, local settlements, and the Chilaw market. The majority of shrimp farms occurring around the lagoon area are semi-intensive in their production methods. That is, ponds are constructed of mud banks, shrimps are fed with formulated feeds, and some aeration takes place. In addition, shrimp farmers also rely on the surrounding lagoon, or canal water, as a source of clean pond water and also for washing wastewater through the ponds out into the lagoon or canal (Cattermoul & Devendra, 2002).

2.2 Sample/Data Collection

2.2.1 Water and Sediment Sampling

Before sampling, a research permit letter received from the University of Ruhuna, Sri Lanka was used in obtaining permission from the Small Fishers Federation of Lanka (SFFL) which is involved in the management and conservation of the mangroves in the study area. Sampling materials and containers were pre-cleaned and air-dried before the sampling exercise. The sampling of water and sediments from the Chilaw lagoon and its fringe mangroves occurred on two different occasions. The first sampling which was a preliminary study was done on 30th June 2020. The actual sampling exercise took place from 9:00 am to 3:30 pm on the 13–14th of August 2020.

To be able to identify the sampling locations in Chilaw lagoon for the collection of water and sediment samples, the lagoon was first divided into three zones from the northern mouth to the southern mouth, at almost equal lengths using ArcMap 10.5. The creation of the sampling zones was to identify which part of the Chilaw lagoon was more polluted since the number and types of land-uses/covers around the lagoon are irregularly distributed on a horizontal gradient. Moreover, since coastal lagoons like Chilaw lagoon exhibit strong horizontal stratification because of longitudinal salt gradients (Kjerfve & Magill, 1989), it was therefore hypothesised that differences may occur in the levels of physicochemical parameters measured at each zone. Three random points were generated at each zone using the Create Random Points tool in ArcMap 10.5 and their coordinates were recorded (Fig. 1). The latitude of each sampling point was also recorded to test the hypothesis that in surface waters, higher concentration of nutrients occurr at higher latitudes. During sampling, records were also taken for the type of weather, air temperature, and water depth at each sampling point.

Due to the reported dynamics in gravitational circulation and layer thickness/density (i.e. vertical stratification driven by a salinity gradient) occurring at surface and bottom waters of coastal lagoons (Kjerfve & Magill, 1989), it was hypothesised that Chilaw lagoon would present differences in levels of physicochemical parameters at different depths. From each zone, triplicates of water samples were collected at three different depths (upper [0–5 cm], middle [27–54 cm], and lower [54–109 cm]) from each of the nine (9) sampling points using pre-cleaned plastic containers. Depth measurements in each sampling point was done using a graduated stick. It is important to note that depth measurements varied in each sampling point. The lowest depths for zones A, B, and C ranged from 54 to 81 cm, 76–109 cm, and 61–109 cm. In total, 81 water samples (9 sampling points × 3 depths × 3 replicates) were collected. A total of 9 composite sediment samples weighing about 100–200 g/sample were also collected using a hand trowel at a < 5 cm depth from each of the 9 sampling points inside the lagoon. At the eastern and western banks of the lagoon, a total of 30 mangrove sediments (2 banks × 3 zones × 5 replicates) were collected from the root area of randomly selected *Rhizophora mucronata* Lam. trees using a hand trowel. This species was selected because it was the most common species occurring parallel to each of the zones along the lagoon. All samples were stored in regifoam cool boxes at a temperature of 6 °C and transported to the Fisheries Department of the University of Ruhuna for physicochemical analysis.

2.2.2 Social-Ecological Data

A research permit letter received from the University of Ruhuna, Sri Lanka and informed consent from

