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Ecohydrological features and biodiversity status of estuaries in Bengal delta, Bangladesh: A comprehensive review

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An estuary represents a transition point between freshwater and saltwater and has a complex but productive environment due to a strong interplay between geological, physical, chemical, and biological processes. In Bangladesh, the ecological factors and biodiversity of different estuaries have been investigated for the last 35 years. However, the data is widely scattered, not easily accessible, unpublished, and/or in the form of grey literature. In this study, an attempt has been made to aggregate information available on the geo-environmental and biodiversity status of estuaries for their sustainable management. The biological and environmental data of 21 estuaries along the Bangladesh coast were collected from previously published literature and analyzed. The analyses revealed that the estuarine environment of Bangladesh is very dynamic and diverse like other tropical estuaries. The physico-chemical and geological parameters in estuaries significantly varied due to monsoon patterns, nutrient influx, salinity intrusion, riverine discharge, siltation, and human interventions in estuaries. Among the key environmental variables, such as salinity (3.7–30 ppt), pH (7.04–8), dissolved oxygen (3.30–13.63 mg/L), and water temperature (21–30°C) varied. Over 830 faunal and floral species of 273 genera were recorded from the estuarine environment, including 208 fishes, 87 species of phytoplankton, and 67 species of zooplankton in this region. This study suggests the development of an appropriate policy to protect valuable, productive, and diverse ecosystems, especially for erosion control, pollution abatement, and habitat destruction, particularly in the mangrove forests and their associated habitats of Bangladesh.

KEYWORDS

estuary, biodiversity, ecology, water dynamics, soil texture, benthos, fish, mangroves

1 Introduction

Estuary, a transition point between fresh and salt water, is the world's most diverse, dynamic, and productive ecosystem (Gray, 2004; Eick and Thiel, 2014). Estuary combines unique physical, chemical, biological, and geological features (Mann, 1982; Elliott and Quintino, 2007). As per a recent estimate, estuaries are four times more productive than ryegrass pastures and 20-times more productive than the open sea, with production occurring through active photosynthesis both throughout the water column and on the sediment surface (Boicourt et al., 2012). The estuarine organism uses productive ecosystems for spawning, feeding, nursing, and migration (Blaber et al., 2000). The coastline of Bangladesh stretches across 710 km of the Bay of Bengal (Hussain, 2013) and contains several river-based estuaries along their tidal zones (Hussain, 2013). The margins of estuaries support important primary producers, *e.g.*, algae, seagrass, and mangroves, which provide large quantities of organic matter (Hoque et al., 1999). Marshes and mangroves may produce up to ten tones of plant detritus per hectare per year (Kamal and Khan, 2009). Thus, in addition to high productivity, estuaries are extremely rich in organic matter and nutrients, transported and trapped through freshwater flow, wind, waves, and tidal action (Mahmood et al., 1978; Ketchum, 1983). As a result of productivity and high nutrient loads, many species of fish and shellfish use estuaries as nursery grounds to spawn and allow juveniles to grow (Chowdhury et al., 2011). Additionally, birds, mammals, fish, and other wildlife depend on estuaries to complete their life cycle (Amin and Mahmood, 1979; Ketchum, 1983; Zafar et al., 1999).

Bangladesh coastal area with 21 major estuaries along the Bay of Bengal has a strong potential impact on fishing and the livelihoods of the local people (Ahmed, 2004; Islam and Wahab, 2005). Realizing the importance of diverse ecohydrological and biodiversity importance, significant studies have been conducted which highlighted the exclusive importance of estuaries and coastal areas for the economic development of Bangladesh as well (Hossain et al., 2012; Ahmed et al., 2019; Siddique et al., 2021). However, accessing these coastal resources is much more difficult for its marginal geography because of the lack of detailed, comprehensive studies and reviews on the total resource tabulation and their possibilities for the economic growth of Bangladesh. Therefore, this review paper summarizes available data on the physico-chemical, geological, and biological aspects of estuaries in Bangladesh along the Bay of Bengal coast. In addition to this, we have also discussed the diversities of various species and established hydrobiological correlations with correlation coefficients in estuary rivers. Future research priorities are identified, and recommendations are put forward.

2 Methods and materials

2.1 Study area

In this study, we examined a meta dataset obtained from 21 estuaries, namely Naf River Estuary, Rezu Cannal Estuary, Bakkhali River Estuary, Matamuhuri River Estuary, Sangu River Estuary, Karnaphuly River Estuary, Feni River Estuary, Choto Feni River Estuary, Meghna River Estuary, Tetulia River Estuary, Galacipa River Estuary, Andharmanik River Estuary, Payra River Estuary, Balaswar River Estuary, Betmore River Estuary, Sela River Estuary, Pussur River Estuary, Arpangachia River Estuary, Sundarban River Estuary, Malanchi River Estuary, Ichamoti River Estuary distributed along the coastal belt of the deltaic plain; the entire coastline of Bangladesh lies in the Bay of Bengal region (Figure 1). Based on the geographical locations, all the estuaries were divided into the south-east, south-west, and mid-coastal regions (Figure 1).

2.2 Systematic data collection and analysis

The data was divided into biotic and abiotic parameters to better understand the processes, concentrations (heavy metals, nutrients, dissolved/suspended solids, trace metals, *etc.*), variabilities, and relationships. The abiotic parameters include physical, chemical, and geological variables. All the data were collected from previous studies conducted during the last 35 years (Table 1), including published manuscripts, theses, books, and other secondary sources, i.e., Marine resource inspector, Upazila fisheries officer, *etc.* All are sorted according to our targeted variables and excluded unnecessary findings. Available data were extracted from these sources, and key parameters associated with each estuary were compiled. Ocean data view (2016) software was used to visualize the concentration of parameters. Sunburst graphs were generated to portray species compositions for each estuary. Cluster analysis was performed using Pearson Coefficient in the Multivariate Statistical Package Software (MVSP 4). Stacked columns were used to present the data for physical properties.

3 Results and discussion

3.1 Geological properties of estuaries

Generally, an estuary is a dynamic and highly productive ecosystem where fresh and saltwater meet, resulting in diverse physico-chemical, biological, and geological features. Mangroves and the sandy deltaic plain lands are the common geological features of the estuaries near the coastal belt of Bangladesh, therefore, termed as Bangladesh estuarine complex (BEC). Deltaic estuaries possess huge sedimental loads through the

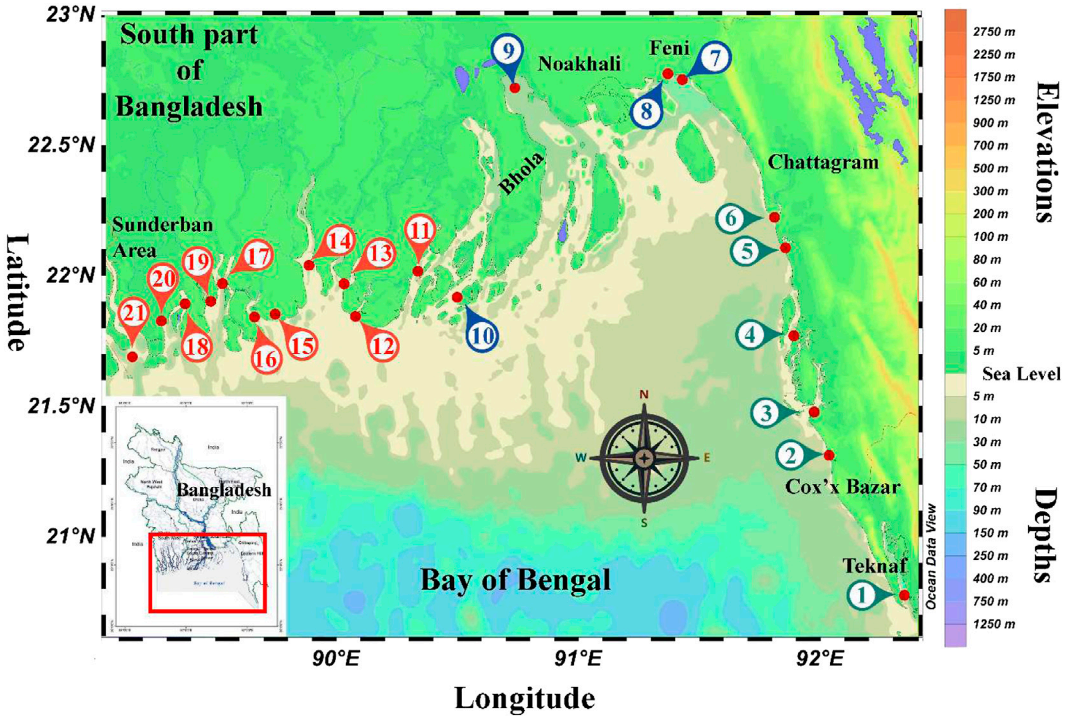

FIGURE 1
Location of each investigated estuaries in this review, where, 1: Naf River Estuary; 2: Rezu Cannal Estuary; 3: Bakkhali River Estuary; 4: Matamuhuri River Estuary; 5: Sangu River Estuary; 6: Karnaphuly River Estuary; 7: Feni River Estuary; 8: Choto Feni River Estuary; 9: Meghna River Estuary; 10: Tetulia River Estuary; 11: Galacipa River Estuary; 12: Andharmanik River Estuary; 13: Payra River Estuary; 14: Balaswar River Estuary; 15: Betmore River Estuary; 16: Sela River Estuary; 17: Pussur River Estuary; 18: Arpangachia River Estuary; 19: Sundarban River Estuary; 20: Malanchi River Estuary; 21: Ichamoti River Estuary.

