Comparative Analysis of Ecological Risk Assessment in Coastal Regions of India: A Case Study of Nagavali Estuary, Srikakulam, Andhra Pradesh

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Abstract
Microplastics (MPs) were detected in all water and sediment samples from six locations in the Nagavali estuarine area, marking the comprehensive assessment of MP pollution in the Srikakulam estuarine region, Andhra Pradesh, India. This ecologically and socio-economically significant area faces pollution due to semi-urban discharge and plastic waste mismanagement. Using filtration, density separation and ATR-FTIR spectroscopy, the study establishes baseline data on MP prevalence and ecological risks in Southeast Asia. Results indicate seasonal variations in MP abundance with polyethylene, polypropylene, polyethylene terephthalate and polyvinyl chloride as dominant polymers. Risk assessments using the pollution load index and potential ecological risk index suggest moderate pollution but high ecological risks, particularly in human-influenced zones. A comparative analysis on India's coastal regions highlights regional and seasonal variations in MP pollution and its ecological impact.

This broad perspective underscores the urgent need for targeted mitigation strategies, sustainable policies and improved waste management. The findings serve as a crucial reference for monitoring temporal trends and shaping environmental policies to combat MP pollution. Addressing this pervasive issue is essential for protecting aquatic ecosystems and ensuring sustainable coastal management in India and beyond.

Keywords: Microplastics, Estuarine environment, Polymer toxicity, Pollution load index (PLI), Potential ecological risk indices (PERI).

Introduction

Rivers and coastal zones are vital for ecological balance and human livelihoods, yet anthropogenic pressures are escalating, with microplastic (MP) pollution emerging as a global concern. The Nagavali River, an important east-flowing river in southern India, traverses through Odisha and Andhra Pradesh before draining into the Bay of Bengal near Srikakulam, Andhra Pradesh.

Spanning a surface area of 9,510 km², the river supports agricultural, fisheries and industrial activities that are vital to the region's population[13]. Seasonal variations in discharge characterized by monsoonal and dry periods, further influence the river's dynamics and its interaction with the adjacent coastal zone[7].

At its terminus, the river meets the Bay of Bengal near Ganagallapeta coastal area, a developing coastal area with ecological and economic significance and forms an estuarine region known for its extensive sandy shoreline and small-scale fisheries. The coastal area is increasingly impacted by seasonal erosion, marine litter and unregulated tourism[7]. Local stakeholders are striving to balance economic activities with the preservation of the coastal area's ecological integrity[14]. Amidst these pressures, microplastic (MP) pollution has emerged as a pervasive environmental issue, influencing both freshwater and marine ecosystems.

MPs, defined as plastic particles smaller than 5 mm, are generated through various pathways including the degradation of larger plastics and the discharge of microbeads from personal care products[17]. These particles are of particular concern due to their potential to accumulate toxic chemicals, to enter food chains and to pose ecological risks to aquatic life[4,5]. While the environmental implications of MPs have been widely studied, data on their distribution and ecological risks in semi-urban regions, particularly in India, remain sparse. This study fills a critical gap by conducting detailed analysis of MP pollution in the Nagavali estuarine area while also providing a comprehensive comparative assessment of ecological risks across India's coastal regions, offering novel insights into regional and Nationwide microplastic contamination patterns.

Material and Methods

Study area and sample collection: The present study was conducted in the Nagavali estuarine area, located along the Bay of Bengal near Srikakulam, Andhra Pradesh It is a developing area with a sandy shoreline extending for several kilometres. The estuarine area is a hub for small-scale fisheries and is gaining attention as a potential eco-tourism destination[6]. However, the estuarine zone faces challenges from seasonal erosion, marine litter and unregulated tourism activities. Local efforts are being made to balance economic activities with the preservation of the coastal area's ecological and aesthetic value.

Sediment and water samples were collected during the pre and post monsoon seasons in April 2024 and December 2024 respectively. Two zones were taken in the estuarine region with three sampling points each (One close to Ganagallapeta coastal area and the other close to nagavali river area). Each

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sampling point at a zone was settled approximately 5-7 km from the next and a total of 6 stations were sampled. Water samples were collected at each station using a 200µm mesh working party zooplankton net[26].