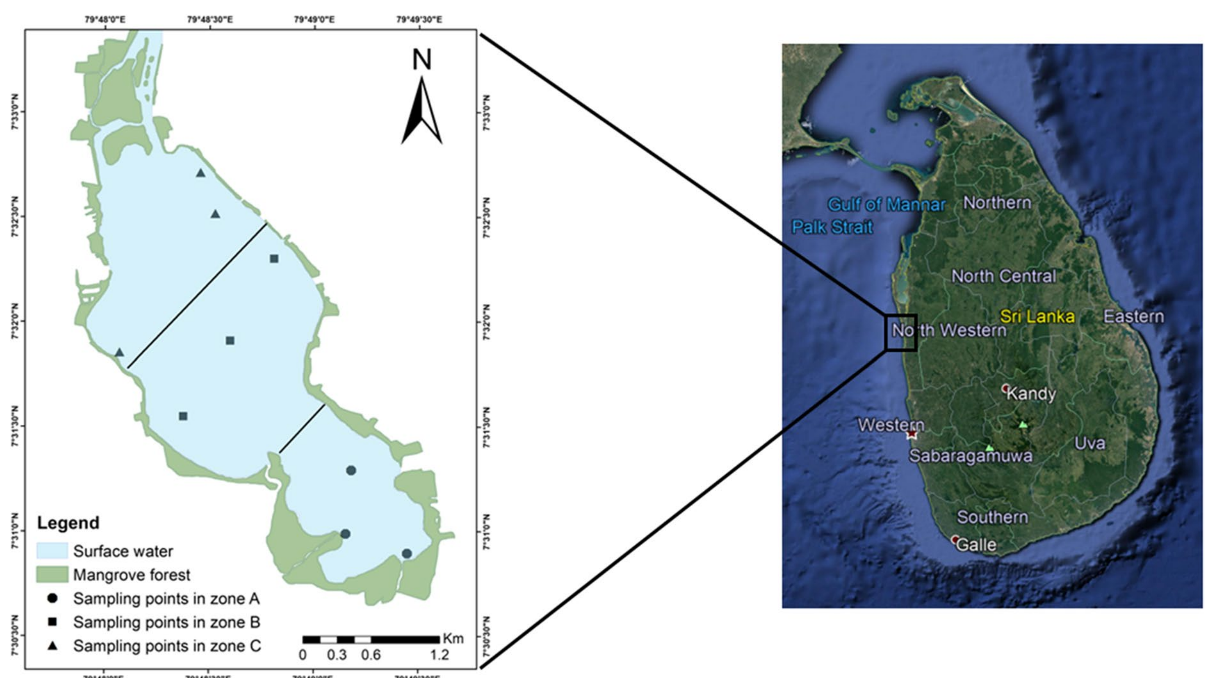


Fig. 1 Map showing the study area. Inset **A** shows Sri Lanka in the Indian ocean. The rectangular box on the inset A signifies the P-CLC on the North-Western coast (province) of Sri Lanka. Inset **B** shows sampling points in zones A, B, and C created for water and sediment sampling in Chilaw lagoon and its fringe mangroves. Inset **A** was accessed on 31/12/2020 from Google Earth; Image: Landsat/Copernicus; 14/12/2015. Data: SIO, NOAA, U.S. Navy, NGA, GEBCO

local people were used for ethical clearance before interview sessions. Interviews were held with local people and fishermen in the study area between the period of 14–28th August 2020 using questionnaires. Thirty (30) households and ten (10) fishermen (exclusive from the 30 households) in the Chilaw lagoon area were interviewed to understand the socio-ecological impacts of lagoon and mangrove ecosystem pollution and their wellbeing. Households located close to mangroves and lagoon were selected with the assumption that a majority of them were more impacted by the changes in lagoon and mangrove ecosystems present in the study area. The first household was randomly selected, and the remaining households were selected at approximately every 30 m interval between them until the last with the help of Google Maps®. In addition, fishermen were interviewed on how the lagoon pollution (in a general sense) may have affected their fishing activities over the years.

2.3 Sample Preparation and Physicochemical Analysis

Sample preparation and physicochemical analysis of water and sediments samples were conducted with the support of the American Public Health Association (APHA) methods and related literature (Baird et al., 2017).

2.3.1 Conductivity and pH Analysis

Before conductivity and pH measurements, a 50 g subsample of sediments was dissolved in 100 mL of distilled water (DW). Conductivity and pH measurements were done using a conductivity/salinity metre (HP9010) and a pH/redox metre (EC8500). For water samples, measurements were done directly in the sample containers. The probes of both metres were rinsed with DW before and after measurements were taken in each sample.

2.3.2 Nitrate Analysis

Preparation of water and sediment samples for nitrate analysis was done following the methods indicated in Monteiro et al. (2003) and Baird et al. (2017) to remove possible interferences before analysis. Nitrate analysis was then performed using the Jenway 6705 UV/Visible Scanning Spectrophotometer, at a wavelength of 220 nm for determining NO_3^- reading and at a wavelength of 275 nm to determine any remaining interference due to dissolved organic matter to correct the NO_3^- values (Baird et al., 2017).

2.3.3 Phosphate Analysis

Preparation of water and sediment samples for phosphate analysis was done following the methods indicated in Shyla and Mahadevaiah (2011) and Baird et al. (2017). Phosphate concentrations in water and sediment samples were quantified using the Jenway 6705 UV/Visible Scanning Spectrophotometer. After about 10 min, the solutions were diluted to the volume with water and the absorbance of the solutions was measured at 840 nm against water using the spectrophotometer (Shyla & Mahadevaiah, 2011).

2.4 Quality Assurance/Control (QA/QC)

The working nitrate and phosphate standard solutions used for QA/QC were 100 mg.L NO_3^-—N and 25 mg.L $P0_4^{3-}$ respectively (Baird et al., 2017; Monteiro et al., 2003). To validate the procedure employed in nitrate and phosphate analysis of samples, a calibration graph was obtained by plotting the different concentrations of the working nitrate and phosphate standard solutions against their respective absorbance values (Supplementary Figs. 1 and 2). Following the International Council for Harmonization's (ICH) harmonised tripartite guideline, the limit of detection (LOD) or limit of quantification (LOQ) were determined using the formula $LOD = 3.3\sigma\ /\ S$ and $LOQ = 10\sigma\ /\ S$, where σ is the standard deviation of the response and slope of the calibration curve, and S is the slope of the calibration curve (European Medicines Agency, 2006). The LOD and LOQ for nitrate analysis were 0.175 mg.L NO_3^-—N and 0.531 mg.L NO_3^-—N respectively, and that of phosphate analyses were 0.008 mg.L $P0_4^{3-}$ and 0.023 mg.L $P0_4^{3-}$ respectively.

2.5 Statistical Analysis

Statistical analysis was conducted using Microsoft Office Excel® for preparing data and R version 3.6.1 (R Core Team, 2020) for descriptive and inferential statistics. Mean values and standard deviations (SDs) of conductivity, pH, and phosphate and nitrate levels recorded across all sampling points were computed using Microsoft Office Excel®. In this view, sample groups included triplicate water samples at each depth of the sampling points, 3 composite sediment samples collected from each sampling zone inside the lagoon, and 15 composite mangrove sediments each collected from the eastern and western lagoon banks.