Ganges-Brahmaputra-Meghna River system. Mid-coastal estuaries are relatable examples of these phenomena (Das et al., 2004). On the other hand, beach formations and hill ecosystems dominated all estuaries across the south-east of BEC (Mallick et al., 2016). Data on common geological features are included here, which helps to interpret the variation of local biodiversity.

3.1.1 Sediment texture

Sediment provides the necessary information about sessile biota, benthos, and water buffering capacity (Farhadinejad et al., 2014). It can also shape an estuary by its increment or removal (Dike and Agunwamba, 2012). Previous studies investigated the sediment texture of only four estuaries (BR, MR, KR, and CR) in Bangladesh (Table 1). It was observed that sediment load, especially the sand content (Figure 2A), was high in these estuaries (Sharif et al., 2017). MRE possessed the highest sand load (43%), including silt (16%) and clay (15%) concentrations. The lowest silt and clay concentrations were found in RE (0.08%) and SE (0.05%), respectively (Quader, 2012). Deltaic position of the river path may be responsible for this sand-loaded scenario across these rivers. Possessing the highest sediment load, RE also had moderate clay (10%) and silt (12%) concentration. It has been observed that hilly areas can provide clay increment towards these rivers (Islam, 2012). However, no studies were conducted on sediment pollutants in these estuaries of Bangladesh.

3.1.2 Bulk density, particle density, and porosity

Transparency of estuarine water depends on particle concentration in brackish water. It can also influence the concentration of other particles (Dike and Agunwamba, 2012). The present study collected available data in RE, BR, MR, KR, SE, and CR (Table 1). The highest bulk density (2.33 µg/g) was recorded in RE, while the lowest (1.34 µg/g) was found in SE (Figure 2A) (Islam, 2012; Quader, 2012). SE has higher particle density (3.19 g/cc) and porosity (59.30%) than IR (1.5 g/cc; 1.24% respectively). Hilly discharge around the year, especially during monsoon, may increase the level. Average bulk density, particle density, and porosity in estuaries were 1.84 µg/g, 2.35 g/cc, and 30.27%, respectively, across all estuaries.

TABLE 1 Available research from various estuaries near Bay of Bengal.

Zone	SL	Name	Code	Environmental parameters	Biological diversity	
					Flora	Fauna
South-east region	1	Naf River Estuary	NE	Chowdhury et al. (2011)	—	Rahman, 1997; Islam et al., 2011; Chowdhury et al., 2011; Noman et al., 2019
	2	Rezu Cannal Estuary	RE	Rocky, 2014; Iqbal et al., 2014; Hossen, 2014	—	Rocky, 2014; Iqbal et al., 2014; Hossen, 2014
	3	Bakkhali River Estuary	BR	Rashid, 1999; Rashed-Un-Nabi et al., 2011; Mahmood et al., 1986	—	Rashid, 1999; Rashed-Un-Nabi et al., 2011; Khohinoor, 2008; Al-mamun, 2010; Ali, 2009; Mahmood et al., 1986; Zafar et al., 1999; Mahmood et al., 1978
	4	Matamuhuri River Estuary	MR	Mallick, 2011; Hossain et al., 2020	—	Al-mamun, 2010; Mallick, 2011; Hossain, 1983; Haque, 1983; Elias, 1983; Begum, 1984; Hoque et al., 1999
	5	Sangu River Estuary	SE	Quader, (2012)	—	Quader, 2012; Islam, 2012
	6	Karnaphuly River Estuary	KR	Mallick, 2014; Islam et al., 2016; Habib etal., 2011; Barua, 2019; Alam, 2013; Mallick et al., 2016; Shamsuzzaman et al., 2016	Ahmad et al., 2019	Kamruzzaman, 2003; Habib etal., 2011; Ahmad et al., 2019; Shamsuzzaman et al., 2016Amin and Mahmood, 1979
Mid coastal region	7	Feni River Estuary	FR	Islam et al. (2018)	—	Islam and Nabi, 2012; Yeasmin et al., 2017
	8	Choto Feni River Estuary	CR	Moshfika and Rahman, (2018)	—	—
	9	Meghna River Estuary	ME	Islam 2004; Ahmed et al., 2003; Islam, 2004; Hossain et al., 2012; Sharif et al., 2017	-	Saeedullah, 2003; Islam and Nabi, 2012; Ahmed et al., 2003; Hossain, 2003; Hossain et al., 2012; Sharif, 2002; Sharif et al., 2017; Sharif et al., 2017; Akter et al., 2016
	10	Tetulia River Estuary	TR	—	—	—
South west region	11	Galacipa River Estuary	GE	—	—	—
	12	Andharmanik River Estuary	AR	—	—	—
	13	Payra River Estuary	PE	—	—	Ahamed et al., 2018; Islam et al., 2015; Saha et al., 2019
	14	Balaswar River Estuary	BE	—	—	—
	15	Betmore River Estuary	BRE	—	—	—
	16	Sela River Estuary	SR	—	—	—
	17	Pussur River Estuary	PR	Ahammed, 1997	—	Ahammed, (1997)
	18	Arpangachia River Estuary	AE	—	—	—
	19	Sundarban River Estuary	SRE	Chowdhury, (2014)	Rahman and Islam, 2010; Hussain, 2013; Rahman and Asaduzzaman, 2010	Naskar and Chakraborty, 1984; Hoq et al., 2006
	20	Malanchi River Estuary	MRE	Quader, 2012; Islam, 2012	—	—
	21	Ichamoti River Estuary	IR	Quader, 2012; Islam, 2012	—	—

[a]GE: 22° 1′4.61″N; 90°20′10.82″E, BRE: 21°51′12.14″N; 89°44′46.81″E and SR: 21°50′30.41″N; 89°39′41.65″E have no available data.

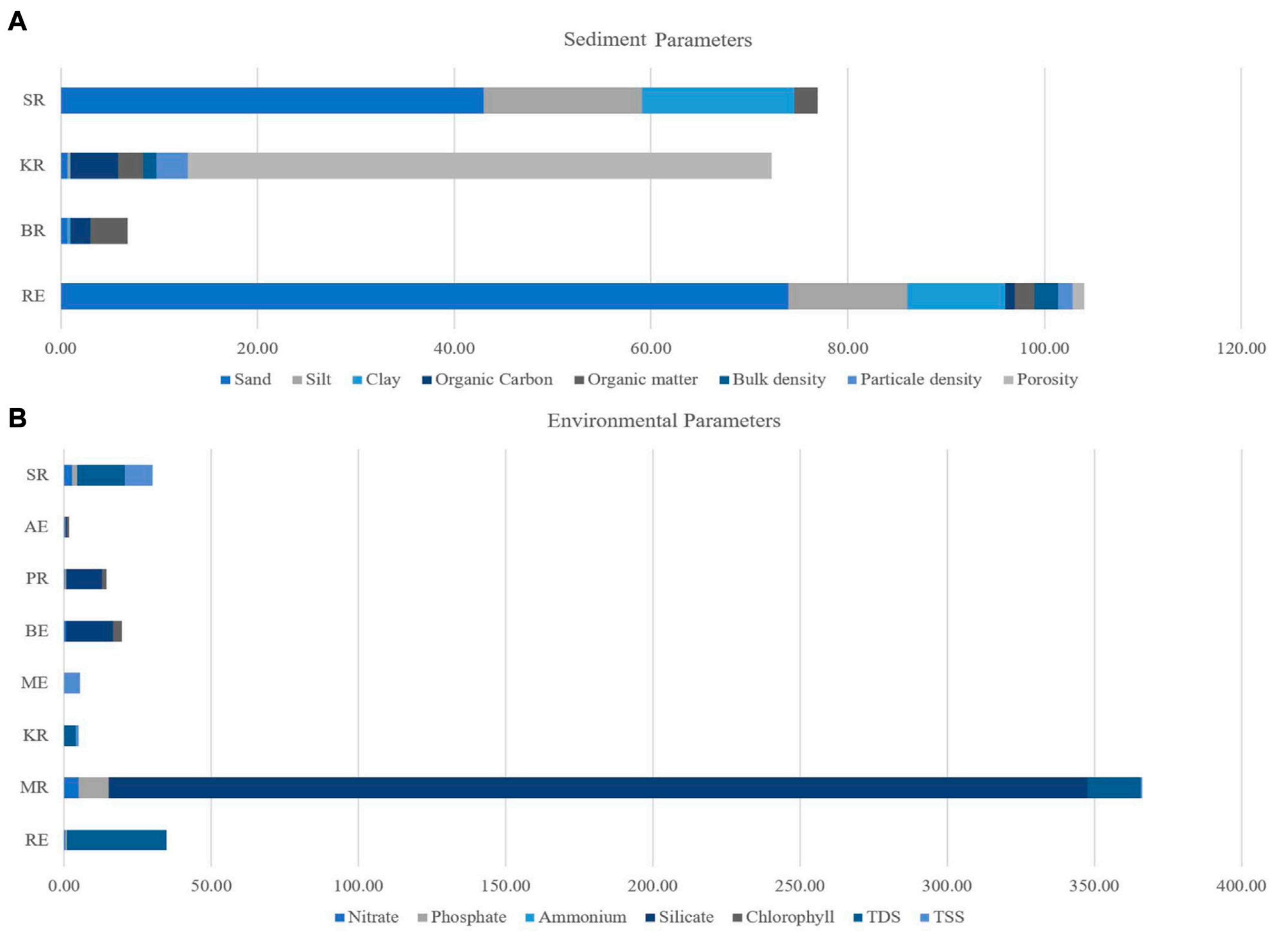

FIGURE 2
Comparative visualization of average sediment compositions **(A)** in various estuaries and comparative concentrations of different environmental parameters **(B)** in percentages for visualizing the enrichments among reported estuaries near Bay of Bengal (Estuary codes according to Table 1)