Materials collected in the cod-end of the net were rinsed thrice. The residue was transferred into a clean 1000 mL glass bottle. Before the next sampling stage, the net was externally rinsed. Bulk surface sediment samples (approximately 1 kg of wet sediment) were collected at each station using a Van Veen grab sampler and stored in an aluminium box covered with aluminium foil. After transport to the laboratory, the samples were stored at 4°C. Sediment samples were dried in a hot air oven at 70°C for five days using a Remi dry hot air oven.

Extraction: A sample volume of 20 mL of water was filtered using GF/A filterpaper and the filter was placed in 100 mL glass beaker. Organic matter was removed by adding 30 mL of 30 % (v/v) H_2O_2. Add 20 mL of aqueous 0.05M $FeSO_4$ and 20 mL of 30 % (v/v) H_2O_2 and stir the solution for 60 minutes. Later the solution is allowed to settle down for 24 hrs. After 24 hrs, the supernatant was filtered through six mesh filters with pore sizes of 500 µm, 230 µm, 125 µm, 60 µm, 25 µm and 13 µm and is collected and is examined for the presence of microplastics[25]. The glass Petri dishes were used to store the filtrate, which will be further analysed. The sediment samples were dried and a 1 mm mesh sieve was used to separate small MPs (<1 mm) from large MPs (>1 mm). Large- sized plastics were removed with forceps. A 10 g portion of sediment was accurately weighed and transferred into a 100 mL glass beaker. Digestion, separation and filtration were conducted in the same manner as for the water samples. The entire procedure was repeated three times per sample to minimize errors.

Determination of abundance, type of polymer, color and shape: Polymer types were identified using attenuated total reflection (ATR) for particles larger than 1 mm. The spectroscopic analysis was carried out using a Bruker alfa-II ATR-FTIR in reflectance mode, covering the IR spectral range from 4000 to 400 cm^{-1}. The spectral resolution was 4 cm^{-1}, using sixteen scans per pixel, representing a good compromise between mapping time and signal-to-noise quality of the spectra. Once the spectral map images were acquired and the spectra of the particles were generated, they were analysed using Opus 7.0 software to obtain information about the polymer types. An image with a map of the Pixels representing the identified MPs was also obtained and the spectrum for each MP was visualized and compared to a spectral reference database. Filters with pore sizes over 100 µm were observed using a Labomed stereo zoom microscope-CSM2 to record the color and shape.

Quality assurance and quality control: All sampling equipment was thoroughly cleaned with chromic acid followed by deionized water prior to each field trip. Water samples were collected in glass bottles while sediment samples were stored in metal containers. During microplastic extraction and analysis, lab coats and nitrile gloves were used to prevent contamination (false positives). The workspace was cleaned with methanol and all glassware was washed with chromic acid, rinsed with deionized water and covered with aluminium foil to protect against airborne contamination. Prior to use, all chemical solutions were passed through a vacuum pump and filtered using a mesh filter. Preparations were conducted under a laminar flow hood and potential contaminations were monitored by using blank samples. Only two blank samples showed the presence of microplastics out of ten.

Pollution load index (PLI): The pollution load index (PLI) has been predominantly employed to investigate the presence of aquatic contaminants by elucidating the pollution levels at specific sampling sites and facilitating an in-depth analysis of pollution within a designated area[8,12] using equations (1) and (2):

$$CF_x = C_x / C_l \quad (1)$$

$$(PLI_{zone})^n = CF_1 \times CF_2 \times \_\_\_\_ \times CF_n \quad (2)$$

where C_x is the abundance MP number in site i, C_l is the lowest detected MP concentration and n is the number of sampling stations

Potential ecological risk index (PERI): The potential ecological risk index (PERI) is done to study the combined effects of multiple pollutants in the environment and quantitatively categorizes the potential ecological risk levels[1,2,8-12]. The potential ecological risk index (PERI) is calculated by the formula given in equations (3) and (4):

$$PERI_l = CF_l \times PHI_l \quad (3)$$

$$(PERI_{zone})^n = PERI_1 \times PERI_2 \times \_\_\_\_ \times PERI_n \quad (4)$$

Results and Discussion

Abundances of microplastics in water and sediment samples: Microplastics (MPs) were detected in all water and sediment samples from the six sampling sites, with significantly high concentrations compared to several riverine and estuarine systems in India. In the present study, post-monsoon MP concentrations in water (59 particles/L) and sediment (53 items.kg^{-1}) were higher than in many Indian water bodies. For instance, the surface water of the Mahanadi River had an MP abundance of 16.6 particles/L while its sediment contained 197.3 particles/Kg[22].