To test for normality of each of the physicochemical parameters in samples and equal variances in sample groups, the Shapiro-Wilk normality test and the Levene's test were respectively used in R. For non-parametric data, non-parametric tests such as Kruskal-Wallis test and Mann-Whitney Wilcoxon test were used while ANOVA was used for parametric data. To check for significant differences in pH, conductivity, nitrate, and phosphate levels in water samples at each depth, and sediment samples collected from the three sampling zones, an ANOVA and Kruskal-Wallis test were conducted in R for parametric and non-parametric data, respectively. Analysis was also conducted to test for the presence of a latitudinal gradient of the physicochemical parameters in water and lagoon sediment samples. A simple linear regression was used to test for the effect of latitude on the levels of physicochemical parameters at the three depths. All analyses in R were conducted with the use of vegan (Oksanen et al., 2020), car, and stats (Fox & Weisberg, 2019) packages in R.

The Mann-Whitney Wilcoxon test was used to compare the physicochemical parameter levels recorded in mangrove sediments from the eastern and western banks of the lagoon. Pearson's correlation was used to test for the correlation existing between parameters in all sample groups. Spatial associations existing within/between physicochemical parameters and sampling points (zones) were tested and visualised using a principal component analysis (PCA) in R software since it works best with environmental data using Euclidean distances. All graphical representations of the recorded physicochemical parameters in samples were produced using Microsoft Office Excel® and the ggplot2 (Wickham, 2016), ggfortify (Tang et al., 2016), gridExtra (Auguie, 2017), and viridis for Daltonism-friendly colour (Garnier et al., 2021) packages in R.

3 Results

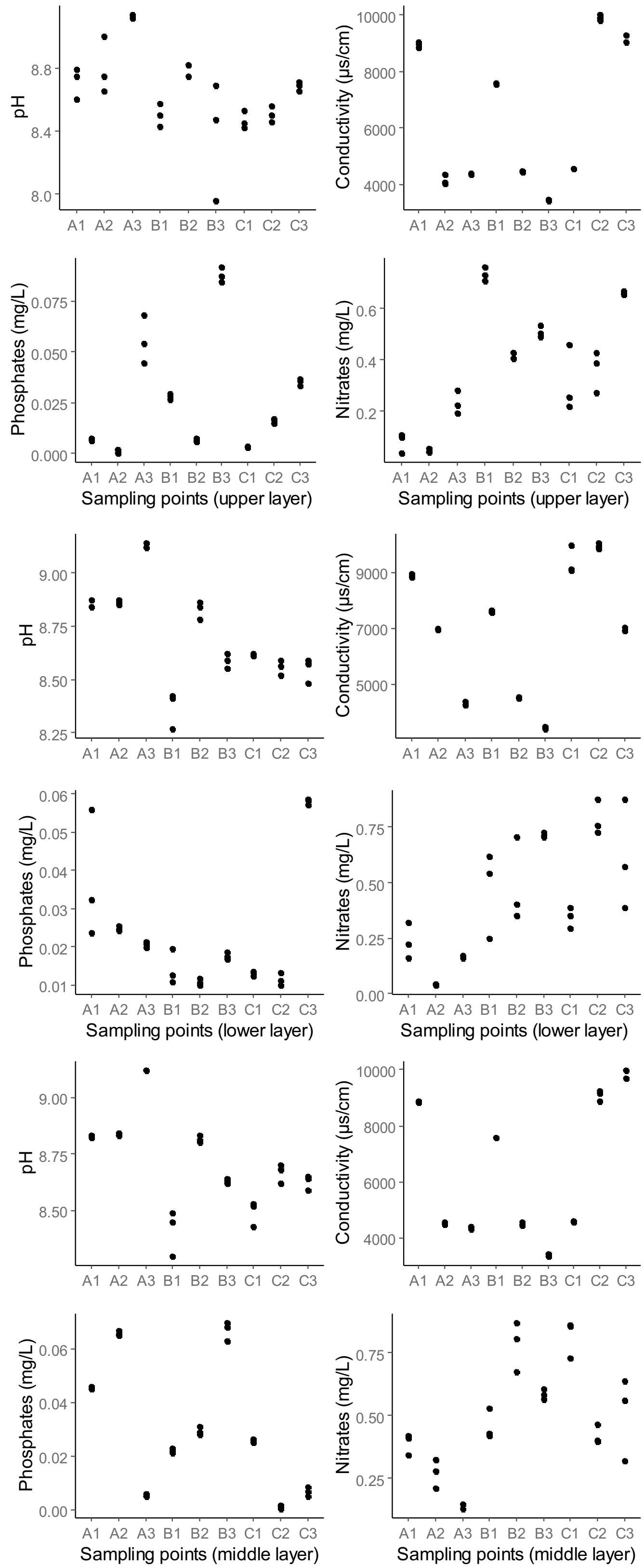
3.1 Levels of Physicochemical Parameters in Water Samples

The levels of conductivity, pH, phosphates, and nitrates recorded in water samples across the three depth layers (upper, middle, and lower) ranged between 3360 and 10,050 μs.cm^{-1}, 8.30–9.14, 0.0005–0.0915 mg.L^{-1}, and 0.039–0.877 mg.L^{-1} respectively. Statistically significant differences (p = 1.39E-14 to 0.00242, F = 139.07 to 23.858) existed between water samples from different zones for each physicochemical parameter (Supplementary Table 1). Statistically significant differences (p = 1.46E-08 to 0.03207, F = 1225.3 to 6.8796) also existed between levels of physicochemical parameters in water samples collected at different depths from each sampling point. The highest record of conductivity, pH, and nitrates were found in the lower depth, while the highest record of phosphates was found in the upper depth (Supplementary Table 2).