3.1.3 Organic carbon (OC) and organic matter (OM)

Estuaries can potentially contribute to the organic carbon (OC) budget along the coastal belt (Khohinoor, 2008). The average OC level was 2.62% across the reported estuarine waters from only four estuaries, i.e., RE, BR, KR, and ME. The highest rate (4.85%) of OC was found in SE, while the lowest (1.01%) was in IR (Islam, 2012; Quader, 2012). The RE had 3.80% organic matter in water, the highest among all estuaries (Rocky, 2014). The lowest levels (2%) were found in IR. The average concentration of organic matter was 2.67%. The MRE (2.32%) and SE (2.55%) contained medium levels of organic matter. Organic plant matter, phytoplankton, and zooplankton contribute to hydrocarbon aggregations which affect the local carbon cycle in these areas (Das et al., 2002). For example, Indian estuaries transported an order of magnitude higher concentration of organic matters to the Bay of Bengal coast (×490 10^9 gC yr^{-1}) than to the Arabian Sea (50 × 10^9 gC yr^{-1}) (Kumar and Sarma, 2018). Since the Bangladeshi estuaries are connected to the northern Bay of Bengal (Figure 1), combined research on organic and inorganic matters is necessary for uncovering the levels and impacts of OC and OM in the Bay of Bengal region.

3.2 Physical parameters of estuaries

Physical parameters are the key factors influencing biodiversity as they directly/indirectly control other estuarine environmental conditions, i.e., biological interactions, chemical cycling, and geological aspirations (Mallick, 2014). Small changes in physical parameters can significantly affect species distribution within an estuary. Notably, though the atmospheric temperature of the North estuarine area was lower, the water temperature was

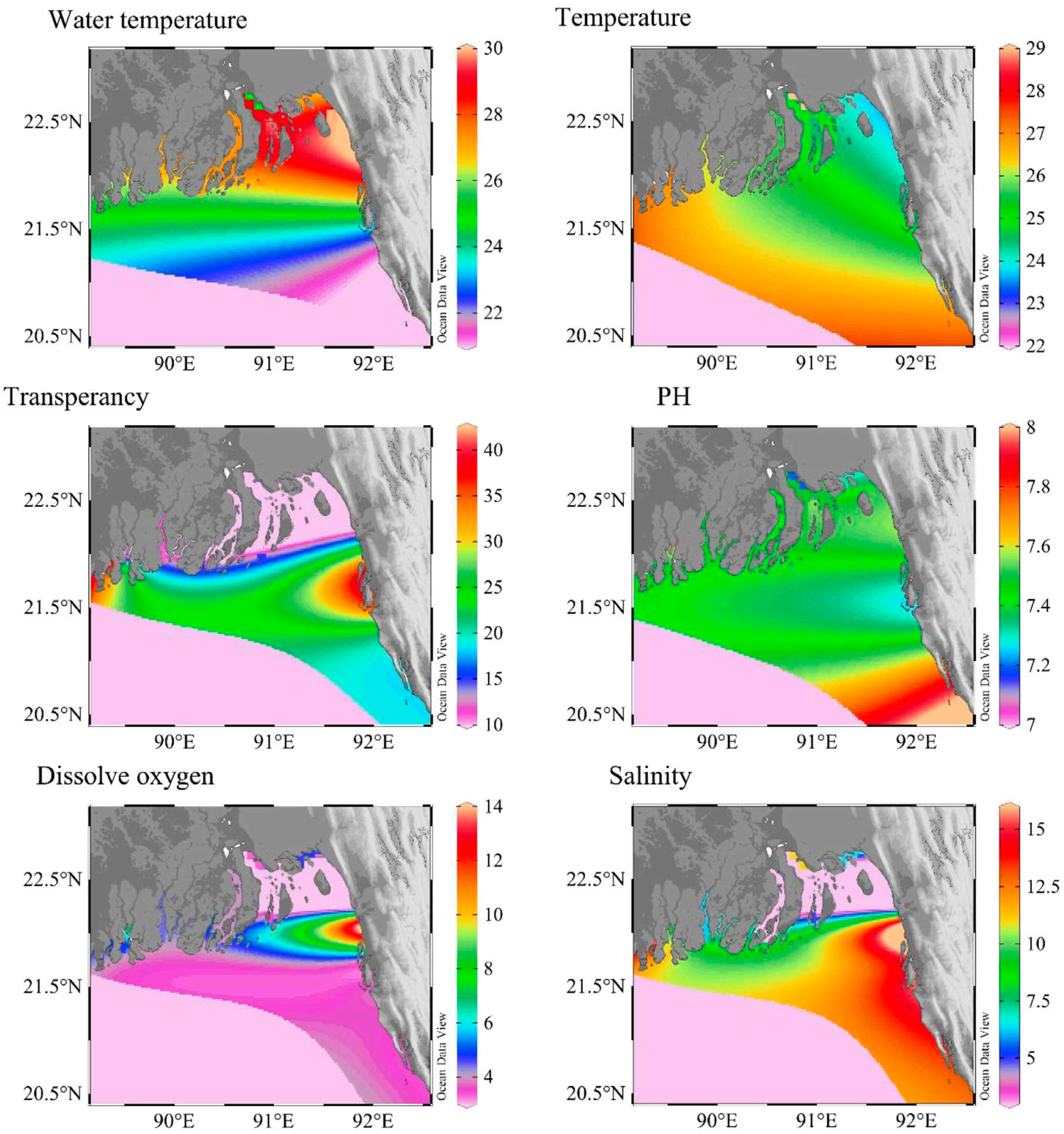

FIGURE 3
Average concentration of environmental parameters (A = water temperature, B = atmospheric temperature, C = transparency, D = pH, E = dissolved oxygen, and F = salinity) in the estuaries of Bangladesh (Greyish pink color indicated the data deficient area).

warmer than the southern estuaries (Figures 3A, B). However, pH and salinity were higher in the southern estuaries compared to the northern estuaries (Figures 3D, F). These conditions are sensitive to seasonal changes around the year (Zafar et al., 1999).

3.2.1 Temperature and salinity

Temperature and salinity are the major physical factors, among others. Temperature fluctuation has been seen in this environment for the past years (Varma et al., 2002; Basak et al., 2013). The salinity increase in the river water was gradually recorded from upstream to downstream. On Bangladeshi coasts, there is no exception broadly. The temperature data of 12 estuaries (NE, RE, BR, MR, SE, FR, ME, AR, BE, PR, AE and SRE) and salinity data of 13 estuaries (NE, RE, BR, MR, SE, KR, FR, ME, AR, BE, PR, AE and SRE) have been reported in the previous studies. The KR possessed the highest average water temperature (27 ± 25°C) (Figure 4B) (Mallick, 2014), and the lowest average temperature (21.50 ± 17°C) was recorded in the IR. Although temperature controls ecosystem diversity to a great extent (Menon et al., 2000), there are no reports on these issues.