The Hirakud Reservoir in Odisha showed even higher MP levels in water (82–89 particles/L) but lower sediment concentrations (159–163 particles/Kg)[13]. Similarly, the northeastern coast of Andhra Pradesh reported an average of 564 particles/Kg in sediment[24] which is substantially higher than the sediment MPs recorded in the present study.

In comparison, pre-monsoon MP concentrations (43 particles/L in water and 51 items.kg^{-1} in sediment) exceeded values reported in other major Indian river systems. For example, MP concentrations in the Yamuna (1.47 items.m^{-3}) and Ganga (1.23 items.m^{-3})[12] were significantly lower than those observed in the Nagavali estuary. However, sediment MP concentrations in the present study were lower than the northeastern coast of Andhra Pradesh (564 particles/Kg), indicating regional variability in MP accumulation across India's coastal and estuarine systems.

When compared to global findings, the present study's MP concentrations in water were higher than those observed in Dongshan Bay, China (1.66 particles/m^3)[19] but significantly lower than the Yangtze River, China (3,598.6 particles/m^3)[21]. Similarly, in the Shiwuli River, China, MP concentrations were recorded at 8.4 particles/L in water and 78.9 particles/Kg in sediment[25], showing that while the Nagavali Estuary has comparable water MP levels, sediment contamination remains lower than in certain highly impacted global sites.

These findings suggest that while MP contamination in the Nagavali Estuary is severe, particularly in water, sediment pollution remains relatively lower than in certain highly contaminated regions like the northeastern Andhra Pradesh coast and the Yangtze River in China. Seasonal variations also played a critical role with post-monsoon MP levels being significantly higher, aligning with patterns observed in both Indian and global studies, where increased runoff and urban discharge contribute to elevated microplastic loads in aquatic systems.

Characteristics of microplastics in water and sediment samples

Shape and color: Nguyen et al[11] found higher percentages in Vietnam's urban drainage channels (77.2%–86.1%) and the Nhue–Day River basin (93.3%). In Southeast Asia, Mazlan et al[8] reported 93.8% and 99% fragments, respectively while Wang et al[24] noted 87%.

In comparison, Indian studies also highlight fibre dominance with Shaji et al[19] reporting 89.67% fibers, 8.17% films, 1.88% fragments and 0.31% foam in the northern coast of Andhra Pradesh. Similarly, Patidar et al[12] found 46.21% fibers in water and 44.86% in sediment in the Hirakud Reservoir, Odisha. In the present study, fibers constituted 82% in water and 75.5% in sediment, demonstrating a higher fiber prevalence than several previous studies in India. These findings indicate significant fiber contamination, likely due to synthetic textile products[19].

Globally, the proportion of fibers in the present study is higher than in many Southeast Asian studies. Kaniyambadi et al[5] recorded 80.1% fibers in the Western Ghats[2]. However, Fiber dominance in the northern Andhra Pradesh coast (89.67%) is even higher than the current study, indicating significant regional variability. Fragment proportions in the current study remain moderate compared to Southeast Asian reports where fragmentation is more prevalent.

Regarding color composition, black and blue fibers constituted 60.4% in water and 53.4% in sediment in the present study, exceeding 48.11% [2]. Microplastics derive their color from their original plastic sources, but photodegradation and extended exposure to aquatic environments can alter their appearance[3]. These findings suggest that while fiber contamination is dominant in the studied region, variations in MP composition reflect differences in plastic waste sources, environmental processes and degradation rates across different geographic locations.

Types of polymers: Regarding the identification of polymers, the results of the analysis via FTIR revealed the presence of four main polymer types: polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyethylene (PE) and polypropylene (PP) accounting for 18.7 %, 38.7 %, 15.2 % and 10.3 % in water and 18.6 %, 27.7 %, 24.8 % and 11.4 % in sediment respectively (Fig. 2). Vietnam's plastic demand explains their high abundance of PE and PP[16]. Consistent with expectations, lower-density microplastics (PVC and PET) were more prevalent in water samples (57.4%) compared to sediments (46.3%) whereas PET, with a higher density than water (1.24–1.29 g/cm^3) was less abundant in water (15.2%) but more concentrated in sediments (24.8%). During flotation denser polymers like PET and PVC cannot be separated using NaCl[8].