Statistical differences were recorded for the levels of some physicochemical parameters measured in water samples from each sampling zone at the upper, middle, and lower depths, respectively (Fig. 2). Considering the three zones, zones A and C respectively recorded the highest levels of pH and conductivity at all depths. Zone B recorded the highest levels of nitrates at all depths and the highest levels of phosphates at the upper and middle depths. Zone A also recorded the highest levels of phosphates at the lower depth.

Spatial associations were recorded between/within physicochemical parameters and water samples (sites) at the upper, middle, and lower depths, respectively (Supplementary Figs. 3, 4, and 5). For the upper layer, samples from site B3 were less associated as compared to samples from other sites (Supplementary Fig. 3). It also reveals the strong association between samples from site B2 and pH as well as the strong association between samples from site C2 and conductivity. For the middle layer, samples from site B1 were less associated with each other as compared to samples from other sites (Supplementary Fig. 4). It further indicates the strong association between samples from site C1 and nitrates as well as the strong association between samples from site C2 and conductivity. For the

Fig. 2 Levels of pH, conductivity, phosphates, and nitrates in water samples from different zones at the upper, middle, and lower depths. A1, A2, A3, B1, B2, B3, C1, C2, and C3 represent the various sampling points



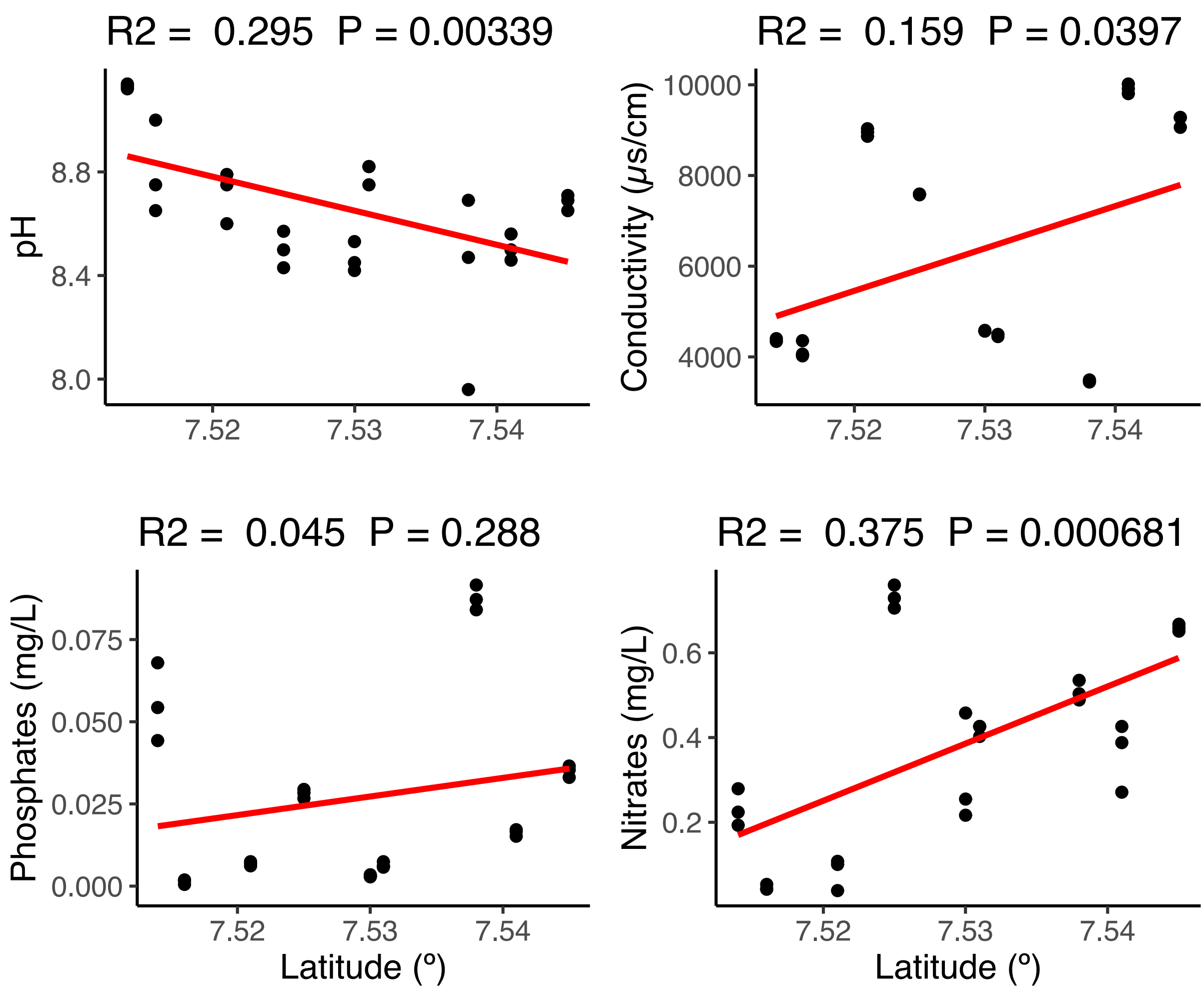


Fig. 3 Levels of pH, conductivity, phosphates, and nitrates in surface water samples from increasing latitudes. $R.^2$ represents the proportion of variation explained by latitude on the levels of each physicochemical parameter and *p* represents the significance of the variation explained by latitude on the levels of each physicochemical parameter

lower layer, a stronger association existed between samples from sites A2 and A3 when compared with samples from other sites (Supplementary Fig. 5). A negative association between pH and nitrates across the different depths was also revealed (Supplementary Figs. 3, 4, and 5). A correlational analysis between nitrate and pH levels in samples revealed an increasing negative correlation coefficient ($r^2 = -0.36742, -0.56192$, and -0.64441) and significance ($p = 0.05938$, 0.002286, and 0.000286) with increasing depth, from upper to lower layer, respectively (Supplementary Table 3).