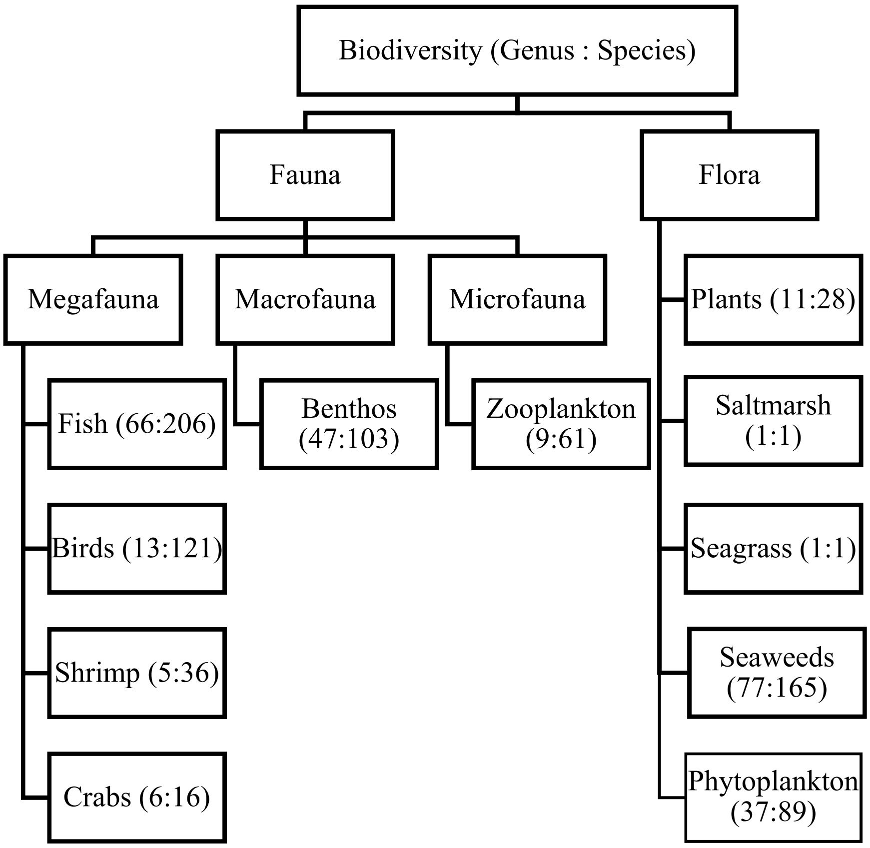

FIGURE 4
Genus and species count through all estuaries from available data (Microfauna: Microscopic organism (Size >1 mm), Macrofauna: Can see by open eye by not clearly (size >1 mm), Megafauna: Higher level species in taxonomy over benthos are considered).

Two main challenges for estuarine communities, like phytoplankton, are high salinity and sedimentation rate variability in the estuaries of Bangladesh (Ahmed et al., 2003). Notably, salinity showed a significant variation across estuaries (Figure 3F). Due to the huge freshwater discharge through the GBM system, average salinity was reported as 11.66 ppt through all estuaries, varying from 0.5 to 30 ppt (Mallick, 2014). The highest salinity was recorded in MR (16 ppt), while the lowest average salinity was recorded in SE through different studies (3.70 ppt) (Islam, 2012; Quader, 2012). The IR, RE, and BR maintained similar approximate salinities of ~15 ppt (Al-mamun, 2010; Rocky, 2014). The KR showed low salinity due to high freshwater influx from hilly areas (6.50 ppt). It regulates low productivity through estuaries and adjacent areas (Aziz and Paul, 2015).

3.2.2 Transparency, pH, and dissolved oxygen (DO)

Productivity inside the water depends on many factors, especially transparency/visibility, pH, and dissolved oxygen. Suitable condition of all these parameters drives proper estuarine vegetation along the coast. However, only a limited number of estuaries have been investigated for transparency (11 estuaries), pH (9 estuaries), and dissolved oxygen (13 estuaries) till this review. In Bangladesh, transparency and DO were higher in the mid estuaries due to larger sand-free freshwater input from rivers to estuaries, i.e., KR and BR possess a lower percentage of clay, silt, and sand than other estuaries (Figure 2A). The presence of sediment in larger amounts reduces transparency and dissolved oxygen (DO) in the river water (Aziz and Paul, 2015). For example, the transparency was nearly zero near the mouth of the ME estuary due to the huge sediment load in the water column (Islam, 2004).

Additionally, tontamination and ecological risk asseotal suspended solids (TSS) was higher in SRE (Figure 2B and discussed in the chemical section). So, siltation from the floodplains may explain low transparency at SRE (Aziz and Paul, 2015). The tidal influxes of ME suspend the huge sediment loads, which potentially reduces the transparency and DO along with mid-estuarine areas. SE has the lowest average water transparency (10 cm), and BR has the highest transparency (40.50 cm). 23.94 cm is the average transparency across all estuaries, as shown in Figure 3C (Al-mamun, 2010; Islam, 2012; Quader, 2012). Moderate transparency was observed in IR, BE, and MRE. Average pH levels (7.47) were recorded year-round (Figure 3D). For example, the lowest pH was observed in CR (pH = 7.20), and sea water level pH was observed (pH = 8) in MRE (Moshfika and Rahman, 2018). The lowest concentration of DO was in CR, which may be due to relatively low productivity and industrial pollution (Moshfika and Rahman, 2018). The average DO was 5.19 ± 2.50 mg L^{-1} across all estuaries. DO level in estuaries was low due to the mixing of saline water with fresh river water and high sedimental load from the Bengal fan (Figure 3E). The highest DO concentration was recorded in MR (13.63 mg L^{-1}) (Mallick, 2011). Many animals burrow themselves in the sand to avoid predation and live in a more stable sediment environment. However, a plethora of bacterial diversity has been reported from the sediment with a very high oxygen demand (Islam, 2004). This reduces oxygen levels within the sediment, often resulting in partially anoxic conditions, which can be further exacerbated if the water flux is limited (Ahammed, 1997). It widely affects local biological production, effectively controlling the biodiversity of the estuary.

3.3 Chemical component: Trace metals, nutrients, dissolved solids

Chemical components are complex controlling variables in estuaries (Förstner, 2004). External environments, i.e., industrial sludge, domestic run-off, *etc.*, may influence these parameters (Anilakumary et al., 2007). The chemical composition of these components is essential for living biota and their diversity (Wang et al., 2014). It controls the biodiversity pattern along the estuaries (Jiang-Qi et al., 2013). This review skimmed previously reported total dissolved solids (TDS), total suspended solids (TSS), nutrients (phosphates, silicates, nitrate, nitrite, ammonia, *etc.*), and particle concentrations as chemical components. Reports on seven estuaries (NE, RE, SE, KR, CR, BE, and BRE) have been found during this review (Table 1). Data deficiency has been found through several estuaries regarding chemical parameters. Future researchers should look at the data monitoring table for further research on the sectors.

3.3.1 Total dissolved solids (TDS) and total suspended solids (TSS)

Siltation and land erosion contribute to the concentration of TDS and TSS (Islam et al., 2016). These factors can help determine productivity and local water quality (Ali et al., 2013). A few reports on TDS (4 estuaries, i.e., RE, MR, KR and SRE) and TSS (5 estuaries, i.e., RE, MR, KR, ME and SRE) were found during this review. In Bangladesh, the highest TDS occurred in IR (33.88 g/L), and the lowest TDS was observed in SE (4.05 g/L) (Islam, 2012; Quader, 2012). The average TDS was 18.02 g/L across all estuaries. MRE showed 16 g/L TDS in its water body. MRE recorded the highest TSS (9.50 g/L), and SE had the lowest TSS (0.85 g/L) due to clean water flows from hilly areas (Islam, 2012; Quader, 2012). The average TSS was 4.05 g/L, and CR has 5.40 g/L in its adjacent areas (Moshfika and Rahman, 2018). Erosion of land margin increases these phenomena along the deltaic estuaries (Ali et al., 2013). It can potentially influence the particle aggregation in estuarine water and, subsequently, characteristics of estuarine bottom topography and siltation processes.

3.3.2 Nutrient concentration: Productivity

Nutrients, i.e., phosphates, silicates, nitrate, nitrite, ammonia, *etc.*, are the key factors of any biological environment, and it drives fluctuations of potential in the water body (Nair, 1984). The present review collected nutrient data from six estuaries from secondary sources, i.e., RE, MR, BE, PR, AE, and SR (Table 1). Unfortunately, there has been no measurement of nutrients in other estuaries. The average phosphate (PO_4-P) concentration was 4.14 µg/L across all estuaries. Heavy Gangetic siltation may be liable for this scenario. The highest concentration (13.34 ± 0.34 to 20.67 ± 0.11 µg/L) was found in the MR (Mallick, 2011), while the lowest concentration (Hussain, 2013) was recorded in SRE (1.72 ± 0.07 µg/L). The ammonium ion was higher in AE than in other estuaries. On the other hand, silicate was found high in ME (Figure 2B). The average nitrate concentration was 2.73 µg/L across all estuaries. At the same time, the lowest nitrate (0.15–0.79 µg/L) and phosphate (0.23–0.92 µg/L) were observed in Razu Khal River Estuary for high coastal vegetation (Iqbal et al., 2014). Thus, less primary production was reported due to low nutrient availability. Salinity and pollution influence the abundance of nutrients in these areas (Billah et al., 2016; Mallick et al., 2016; Alam et al., 2017), which are also similar factors in Indian estuaries (Nair et al., 1984a). However, the rest remain data deficient areas, except for six estuaries (RE, MR, ME, AE, SRE, and MRE). Deployment of nutrient profiling along coasts, especially estuaries, is vital for further scientific progress.

3.3.3 Metal concentrations in estuarine sediment and water

Estuaries demonstrated a spatial gradient in metal concentrations from river-to-river mouth to open BB (Rakib M. R. J. et al., 2021; Islam et al., 2021). Metal concentrations in estuarine sediment in nine estuaries (SE, MR, PE, BR, FR, KR, PR, SRE and ME) were reported (Table 1), whereas metal concentrations in adjacent water were available for four estuaries (ME, PR, MR and BR). In Bangladesh, sediments of FR showed low trace metal concentrations observed spatially and seasonally (Islam et al., 2018). Besides, the water of MR possessed low TMC as well for its dilution with open BB water (Ashraful et al., 2009). On the other hand, PR demonstrated the highest concentrations of trace metals both in sediment (Table 2) and

TABLE 2 Trace metal concentrations in sediment of different estuarine systems, Bangladesh.