These thermoplastics are integral to manufacturing various products for industrial and domestic use, with PET primarily utilized in packaging (especially bottles) and PVC in construction materials, piping and cable insulation. In India, rapid industrialization and the expansion of packaging and construction sectors increase the discharge of these polymers into the environment. Their higher densities make them prone to accumulating in sediments and water bodies, posing significant risks of long- term pollution.

Risk assessment of microplastics: The pollution load index(PLI), polymer hazard index(PHI) and the potential ecological risk (PERI) due to MP pollution were estimated to quantify the state near the Nagavali River and Ganagallapeta coastal area and allow comparisons with other environments in the future.

Pollution loading index (PLI): The present study evaluates the pollution load index (PLI) for both water and sediment samples across different zones in the Nagavali estuarine region, considering seasonal variations. The results indicate that the PLI values for water in zone 1 are 2.28 (post-monsoon) and 1.98 (pre-monsoon), while in zone 2, they are 3.77 (post-monsoon) and 2.39 (pre-monsoon). Similarly, for sediment, the PLI values in zone 1 are 2.84 (post-monsoon) and 2.35 (pre-monsoon), whereas in zone 2, they are 4.15 (post-monsoon) and 3.92 (pre-monsoon). Given that a PLI greater than 1 denotes pollution, all analysed zones exhibit contamination, with higher PLI values in zone 2, particularly in the post-monsoon season.

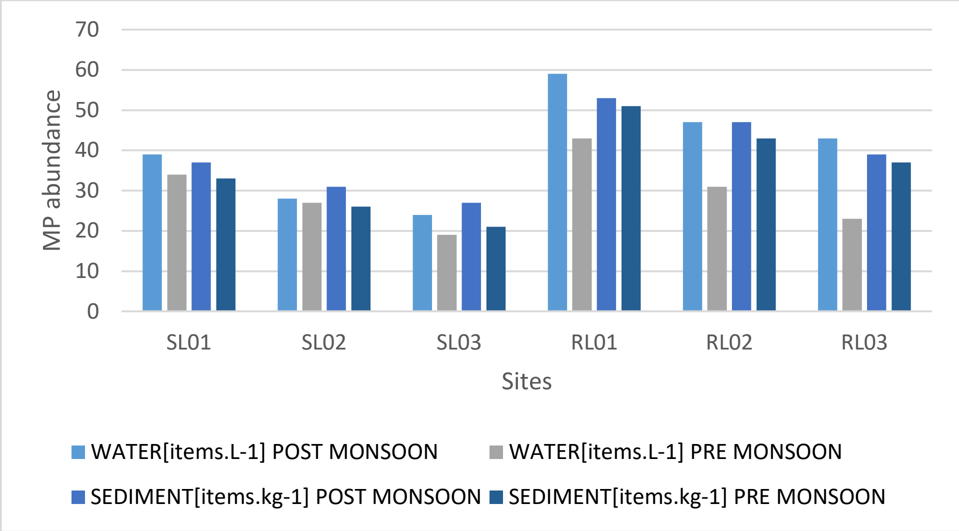

Fig. 1: Microplastics abundance in water [items.L^{-1}] and sediment [items.Kg^{-1}] for samples collected near the Nagavali River and Ganagallapeta coastal area (Nagavali estuary)

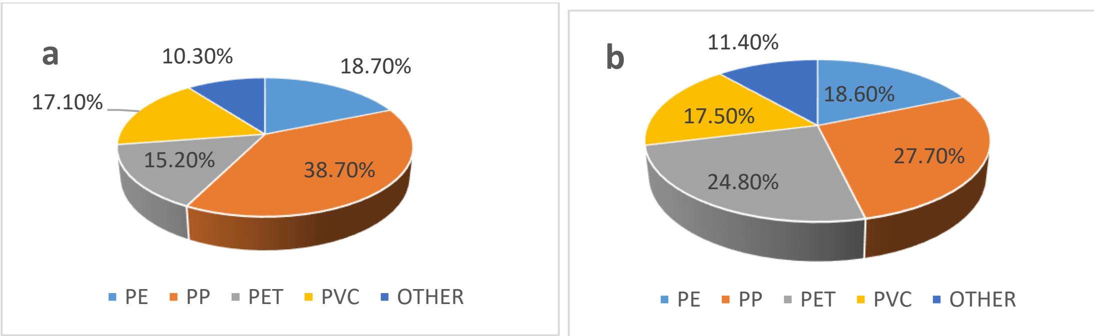

Fig. 2: (a) Percentage of different polymer types present in Water; (b) Percentage of different polymer types present in Sediment.