3.2 Latitudinal Gradient of Physicochemical Parameters in Water Samples

The relationships between latitude and the physicochemical parameters recorded in surface water samples were assessed to test the generality of the rule that, in surface waters, higher nutrient concentrations occur at the higher latitudes. Significant differences ($p = 7.44\text{E-}08$ to 0.007197) were recorded between all physicochemical parameters measured in surface water samples collected from different latitudes except for phosphate levels (Fig. 3, Supplementary

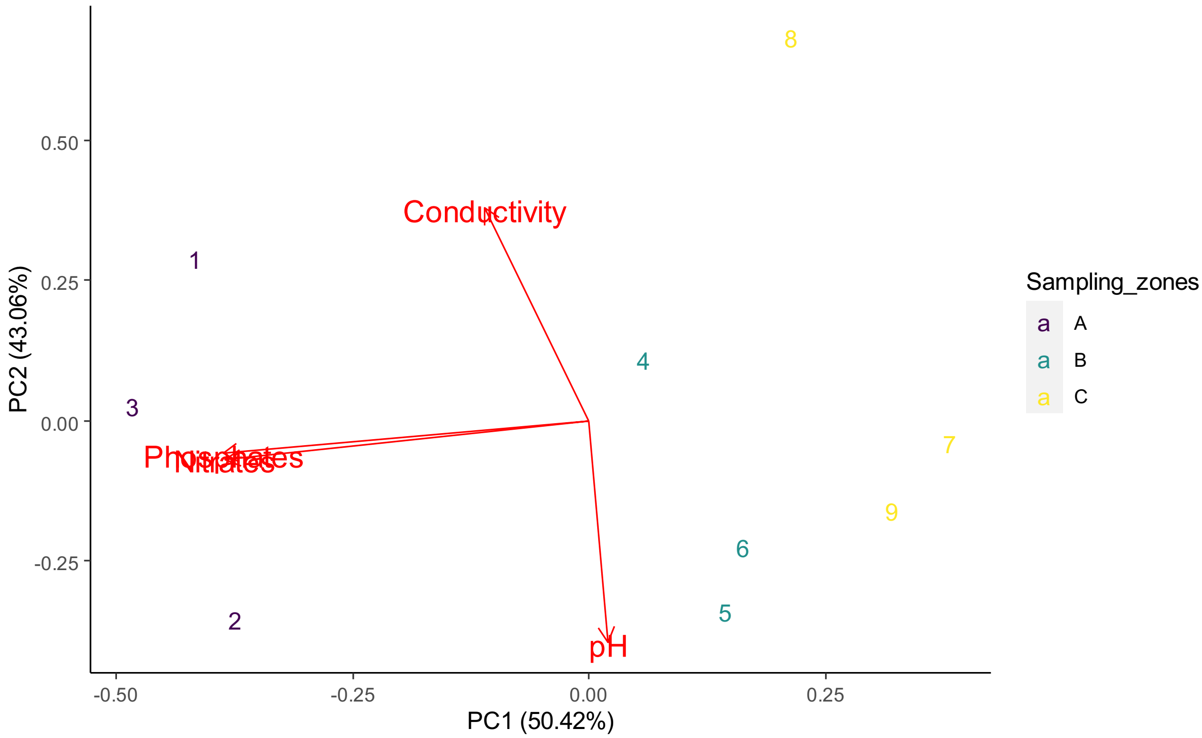


Fig. 4 A PCA showing the spatial associations between/within physicochemical parameters (pH, conductivity, nitrates, and phosphates) and lagoon sediment sampling points (1 to 9) in each sampling zone (A, B, and C). The relative distances between/within physicochemical parameters and lagoon sediment sampling points indicate the degree of spatial associations

Table 4). Latitude had significant effects on the levels of physicochemical parameters except phosphates (Fig. 3, Supplementary Table 5).

3.3 Levels of Physicochemical Parameters in Lagoon Sediments

The levels of conductivity, pH, phosphates, and nitrates recorded in lagoon sediments ranged between 521 and 2954 µs.cm^{-1}, 7.70–7.88, 0.069–0.111 mg.kg^{-1}, and 0.995–1.942 mg.kg^{-1} respectively. Statistically significant differences were recorded for phosphate ($p=0.02732$, $F=7.2$) and nitrate ($p=6.79$e-05, $F=70.535$) levels measured in lagoon sediment samples from the three sampling zones (Supplementary Table 6 and Supplementary Fig. 6). Sampling zones A and C respectively recorded the highest and lowest levels of phosphates and nitrates in samples. A positive correlation ($r^2=0.98$, $p=1.475$e-06) between phosphate and nitrate levels and a negative correlation between conductivity and pH levels ($r^2=-0.73$, $p=0.02551$) were recorded across sampling zones (Fig. 4).