Estuary name	Cr	Cu	Mn	Zn	Fe	Co	Pb	Ni	Cd	As	References
SE	25.15 ± 5.21	29.24 ± 10.78	—	88.97 ± 58.97	—	—	19.58 ± 7.017	32.75 ± 16.09	—	2.58 ± 0.25	Hossain et al. (2019)
MR	—	84.81	229.84	71.17	2196	—	26.42	—	—	—	Ashraful et al. (2009)
PE	45	30	—	—	—	—	25	34	0.72	12	Islam et al. (2015)
BR	—	34.93 ± 6.7	—	100.85 ± 5.6	—	—	27.14 ± 5.1	—	0.25 ± 0.1	—	Siddique et al. (2021)
FR	35.28	—	37.85	—	—	31.02	6.47	—	—	0.85	Islam et al. (2018)
KR	20.3	—	—	—	—	—	43.69	—	—	81.09	Ali et al. (2016)
PR	17.60 ± 0.35	29.25 ± 0.59	515 ± 10.30	50.43 ± 1.01	27800 ± 556	14.50 ± 0.29	12.20 ± 0.24	32.00 ± 0.64	2.50 ± 0.05		Rahman et al. (2011)
SRE	67.0 ± 10.6	22.3 ± 3.83	634 ± 132	67.7 ± 12.3	3.81 ± 0.51	13.9 ± 1.67	15.8 ± 3.11	28.6 ± 4.49	0.46 ± 0.11	6.76 ± 1.39	Islam et al., 2017
ME	—	38.10 ± 1.18	—	34.64 ± 1.70	23961.50 ± 1236.55	9.81 ± 1.96	—	—	—	—	Hossain et al., 2020

TABLE 3 Trace metal concentrations in water of different estuarine systems, Bangladesh.

Estuary name	Cr	Cu	Mn	Zn	Fe	Pb	Co	As	Se	Sr	Ni	References
ME	NA	5.24 ± 0.40	17.63 ± 3.10	6.90 ± 2.32	188.13 ± 123.90	41.32 ± 33.36	4.39 ± 0.15	4.25 ± 0.37	5.93 ± 3.32	7.51 ± 0.47	7.51 ± 0.47	Hossain et al., 2020
PR	39.00 ± 0.78	34.40 ± 0.69	50.00 ± 1.00	7.70 ± 0.15	111 ± 2.22	10 ± 0.2	4.40 ± 0.09	1.250 ± 0.03	—	<3.60	<3.60	Rahman et al. (2011)
MR	0.94	0.32	0.4	—	0.46	—	—	—	—	—	—	Ashraful et al. (2009)
BR	—	3.19	0.59	0.67	—	0.75	—	—	—	—	—	Ashraful et al. (2009)

water (Table 3), accordingly due to high pollution from land run-off (Rahman et al., 2011). It can help forming a coastal pollution order of metals (Fe > Ti > Zr > Rb > Zn > Sr > Pb > Y > Cu > Cr > As) from estuarine sampling (Rahman et al., 2019). Studies have reported that possible metal contamination sources are diesel and petrol from mechanized fishing trawlers and domestic disposals accordingly (Hossain et al., 2019; Rakib M. R. J. et al., 2021). Considering the sources of metals, land erosion by waves and tidal action, an influx of water and sediment from the surrounding rivers, agricultural waste, industrial effluent, and sewage are the most likely sources of metal pollution in the study area (Ashraful et al., 2009; Ali et al., 2016; Islam et al., 2018; Rakib M. R. J. et al., 2021). Even estuarine mangroves are reported risky for food and fodder due to accumulating heavy metal complexes (Rakib et al., 2021c). It has become a global estuarine problem. For example, Indian estuaries showed heavy metal enrichment to a hazardous level due to acidification through industrial disposals (Mitra, 2015). Ecosystem protection with riverine resource management was recommended in the available reports for minimizing metal concentration in brackish water and sediment as well (Bhuyan et al., 2017; Ali et al., 2021; Rakib M. R. J. et al., 2021; Rakib et al., 2021d; Jolly et al., 2021; Ali et al., 2022). Recently, Rakib et al. (2022) analyzed that microplastics have been found in sediments of Karnaphuli River Estuary, Bangladesh. Therefore, microplastics should be considered to be investigated in future studies across various estuaries of Bangladesh.

3.4 Estuarine biodiversity

Biodiversity can broadly divide into flora and fauna (Figure 5). For better understanding, this review will discuss major reported biodiversity groups from flora to fauna accordingly.

3.4.1 Phytoplankton diversity

Estuaries provide some of the most productive habitats on Earth because of the accumulation and availability of nutrients

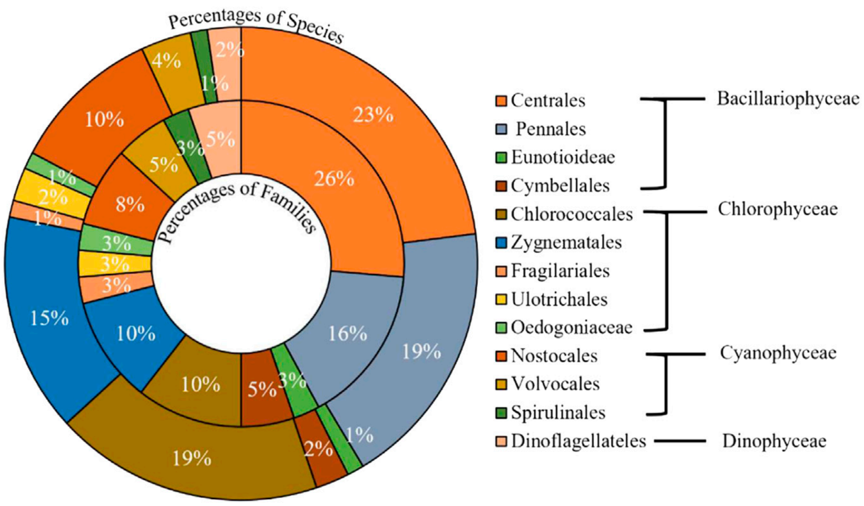

FIGURE 5
Diversity of Phytoplankton in the estuarine waters of Bangladesh.

TABLE 4 Diversity of phytoplankton (87 spp.) in the estuarine waters of Bangladesh.

Class	Genus/Species
Bacillariophyceae (39 spp.)	*Bacillaria* sp., *Skeletonema* sp., *Coscinodiscus* sp., *Coscinosria polychorda, Cyclotella* sp., *Schroderella* sp., *Ditoma* sp., *Rhizosolenia* sp., *Biddulphia* sp., *Ditylum* sp., *Triceratium* sp., *Melosira* sp., *Melosira varians, Melosire Agardh, Melosire Sulcate, Melosira varians, Thalassiosira* sp., *Chaetoceros* sp., *Eucampia* sp., *Leptocylindrus* sp., *Navicula* sp., *Diatomella* sp., *Neidium* sp., *Pleurosigma* sp., *Nitzchia sigma, Nitzchia Pacifia, Synedra* sp., *Thalassiothrix* sp., *Thalassionema* sp., *Fragillaria* sp., *Navicula salinarum, Pleurosigma* sp., *Cymbella* sp., *Tablelaria* sp., *Climocospenia* sp., *Surirella* sp., *Eunotia* sp., *Gomphonema* sp., *Anomoeoneis* sp
Cyanophyceae (46 spp.)	*Legerheimia* sp., *Oocystis* sp., *Gloeocystis* sp., *Tetraedron* sp., *Oedogonium* sp., *Legerheimia Nuov, Chlorella* sp., *Chlorella Beyerinck, Chlorella variegatue, Pediastrum* sp., *Planktoosp haaeria* sp., *Palmella* sp., *Dictyophimus* sp., *Pediastrum Meyen, Pediastrum Simplex, Actinastrum* sp., *Cosmarium* sp., *Closterium* sp., *Desmidium* sp., *Pleurotaenium* sp., *Gymnazyma* sp., *Micrasterias* sp., *Spirogyra* sp., *Cosmarium corda, Cosmarium globosum, Netrium* sp., *Spirogyra* sp., *Scenedesmus* sp., *Crucigenia* sp., *Synedra* sp., *Microspora* sp., *Ulothria* sp., *Oedogonium* sp., *Nostoc* sp., *Anabaena* sp., *Oscillatoria* sp., *Oscillatoras* sp., *Chroococcus* sp., *Microcystis* sp., *Merismopdia* sp., *Aphanocapsa* sp., *Polycistis* sp., *Volvox* sp., *Eudorina* sp., *Sp.irogyra* sp., *Spirulina* sp
Dinophyceae (2 spp.)	*Ceratium* sp., *Peridinium* sp

and adequate light conditions (Hossain and Lin, 2001). Phytoplankton produces organic compounds by utilizing solar energy during photosynthesis and releases oxygen into the estuarine water (Ahsan et al., 2012). This system controls the oxygen balance in any aquatic environment, mainly near the surface (0.4–0.6 m), where productivity is high (Haque, 1983; Kamal and Khan, 2009). Their productivity largely depends on light, nutrients, and water turbidity (Sharif and Islam, 2017). Main phytoplankton presents diatoms and dinoflagellates, abundant in the water column and the sediment of estuaries (Rahman, 1997). In BEC, reports on five estuaries (NE, RE, MR, CR, and TR) have been found during this review (Table 1). Likely, 87 species representing phytoplankton genera were recorded from BEC estuaries, as shown in Figure 5 (Kamal and Khan, 2009). The most commonly reported species were *Legerheimia* sp., *Oocystis* sp., *Gloeocystis* sp., *Tetraedron* sp., *Oedogonium* sp., *Legerheimia Nuov, Coscinodiscus* sp., *Coscinosria polychorda, Cyclotella* sp., *Schroderella* sp., *Ditoma* sp., *Synedra* sp., *Thalassiothrix* sp., *Thalassionema* sp., *Fragillaria* sp., *Navicula salinarum,* and *Pleurosigma* sp. (Table 4). However, no relative reports were found about BEC during this review. Further designative research is recommended for understanding estuarine phytoplankton more clearly.