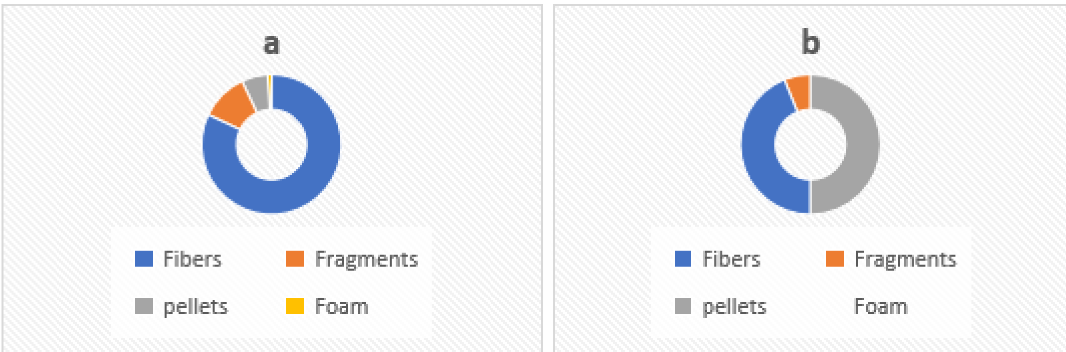

Fig. 3: (a) Distribution of microplastics in zones 1 and 2 according to shape in surface water; (b) Distribution of microplastics in zones 1 and 2 according to shape in surface sediment.

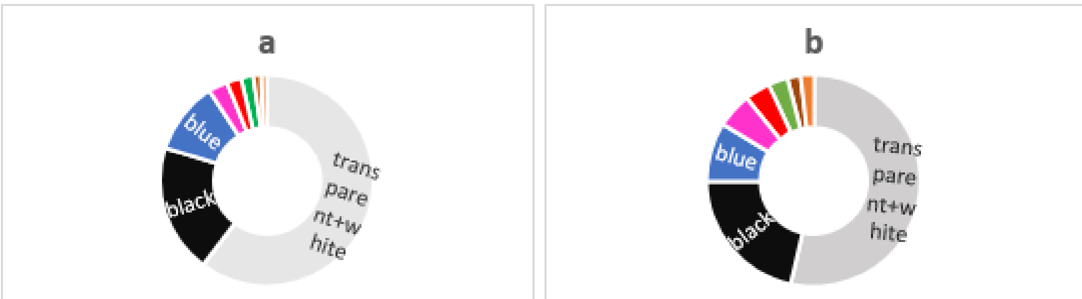

Fig. 4: (a) Distribution of microplastics in zones 1 and 2 according to color in surface water; (b) Distribution of microplastics in zones 1 and 2 according to color in surface sediment.

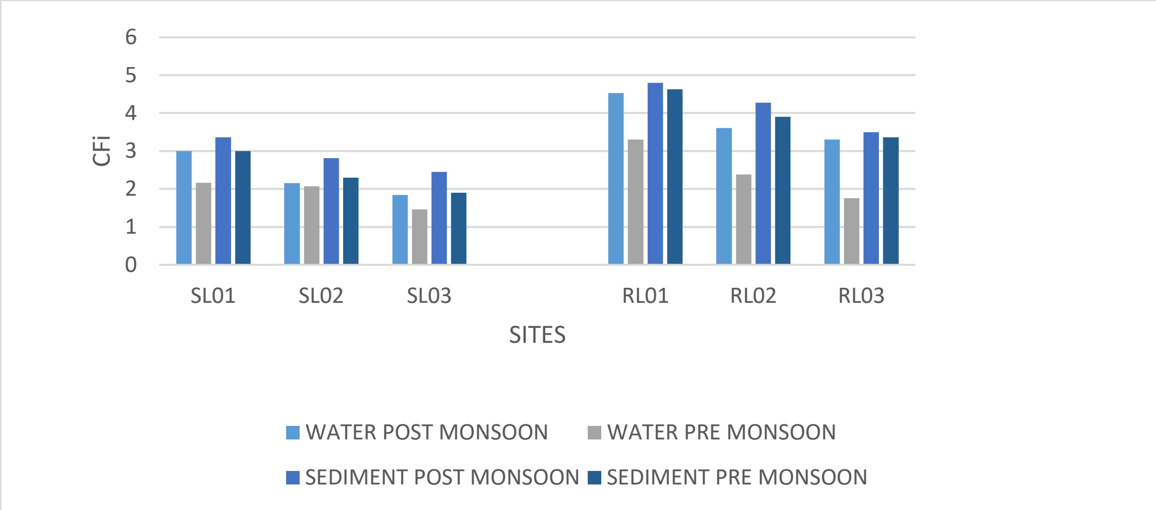

Fig. 5: CF values of water and sediment of zone 1(SL01, SL02, SL03) and zone 2(RL01, RL02, RL03) in pre monsoon season and post monsoon season.