3.4 Levels of Physicochemical Parameters in Mangrove Sediments

The levels of conductivity, pH, phosphates, and nitrates recorded in mangrove sediments ranged between 583 and 6850 µs.cm^{-1}, 6.70–7.99, 0.068–0.114 mg.kg^{-1}, and 1.010–2.291 mg.kg^{-1}, respectively. Among the physicochemical parameters measured in mangrove sediments from the eastern and western banks of Chilaw lagoon, only pH levels indicated a statistically significant

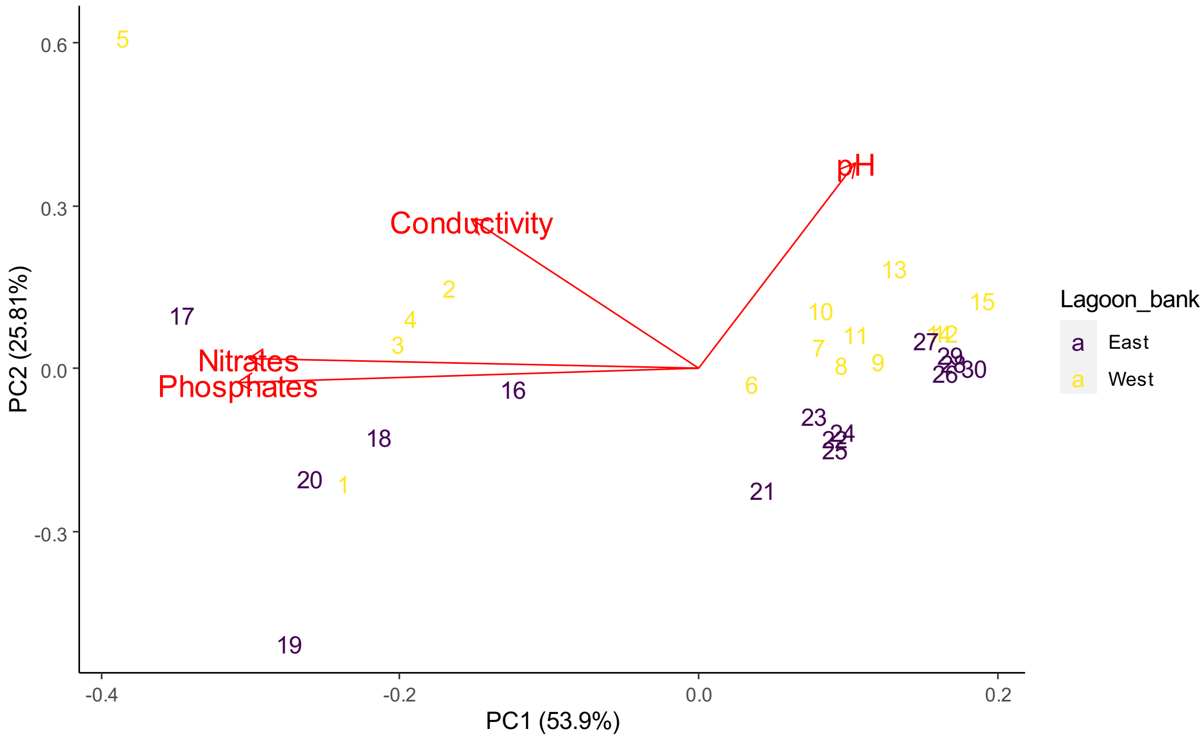


Fig. 5 A PCA showing the spatial associations between and within physicochemical parameters (pH, conductivity, nitrates, and phosphates) and mangrove sediment sampling points (sites) collected from the Eastern and Western banks of Chilaw lagoon. The relative distances between/within physicochemical parameters and mangrove sediment sampling points indicate the degree of spatial associations

difference ($p = 0.0003842$). The western bank recorded a higher pH (Supplementary Fig. 7 and Supplementary Table 7) with the majority of samples being positively correlated with pH (Fig. 5). Nitrate and phosphate levels were positively correlated ($r^2 = 0.94$, $p = 1.554e\text{-}14$).

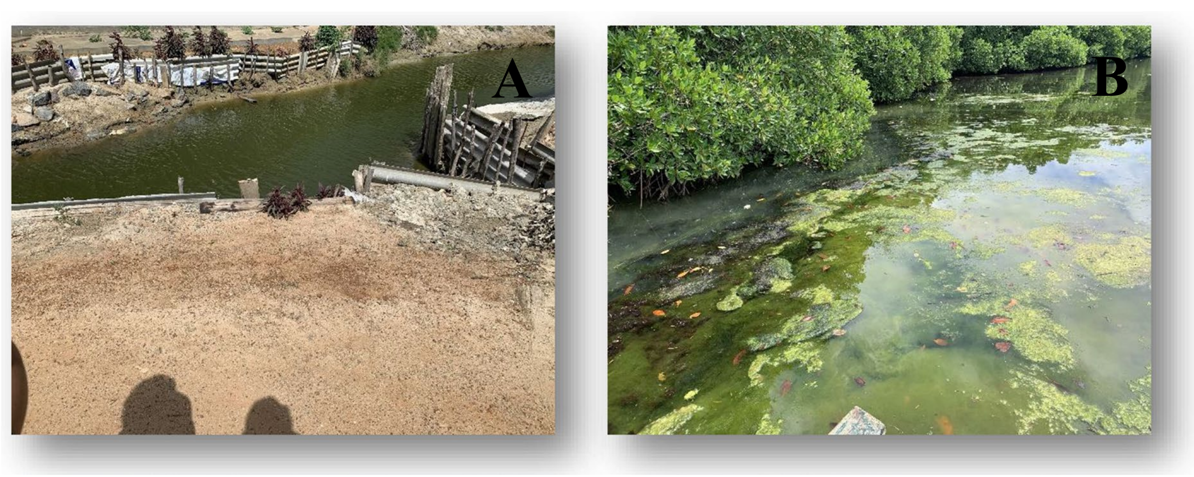


Fig. 6 Inset **A** reveals effluents discharged from a shrimp farm into the Chilaw lagoon, and inset **B** shows the development of algal blooms causing eutrophication in Chilaw lagoon. Pictures were taken by authors during field visits