3.4.2 Seaweeds

Sub-tidal macroalgal beds, i.e., *Sargassum*, *Dictyota,* and *Codium* play an essential role in the life cycle of numerous economically important commercial fish species. Benthic forms of seaweeds are attached to the pneumatophores of mangroves in inter-tidal areas of the coast (Kamal and Khan, 2009) and rocky substratum, e.g., Saint Martin's Island (Rakib et al., 2021d). Few estuarine and coast seaweed reports have been

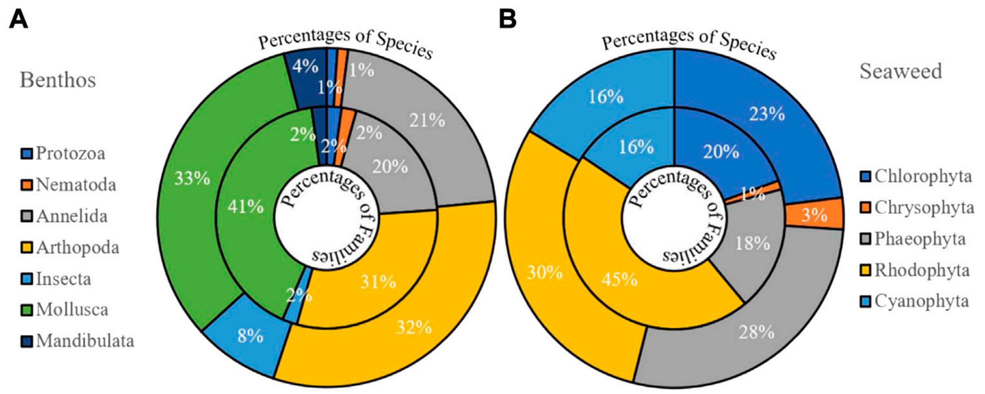

FIGURE 6
Representing available benthos **(A)** and seaweed **(B)** distribution in the coastal estuarine areas of Bangladesh.

found in Bangladesh (Table 1). Here, about 165 species belonging to 77 genera of seaweeds have been recorded in the coastal and estuarine areas of Bangladesh (Figure 6B). Generic diversity of Rhodophyta was higher, but species diversity was higher in Phaeophyta (Figure 6B). Productive water with chlorophyll enriched environment derived these diversities along adjacent waters (Talukder, 2004). In India, nutrients were key marks for the number of seaweed assemblages along estuaries (Jansi and Ramadhas, 2009). However, seaweeds are not part of the traditional diet of Bangladesh, whereas they are often consumed elsewhere in the world. It can serve as a potential food source for cattle, poultry farms, and humans.

3.4.3 Seagrass and salt marsh

Salt marshes and seagrass are recognized as essential components of coastal productivity worldwide (Kamal and Khan, 2009). These systems serve as feeding areas for various species, including avifauna (birds), and contribute considerable leaf detritus to the water column. The detritus from seagrass plays an active part in nitrogen and phosphorus cycles that provide essential elements to primary producers of all ecosystems. Seagrass also serves as a protective canopy, shielding the inhabitants of the bed from the effects of strong sunlight (Kamal and Khan, 2009). They also help to reduce sedimentation by trapping siltation locally (Neumeier and Ciavola, 2004). When seagrasses occur in the inter-tidal zone, the leaves may cover the substrate during low tide, protecting the inhabitants from desiccation. Although both salt marsh and seagrasses occur in Bangladesh's estuaries, information on the diversity and distribution of these is lacking. Thus far, three species of salt marsh (*spartina* sp., *Imperata cylindrical*, *Porteresia coarctata*, and *Porteresia* sp.) and only five seagrasses (*Halophila decipiens, Halophila beccarii, Halodule uninervis, Halodule pinifolia* and *Ruppia maritime*) has been recorded (Hena et al., 2007; Billah et al., 2016; Hossain et al., 2021). Cultivating seagrasses has been encouraged worldwide (Neumeier and Ciavola, 2004). Besides, Indian researchers mentioned seagrass as a heavy metal consumer in coastal ecosystems, contributing to pollutant buffering and environmental health monitoring markers (Thangaradjou et al., 2010). In Bangladesh, some unpublished work was also found along the coastal zone of BB for investment, and research should be deployed in this sector to develop it for the betterment of renewable food sources for different biota. Very little research on estuarine salt marsh has been found in the coastal zone of Bangladesh. More investigation on the culture and management of estuarine salt marsh and sea grass should be deployed in the near future.

3.4.4 Mangroves forest

In BEC, mangrove covers six estuaries broadly, i.e., SR, PR, AE, SRE, MRE and IR. Total of 23 mangrove species representing 11 genera has been recorded till now. Some common species were *Acanthus ilicifolius, Cynometra ramiflora, Acrosticum aureum, Phoenix paludosa, Rhizophora mucronata, R. apiculata, Bruguiera grymorrhiza, B. seangula, Ceriops decandra, C. tagal, Kandelia candel, Aegiceras corniculatum, Avicennia alba, A. marina, A. officinalis, Excoecaria agallocha,* and *E. indica* (Table 5). Previous reports show that the *Rhizophoraceae* family is most common and *Acanthaceae*, *Leguminosae*, *Pteridiaceae*, *Combretaceae*, and *Palmae* are less diverse in this area. Along with providing an important coastal habitat for many species, a mangrove forest forms a community that helps stabilize riverbanks and coastlines. Mangroves also export large amounts of detritus and nutrients into nearby systems that form the basis of complex food webs (Rahman and Islam, 2010).

The plantation of mangroves was introduced in the BEC in 1964 to avoid natural disasters and is still carried out in the coastal belt of Cox's Bazar, Chittagong, Barisal, and Patuakhali off-shore islands and now covers an area of 100,000 ha. Small

TABLE 5 Diversity of mangroves (23 spp.) in the estuarine waters of Bangladesh.

Family	Species
Dicotyledonae (1 spp.)	*Acanthus ilicifolius*
Magnoliopsida (18 spp.) 1	*Aegialitis rotundifolia, Rhizophora mucronata, R. apiculata, Bruguiera grymorrhiza, B. seangula, Ceriops decandra, C. tagal, Kandelia candel. Aegiceras corniculatum, Avicennia alba, A. marina, A. officinalis, Luminitzera racemose, Sonneratia caseolaris, Xylocarpus granatum, X. mekongensis, Heritiera fomes, H. littoralis*
Polypodiopsida (1 spp.)	*Acrosticum aureum*
Dicotyledonae (2 spp.)	*Excoecaria agallocha, E. indica*
Monocotyledonae (1 spp.)	*Nypa fruticans*

TABLE 6 Diversity of zooplankton (67 spp.) in the estuarine waters of Bangladesh.

Class	Genus
Hexanauplia (7 spp.)	*Calanus, Microsetella, Oncaea, Calanopia, Coryeacus, Cyclops, Diaptomus*
Maxillopoda (3 spp.)	*Calanoid, Mesocyclops, Diaptomus*
Malacostraca (11 spp.)	*1. Penaeus, Metapenaeus, Macrobrachium, Acetes, A. japonicas. Metapenaeus, Lucifer, Nauplius, Copepodite, Gnathophausia, Hydromedusae*
Insecta (4 spp.)	*M. brevicornis, Cypris* sp., *Aethus, Dyallacta*
Sagittoidea (1 spp.)	*Sagitta* sp
Branchiopoda (8 spp.)	*Evadue, Daphnia, Cladochera Bosmina, Diaphanosoma, Macrothrix, Cydorus, Moina*
Bdelloidea (11 sp.p)	*Brachionus, Trichocerca, Kellicottia, Keratella, Gastropus, Polyarthra, Brachionus, Angularis, B. falcatus, Kelicotia, Hexerthra*
Monogononta (2 spp.)	*Monostyla, Rotaria*
Eurotatoria (11 spp.)	*Polyarthra, Asplanchna, Anuraeopsis, Keratella, Filinia, Lecane, Ascomorpha, Cephalodella, Trichocerca, Platyias, Lindia*
Euglenoidea (4 spp.)	*Euglena, Phacus, Volvox, Arcel*
Imbricatea (1 spp.)	*Euglepha*
Dinophyceae (1 spp.)	*Ceratium*
Colpodea (1 spp.)	*Colpoda*
Tubulinea (1 spp.)	*Difflugia*
Secernentea (1 spp.)	*Enterobius*

patches of mangroves are also found along the belt of nearly all coastal sub-districts (Hossain and Lin, 2001). Additionally, salinity variation was reported to influence the mangrove species composition (Ahmed and Khurshid, 2011). It limits the growth of mangroves (Rahman and Islam, 2010). In Indian estuaries, it was already found as a looming danger to coastal biodiversity (Sandilyan et al., 2010). Increasing freshwater inputs by dredging coastal rivers may solve this problem periodically. Further steps should plan early in Bangladesh by deploying potential research projects to minimize these problems in the future.