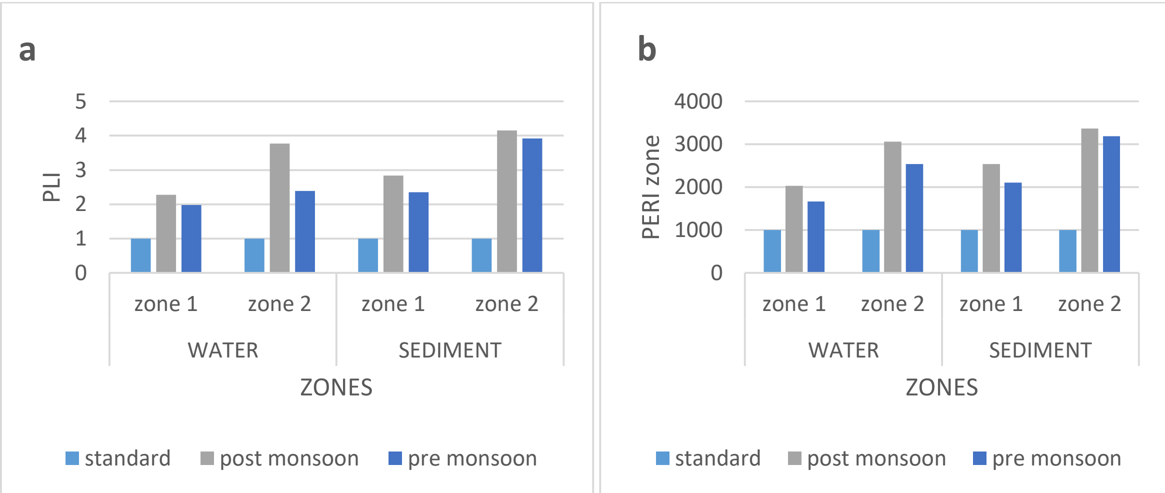

Fig. 6: Contamination factors in surface water and sediment (a) Pollution loading index [Level-3(3<CF<6): Considerable degree]; (b) Potential Ecological Risk Index [Level 5 (>1200)- very high risk]

Compared with existing Indian literature, the observed PLI values align with other polluted coastal and estuarine regions. Ranjani et al[17] reported PLI values of 3.03 for coastal sediments along the west coast of India, 1.0 for the east coast, 15.5 for Maharashtra, 11.4 for Karnataka and 10.45 for the Vembanad lake. The significantly higher values in Maharashtra and Karnataka indicate severe pollution, while the values from the east coast are comparatively lower. The current study, conducted in the Nagavali estuarine region, presents PLI values that are lower than those observed in highly industrialized regions such as Maharashtra and Karnataka but higher than the east coast average.

Shaji et al[19] reported PLI >1 along the northern coast of Andhra Pradesh, confirming pollution in this region. However, their study did not consider seasonal variations to assess the Nagavali estuarine area, highlighting a gap that the present study aims to fill. PLI values of <10 for the Mahanadi River placing it in category 1 align with the current study's findings but lack a seasonal analysis. Similarly, a PLI <1 in the Hirakud Reservoir, Odisha, suggested minimal pollution in that region, contrasting with the current study, which shows clear pollution signatures in the Nagavali estuary.

Beyond Indian literature, the PLI values reported in international studies exhibit considerable variation. A PLI of 14.2 in the estuarine area of Dongshan Bay, China is significantly higher than the values reported[20] in the current study. However, it did not analyse seasonal variations, a key component of this study. PLI values exceeding 30 in freshwaters in China, highlighting severe pollution conditions were much higher[25] than those reported in the Nagavali estuary.

In the Yangtze River, China, the PLI for water was 2.24 and for sediment it was 2.34[22], closely matching the present study's findings. This similarity reinforces the presence of pollution in estuarine environments and supports the significance of the seasonal variability analysis conducted in the present work.