4 Discussion

4.1 Physicochemical Status of Chilaw Lagoon and Its Fringe Mangroves

The release of effluents from diverse sources into the Chilaw lagoon and the mangroves has contributed to changes in their physicochemical characteristics over the years (Maddumage et al., 2016). Shrimp farmers in the P-CLC use vitamins, growth enhancers, medicines, and sometimes supplementary fresh food materials including thrash fish, mollusc meat, or egg; the uneaten balance of these supplementary feeds also contribute to the quality of effluents (Corea, 2019). The effluents which are usually untreated therefore contain higher levels of nutrients such as nitrates and phosphates going into the Chilaw lagoon and mangroves (Fig. 6). Leslie (2011) indicated other sources of pollution into the lagoon to be effluents and solid waste from the residential area and organic waste from the Chilaw market located in the Chilaw town.

When compared to the most recent study which investigated the levels of some selected physicochemical parameters in water samples from the Chilaw lagoon in 2016, it can be estimated that the current maximum levels of nitrates are about three times higher, while that of phosphates are three times lower (Maddumage et al., 2016). Moreover, while the minimum pH level increased by 1.6 pH units and the maximum pH level decreased by 0.14 pH units, the maximum level of conductivity was five times lower (Maddumage et al., 2016). Conditions of high pH (≥ 9) as evidenced in the water samples are usually accompanied by algal blooms and low oxygen concentrations. While we cannot trace the source of the nutrients in this study, this situation is typical of lagoons that receive anthropogenic effluents (Chen & Durbin, 1994). The increased productivity of algae leads to the high uptake of dissolved oxygen in the water and consequently limiting aquatic species in the lagoon of adequate oxygen. During conditions of limited oxygen, vulnerable species suffocate and die, adding up to the high nutrient levels in the lagoon, and causing eutrophication (Isiuku & Enyoh, 2020) as observed in the Chilaw lagoon (Fig. 6).

Kjerfve and Magill (1989) indicated that tidal currents coupled with the mixing of ocean and river waters incline density surfaces, yielding both a horizontal (i.e. length-wise) and vertical (i.e. depth-wise) density stratification in restricted coastal lagoons like the Chilaw lagoon. The results in this study agree with Kjerfve and Magill (1989) as the majority (61%) of the physicochemical parameters measured in water samples from each sampling point was statistically different along a depth gradient (Supplementary Table 2). Moreover, there existed statistically significant differences ($p = 1.39\text{E-}14$ to 0.00242, $F = 139.07$ to 23.858) between water samples from different zones for each physicochemical parameter measured at the three depths. It can thus be said that the Chilaw lagoon presents both vertical and horizontal stratification. These observations can be explained by the occasional inflow of freshwater from Deduru Oya and Lunu Oya into Chilaw lagoon and the opening and closure of the lagoon with sandbar at the north and south mouths altering the water salinity and density (Wijeratne et al., 2004) .

The lower depths recording the highest records of conductivity, pH, and nitrates can be explained by the shallow nature of the lagoon and its nutrient fluxes. In shallow lagoons, benthic macroalgae or submerged aquatic vegetation (SAV) serves as important sources of nitrogen which is transformed by the microbial communities for use by the overlying algal communities (Glibert et al., 2010). In cases where there is limited light reaching the benthic layer, the macroalgae or SAV may die, leading to increased flux of reduced forms of nitrogen from the sediment layer (Glibert et al., 2010). Moreover, the vertical stratification where gravity forces denser water to settle downward causes a higher proportion of these nutrients to be carried down the water column (Pickup and Tyrrell, 2020). An increasing negative correlation identified between pH and nitrates with increasing depth explains the lowering effect of increased nitrates on pH in the water column, making the bottom waters of the lagoon more acidic.

Latitude also being identified as having a strong influence on the levels of the physicochemical parameters (except phosphates) in water at all depths supported the principle that higher concentrations of nutrients occur at higher latitudes of surface waters

(Pickup and Tyrrell, 2020). This however implies that other factors such as salinity, depth, tidal currents, biological processes, number of pollution sources along the lagoon, and their interactions with latitude could determine the existing variation in the levels of physicochemical parameters recorded in this study.

The sampling zone C recording the highest average levels of conductivity in water samples across all depths agrees with the findings of Leslie (2011) which indicated that the northern part of the lagoon was with the highest levels of conductivity. The sampling point B which also recorded the highest levels of nitrates across all depths can be supported by the intermittent mixing processes and inputs from both mouths of the lagoon which allow mobile nutrients such as nitrates to be temporarily accumulated in the middle part of the lagoon. The pattern is however different from sediment samples as sediments from sampling zone A rather records the highest average levels of both nitrates and phosphates. This pattern can be explained by the higher water retention time at the southern part of the lagoon as the water flows from the north towards the south. During times where the sandbar of the lagoon is closed, water flow is limited, and this makes it difficult for water transporting nutrients from the north of the lagoon to exit. Consequently, the highest pH levels of water recorded in sampling zone A enhance nutrients to be gradually released down the water column to the sediment layer which is of lower pH levels.

The pH of most mangrove sediments located in the North-Western, Western, and Southern provinces of Sri Lanka are typically acidic due to anaerobic decomposition with a high supply of sulphates via seawater inundation (Phillips et al., 2017; Vithana et al., 2021). The high level of pH recorded in mangrove sediments collected from both banks of the lagoon could therefore be associated with the release of highly alkaline effluents into the mangroves (Suárez-Abelenda et al., 2014). The western bank recording the higher pH levels can also be explained by the higher number of shrimp farms located on the western bank of the lagoon, indicating a higher level of effluent release (Fig. 1).