3.5 Faunal biodiversity

3.5.1 Zooplankton communities

In estuaries, plankton plays a vital role in nutrient circulation and the transport cycle (Zhou et al., 2009). They followed the productivity line of phytoplankton accordingly (Iqbal et al., 2014). As a vital zooplankton taxa group, copepod, and crustacean larva were the most abundant zooplankton in estuaries (Ahmed et al., 2003). They acted principally as primary consumers in these estuarine food webs. Only six estuaries (NE, RE, BR, MR, FR, CR and TR) have conducted studies on this matter (Table 1). Previous reports show that the Rotifers family is the most common, and Decapoda larvae, Chaetognatha, and Ostracoda showed less diversity than BEC. So far, 67 species of zooplankton genera have been recorded from nearby areas of estuaries (Table 6) which is relatively less than a single estuary of India, i.e., Kaduviyar estuary (Vengadesh et al., 2009). Common zooplankton species were *Calanus* sp., *Microsetella* sp., *Oncaea* sp., *Calanopia* sp., *Coryeacus* sp., *Oithona* sp., *Calanoid, Cyclops, Diaptomus, Nauplius, Mesocyclops edax, Cyclops* sp., *Diaptomus* sp., *Bryocvamptus* sp., *Penaeus monodon, P. merguiensis, Metapenaeus monoceros, M. brevicornis, Penaeus indicus, Macrobrachium*

TABLE 7 Diversity of benthos (109 spp.) in the estuarine waters of Bangladesh.

Phylum	Genus
Prtozoa (1 spp.)	Opalinidae
Nematoda (1 spp.)	*Nematoda*
Polychaeta (22 spp.)	*Nephytus poalybranchita, Nephtys Oligobranchia, Nephtys, Glycera, Glycera, Namalycastis, perineris, Ceratonereis, Lumbrineries,* Sabellidae, Maldanidae, Naididae, *Limnodrilus, Capitella, Lycastonereis, Glycera, Nephtys*
Clitellata (4 spp.)	*Tubifex, Tubifex, Limnodrilus, Adelodrilus*
Arthopoda (36 spp.)	*Caldocera, Ostracoda, corophium* Sp., *Urothoe, Copepoda, Cyclopoid copepod, Cyclops, Calanoid copepod, Limnocalanus* Sp., *Harpecticoid copepod, Mysidacea,* Mysidae, *Isopoda,* Cirolanidae, *Decapoda, Crabmegalopa. Gammarus, Belostoma sp., Scopimera*
Insecta (8 spp.)	*Coleoptera, Diptera, Hymenoptera, Hemiptera, Dubiraphia vittata, Lutaria, Dubiraphia vittata, Promoresia tardella, Drunella lata, Acentrella Alachua, Baetis Pluto, Iswaeon anoka, Cryptochironomus, Corydalus, Epicordulia, Boyeria, Epicordulia, Orthocladius, Cricotopus, Ablabesmyia, Microtendipes, Tribelos, Ocypode*
Malacotraca (4 spp.)	*Procellio, Palaemonetes, Amphipoda, Canthocamptus*
Gastropoda (32 spp.)	*Mesogastropoda, pila globose, Bivalvia, Crab Megalopa, Corbicula,* Pisidiidae, *Thiara lineata, Stenothyra echinata, Stenothyra deltae, Cerithidea cingulate, Helisoma anceps, Laevapex fuscus, Micromenetus dilatatus, Plicarcularia leptosp.era, Valvata cristata, Valvata cristata, Corbicula fluminea, Elliptio complanata, Elliptio complanata, Haploperla brevis, Modiolus striatulus, Cerithium* sp., *Neritina* sp., *Neritina violacea, Neritina sulculosa, Assiminea brevicula, Architectonica* sp., *Littorina* sp., *Littoraria undulate, Natica* sp., *Meretrix* sp., *Namalycastis fauveli*
Nemertea (1 spp.)	*Nemertian worm*

rosenbergii, Acetes erythraeus, A. indicus, A. japonicas, Cladochera sp., *M. Monoceros,* and *M. brevicornis.* Suitable nutrients with active photosynthesis influence the phytoplankton community (Sharif, 2002; Aziz et al., 2012; Rahman et al., 2013; Mehedi Iqbal et al., 2017; Sharif et al., 2017), which directly increase the zooplankton diversity at these estuarine zones locally (Haque et al., 2015). Nutrient-rich estuaries amplify phytoplankton production, leading to higher growth of zooplankton (Iqbal et al., 2014). As a result, estuaries acted as suitable nursing grounds for fishes and crustaceans (Rahman et al., 2013).

3.5.2 Benthic communities

Benthic organisms are important for the ecology of estuaries both as consumers of plankton and as food for bottom-feeding fish (Chowdhury, 2014). They provide vital linkages between primary producers and higher trophic levels in estuarine food chains (Islam et al., 2013). For example, many clams and oysters feed on plankton in the water column (Hossain, 2003). Benthic organisms (i.e., polychaeta worms and crustaceans) form an important part of the diets of commercially important bottom-feeding fishes, such as Spot (*Leiostomus xanthurus*) and Croaker (*Micropogonias undulatus*) accordingly (Sharif et al., 2017) and commercially important invertebrate species such as Oysters (*Ostrea edulis, Crassostrea belcheri*) and Blue Crabs (*Portunus pelagicus*) (Kamruzzaman, 2003), are important commercially and recreationally.

Total of 44 species was found in the Naf estuary (Noman et al., 2019), but 109 species of the benthos genus were recorded from nearby estuaries (Kamal and Khan, 2009). Common species were *Calanus* sp., *Microsetella* sp., *Oncaea* sp., *Calanopia* sp., *Coryeacus* sp., *Oithona* sp., *Calanoid, Cyclops, Diaptomus, Nauplius, Mesocyclops edax, Cyclops* sp., *Diaptomus* sp., *Bryocvamptus* sp., *Penaeus monodon, P. merguiensis, Metapenaeus monoceros, M. brevicornis, Penaeus indicus, Macrobrachium rosenbergii, Acetes erythraeus, A. indicus, A. japonicas, Cladochera* sp., *M. monoceros, M. brevicornis, Limnodrilus hoffmeister, Limnodrilus profundicola, Tubifex heterochaetus, Tubifex tubifex, Coleoptera, Unidentified Diptera, Hymenoptera, Hemiptera, Dubiraphia vittata,* and *Lutaria* sp. (Hossain, 2003; Kamruzzaman, 2003; Islam et al., 2013) (Table 7; Figure 6A). Polychaetes were the dominant benthos reported from NE. Seasonal food availability may be liable behind these local diversities along the estuaries (Noman et al., 2019). Recently, benthos research accelerated into a new dimension, coupling with ocean acidification along these estuaries (Hossain and Rahman, 2017). New species (*Nephtys Bangladeshi*) discovered with the spatial and seasonal distribution of benthos under the tidal influence of estuaries have been started (Hossain and Hutchings, 2016). However, reports on seven estuaries (NE, BR, MR, KR, CR, TR, and BE) have been found during this review (Table 1). Even Indian estuaries have limited research on benthos (Nair et al., 1984b; Khan and Murugesan, 2005). Recently, Sivadas and Carvalho (2020) have reported the richness of marine annelid (727 species) belongings to 334 genera and 72 families. Of these, 152 marine annelid species are locally abundant in India, whereas 88 are endemic. Sukumaran et al. (2021) have also reported 2078 macrobenthic taxa in North-west India, belongings to 14 phyla, and the most abundant were *Polychaeta*, *Gastropoda*, and *Bivalvia*. Previous reports show that Mollusca species are common, and protozoa and nematodes are less diverse in this area. More innovations with life-focused

TABLE 8 Diversity of shrimp (36 spp.) and Crab (16 spp.) in the estuarine waters of Bangladesh.