The novelty of this study lies in its comprehensive assessment of PLI across both water and sediment in the Nagavali estuary, with a specific focus on seasonal variations, an aspect that previous studies in the region have overlooked. Unlike prior research in northern Andhra Pradesh and international studies, which do not incorporate seasonal dynamics, this study provides a more detailed and nuanced understanding of pollution trends over different periods. Additionally, by incorporating both sediment and water PLI values, the study presents a holistic view of the pollution status, making it a valuable addition to both regional and global environmental assessments. The results indicate that the pollution levels in the Nagavali estuarine area are significant, requiring immediate attention for pollution control and mitigation. This study establishes baseline data for future monitoring and provides critical insights for environmental management strategies specific to estuarine ecosystems.

Potential ecological risk index (PERI): The present study evaluates the potential ecological risk index (PERI) for both water and sediment samples across different zones in the Nagavali estuarine region, considering seasonal variations. The results indicate that the PERI values for water in zone 1 are 2033.32 in post-monsoon and 1665.99 in pre-monsoon, while in zone 2, they are 3064.39 in post-monsoon and 2537.39 in pre-monsoon. Similarly, for sediment, the PERI values in zone 1 are 2537.39 in post-monsoon and 2101.91 in pre-monsoon, whereas in zone 2, they are 3369.39 in post-monsoon and 3186.40 in pre-monsoon. Given that a PERI greater than 1200 denotes extreme danger (Level IV), all analysed zones exhibit severe contamination, with higher PERI values in zone 2, particularly in the post-monsoon season.

Compared with existing Indian literature, the observed PERI values are significantly higher than those reported in previous studies. The documented PERI values of less than 150 in coastal regions of Tamil Nadu, Maharashtra and Karnataka, with Kerala reporting 597.5, Goa 345.9 and some regions of Karnataka and Maharashtra showing values of 303.2 and 332.1 respectively[12]. The values reported in these regions are considerably lower than those found in the present study, emphasizing the severity of pollution in the Nagavali estuarine region. The stark contrast highlights the uniqueness of the current study, as it provides new insights into an underexplored estuarine system with alarming contamination levels.

Internationally, the reported PERI values show broad variability. The recorded PERI values are 16.26 in seven lakes of Da Nang City, Vietnam and 10580.44 in Kallavesi lake, Finland. Additionally, nine lakes in the Patagonia region of Argentina exhibited a PERI of 6059.34, while Guiba lake in Brazil reported 26138.18. The Nakdong River in South Korea had a PERI of 1660.11 and the Han River recorded 4742.66[25]. The values in Nagavali estuary are higher than those of Nakdong River but lower than those in highly contaminated international water bodies like Guiba lake and Kallavesi lake. The study's findings bridge the gap between domestic and international pollution studies, demonstrating that the Nagavali estuarine system faces contamination levels comparable to some of the most polluted aquatic systems worldwide.

The significance of this study lies in its assessment of PERI across both water and sediment with a focus on seasonal variations, an aspect overlooked in prior studies. Unlike previous research that either neglected seasonal dynamics or focused on broader coastal assessments, this study presents a detailed and site-specific analysis of contamination in the estuarine environment. The results highlight a critical pollution hotspot that demands urgent intervention.

Conclusion

MP concentration is recorded higher in zone 2 (post monsoon season). Polyethylene, polypropylene, polyethylene terephthalate and poly vinyl chloride were identified as the predominant polymer types in both water and sediment samples. Overall, in the Nagavali estuarine area, the MP pollution load is moderate, but the type of particles detected represents a high to dangerous polymer risk, resulting in a very high potential ecological risk near the river when compared to the sea (coastal area). Therefore, stakeholders should carefully evaluate polymer types and their hazard scores when developing regulations for plastic reduction and alternative products.

In addition, the predominance of fibers of small size is a cause for concern as this type of particle is more likely to be absorbed by aquatic life through oral ingestion or dermal exposure. These findings underscore the urgent need for more comprehensive studies on the extent of microplastic pollution in aquatic systems, particularly in developing districts such as Srikakulam, where plastic production, consumption and recycling activities are rapidly increasing. This study assesses MP contamination in the Nagavali estuarine, Srikakulam, Andhra Pradesh. These findings call for immediate policy measures to curb plastic waste and to promote sustainable practices, particularly in regions with escalating industrialization. The outcomes also establish a robust baseline for longitudinal studies, fostering global collaborations to combat MP pollution.

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