The higher levels of nitrates and phosphates recorded in mangrove sediments as compared to lagoon sediments reveal the ability of fringe mangroves in reducing pollutants such as nutrients reaching coastal waters such as lagoons (Sun et al., 2020). Amidst this ability of mangroves, an increasingly high level of physicochemical parameters and subsequent formation of algal blooms in lagoons can cause abiotic stress to mangroves, especially during the early stages of development (Kodikara et al., 2017, 2020). For instance, levels of inorganic forms of nitrogen (e.g. nitrates) at 1–5 $mg.L^{-1}$ in lagoon water and sediments can cause a significant reduction in nitrogen fixation in its fringe mangrove habitats (Sweatman, 2002). This can further cause an increase in mangrove vulnerability to water stress during events of drought, resulting in mangrove mortality (Lovelock et al., 2009). A study in mangroves in the Ganges River estuary of India revealed lower rates of nitrogenase activity present in mature stands as compared to pioneer stands (Sweatman, 2002). This situation consequently causes a change in the structure of the mangroves and further limits the success of mangrove restoration projects (Kodikara et al., 2017).

A positive correlation between nitrate and phosphate levels witnessed in the lagoon and mangrove sediment samples was not present in water samples due to the ease of nutrient transport in water than in sediments. It is estimated that a stronger positive relationship between nitrates and phosphates in samples are indicative of similar pollution sources (Isiuku & Enyoh, 2020). A negative correlation between pH and conductivity in lagoon sediments may indicate how conductivity may partly increase with decreasing pH and vice versa. However, since this relationship was only seen in lagoon sediment samples, other unknown factors could influence the relationship.

4.2 Socio-Ecological Impacts of Pollution in Chilaw Lagoon and Its Fringe Mangroves

The local people and fishermen responded that there were consequences of lagoon pollution as algal bloom and a reduced population of lagoon fauna (fish, crabs, shrimps) occurred in the Chilaw lagoon over the years. All the fishermen, having a fishing history in Chilaw lagoon for 12–40 years, confirmed a decrease in their fish and shrimp catch over the past years. Some of these evidenced fish and shrimp species are listed in Table 1. The fishermen further mentioned that the phenomenon of reduced catch has led to low-income generation from their fishing business. Cattermoul and Devendra (2002) also reported a vast decline of the

Table 1 List of fish and shrimp species with a reduced catch in the Chilaw lagoon

Aquatic organism	Common name	Scientific name
Fish species	Dussumier's mullet	*Mugil dussumieri* Valenciennes, 1836
	Giant Perch	*Lates calcarifer* Bloch, 1796
	Greasy reef cod	*Epinephelus tauvina* Forsskål, 1775
	Mangrove red snapper	*Lutjanus argentimaculatus* Forsskål, 1775
	Jumping halfbeak	*Hemiramphus archipelagicus* Collette & Parin, 1978
	Congaturi halfbeak	*Hyporhamphus limbatus* Valenciennes, 1847
	Spotted scat	*Scatophagus argus* Linnaeus, 1766
Shrimp species	Giant tiger shrimp	*Penaeus monodon* Fabricius, 1798
	Indian shrimp	*Fenneropenaeus indicus* Milne-Edwards, 1837

wild-caught shrimp population observed in lagoons and coastal waters of Sri Lanka between 1995 and 1998, confirming the fishermen's observation. The decline was however potentially attributed to increased harvesting of wild-caught adult shrimps and lagoon pollution from different sources (Cattermoul & Devendra, 2002).

The local people mentioned that the release of effluents containing pollutants and redworms from shrimp farms affected mangrove flora and fauna, causing eutrophication in pools inside the mangroves (de Lacerda et al., 2021). It was identified that these redworms (*Eisenia fetida* Savigny, 1826) which are resilient to harsh environmental conditions (Pochron et al., 2017) were used as a major ingredient in shrimp feed. Shrimp farmers choose redworms because of their high nutritional value (about 65% protein and 11% lipids) and the higher yields they present (Chiu et al., 2016) . Hence, when they are not well managed by the shrimp farmers, they find their way through the effluents into the mangroves, feeding on the mangrove leaves. It is crucial to note that such an observation of herbivory of mangrove leaves by redworms has not been reported in any scientific literature; hence, it was worth knowing this from the local people.

5 Conclusion

The study has revealed that effluents released from different sources into Chilaw lagoon and its fringe mangroves have contributed to a decline in the population of some fish and shrimp species, causing fishermen to lose their jobs. The continual discharge of effluents into the lagoon ecosystem may result in the reduced health of the mangroves and the increased decline in the population of the aquatic organisms present in the lagoon, causing the lagoon to gradually become ephemeral. It is recommended that there are effective regulations to stop the pollution activities from the different sources. Shrimp farms are encouraged to install wastewater treatment systems and sedimentation tanks before discharging their wastewater.

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Author Contribution SAO: conceptualisation, investigation, formal analysis, and writing-original draft preparation. SKA: conceptualisation, supervision, and writing — review and editing. LPJ: conceptualisation and supervision. UVG: investigation. IW: investigation and writing — review and editing. TWGFMN: supervision and writing — review and editing. FD-G: conceptualisation, supervision, and writing — review and editing.

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Data Availability Data will be available upon reasonable request.

Declarations

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