Family	Species
Shrimp	
Malacostraca (36 spp.)	*Penaeus monodon, M. dobsoni, P. merguiensis, P. indicus, P. uncta, Metapenaeus monoceros, M. lysianass, M. spinulatus, M. brevicornis, M. affinis, Parapenaeopis sculptilis, P. stylifera, P. hardwickii, P. semisulcatus, P. Japonicus, M.villosimanus. M.mirabilis. P. melastigma, P. koelreuteri, M. dobsoni, Solenocera subnuda, Acetes erythraeus, A. japonicus, A. indicus, Exopalaemon Styliferus, Macrobrachium rosenbergii, M. lamarrei, M. rude, M. villosimanus, M. mirabile, M. birmanicum, Palaemon Styliferus, P. (Nematopalaemon) tenuipes, P. karnafuliensis, Alpheus euphrosyne, A. crassimanus*
Crab	
Malacostraca (16 spp.)	*Scylla serrate, Portunus inolentus, Portunus pelagicus, Metopograpsus thukuhar, Metopograpsus messor, Prasesarma plicatum, Sesaema lanatum, Episesarma versicolor, Potamon wood-masoni, Potamon martensi, Paratelphusa lamellifrons, Uca urvillei, Uca annulipes, Ocypode ceratophthalmus, Anapagurus laevis, Ebalia cranchii*

techniques to develop sustainable management and conservation of the estuarine environment should be practiced in benthos communities (Mondal et al., 2018).

3.5.3 Crustaceans' communities (shrimp and crab)

In BEC, 36 shrimps and 16 crab species were reported from the estuaries (Table 8). Common crabs species were *Scylla serrate, Portunus rinolentus, Portunus pelagicus, Metopograpsus thukuhar, Metopograpsus messor, Prasesarma plicatum, Sesaema lanatum, Episesarma versicolor, Potamon wood-masoni, Potamon martensi, Paratelphusa lamellifrons, Uca urvillei, Uca annulipe,s Ocypode ceratophthalmus, Anapagurus laevis*, and *Ebalia cranchii*. Among crabs, *Grapsidae* was abundant in estuaries of Bangladesh (Table 8). Fishing in the mangroves is one of the major activities in the coastal area (Kamal and Khan, 2009). Common shrimp species were *Penaeus monodon, M.dobsoni, P. merguiensis, P. indicus., P. uncta, Metapenaeus monoceros, M. lysianass, M. spinulatus, M. brevicornis, M. affinis, Parapenaeopis sculptilis, P. stylifera, P. hardwickii, P. semisulcatus, P. Japonicus, M. villosimanus, M. mirabilis, P. melastigma, P. koelreuteri, M dobsoni, Exopalaemon Styliferus, Macrobrachium rosenbergii, M. lamarrei, M. rude, M. villosimanus, M. mirabile, M. birmanicum, Palaemon Styliferus, P (Nematopalaemon) tenuipes* and *P (N) karnafuliensis, etc.* However, *Penaeus monodon* (black tiger shrimp), *Metapenaeus monoceros, M. brevicornis, P. indicus*, and *Macrobrachium rosenbergii* were diverse. *Penaeus indicus,* and *P. monodon* were the most abundant shrimp in estuaries. Besides, shrimp culture by collecting post larva from marine water is a seasonal practice along the south coast of Bangladesh (Rahman et al., 2008). However, expanding commercial culture of tiger shrimp has already led to the destruction of mangroves in Chakaria Sunderban, Moheskhali, Teknaf, and Sonadia Island on the south-east coast of Bangladesh (Akber et al., 2017; Saha, 2017). The government should take strict actions and implement laws under potential monitoring systems to mitigate this problem and preserve the biota at BEC and coastal areas.

3.5.4 Fish communities

Only 13 estuaries (NE, RE, BR, MR, SE, KR, FR, CR, TR, AR, BE, BRE, and AE) have been investigated previously on this aspect (Table 1). Previous reports show that the most common are *Ariidae*, *Clupeidae*, *Gobiidae*, and Sciaenidae families. In the present state of the investigation, proper classification of fish species based on their period of life and availability in the estuaries is difficult (Begum, 1984; Islam et al., 2015; Ahamed et al., 2018; Saha et al., 2019). The estuarine and adjacent coastal areas of BEC support a variety of economically important fishes. In BEC, 208 brackish water fish species were reported from the estuaries (Table 9). The most common species of fishes are found in the coastal and estuarine mangrove areas, such as mullet (*Mugil* sp. and *Liza*), marine catfish (*Mystus* sp.), seabass (*Lates calcarifer*) *Eleutheronema tetradactylum, Polynemus paradiscus, Mugil cephalus, Liza tade, Rhlnomugli corsula, Mystus golio, Tenualosa toil, Gonialosa manminna, Tenualosa ilisha, Ilisha megalopetra, Setipina taty, Collia ramcarati, Septipinns phasa,* and *Trichurus Havmela.* A tentative list of estuary fishes was reported, while the Food Agriculture Organization (FAO) gave a general list of the most common finfish for the estuaries (Kamal and Khan, 2009). The fishes spend all or a major part of their lifetime in the estuarine environment; marine or freshwater species migrate seasonally into or through the estuaries (Rashid, 1999). The diversity of fish depends on local environmental factors (Ahamed et al., 2018). So, habitat loss may potentially threaten fishes and other species along the brackish water (Barletta et al., 2010; Blaber and Barletta, 2016; Nanjo, 2020). Proper investigation of data deficient estuaries with intense monitoring of coastal habitat may resolve this problem actively.

TABLE 9 Diversity of fish (208 spp.) in the estuarine waters of Bangladesh.

Family	Species
Chondrichthyes (9 spp.)	*Scolidon lacticaudus, Eusphyra blochii, Carcharhinus melanopterus, Rhynchobatus djiddensis, Dasyatis zugei, Himatur uarnak, H. imbricata, H. fluviatilis, Pastinachus sephen*
Actinopterygii (197 spp.)	*Spratelloides* sp., *Corica soborna, Escualosa thoracata, Gudusia chapra, Hilsa (Hilsa) kelee, H. (Tenualosa) ilisha, H. (T.) toil, Anodontosoma chacunda, Gonialosa manmina, Dussumieria acuta, Sardinella gibbosa, S. melanura, S. fembriat, llisha megaloptera, L. melastoma, Rconda russelliana, Thryssa dussumieri, T. hamiltonii, Setipinna phasa, S. taty, Coilia dussumieri, C. neglecta, C. ramcarati, Stolephorus tri, Chirocentrus dorab, C. nundus, Elops machnata, Congresox talabon, Muraenesox cinereus, Cuchia cuchia, Mystus gulio, Silonia silondia, Pangasius pangasius, Congresox felabonondes, Gonialosa manminna, Hamiarius sona, Arius sona, A. gogora, A. maculatus, A. buchanani, A. caelatus, A. thalassinus, A. dussumieri, A. arius, A. nenga, Batrachocephalus mino, Osteogeneiosus sp., Plotosus canius, P. lineatus, Harpodon nechereus, H. nehereus, Saurida tumbil, H. limbatus, Hemiramphus georgii, Fistularia villosa, Hippocampus kuda, Pterois russeli, P. miles, P. indicus, Platycephalus crocodilus, P. scaber, Rogadius asper, Chanda nama, Pseudambassis baculis, P. ranga, Lates calcarifer, Cephalopholis miniatus, Epinephelus fasciatus, E. tauvina, Promicrops lanceolatus, Therapon jarbua, T. theraps, Apogon novemfasciatus, A. septemstiastus, Sillago domina, S. shihama, Sillaginopsis panijus, Lactarius lactarius, Alectis indica, A. melanoptera, Alepes djedaba, Megalaspis cordyla, Atropus atropus, Scomberoides commersonianus, Carangoides malabaricus, Selar boops, S. crumenophthalmus, Formio niger, Mene maculate, L.blochii, Gazza minuta, Leignathus bindus, L. equulus, L. fasciatus, Secutor ruconius, S. insidiator, Lutjanus johnii, L. 5ineus, Pinjalo pinjalo, Lutjanus russeli, Nemipterus japonicus, N. nematophorus, Lobotes surinamensis, Gerres filamentosus, Pentaprion longimanus, Pomadasys argentus, P. maculates, P. hasta, Acanthopagarus latua, Argyrops spinifer, Johnius belangerii, Johnius carutta, Atrobucca nibe, Dendrophysa russelli, Macrosp.inosa cuja, Protonibea diacanthus, Pama pama, Panna microdon, Johnius argentatus, Johnius dussumieri, Pterotolithus maculatus, Otolithes ruber, Pennahia macropthalmus, Upeneus sulphureus, Parupeneus heptacanthus, Drepane longimanus, D. punctatus, Ephippus orbis, Liza parsia, L. subviridis, L. tade, Mugil cephalus, M. cascasia, Valamugil speigleri, Rhinomugil corsula, Sphyraena barracuda, S. putnamiae, Eleutheronema tetradactylum, Polynemus paradesius, Polydactylus indicus, P. sexfilis, P. sextarius, Uranoscopus quttatus, Butis Butis, Eleotris fusca, Butis melanostigma, Odontamblyop rybicundus, Brachygobius nunus, Glossogobius giuris, Pogonogobius planiformes, Stigmatogobius sadanundio, Apocryptes bato, Boleopthalmus boddarti, Parapocryptes batoides, Pseudapocryptes lanceolatus, Scartelaos viridis, Periopthalmodon schlosseri, Periopthalmus koelreuteri, Odontamblyopus rubicundus, Trypauchen vagina, Kurtus indicus, Eupleurogrammus muticus, Lepturacanthus savala, Trichiurus lepturus, Euthynnus affinis, Rastrelliger brachysoma, R. kanagurta, Sarda orientalis, Scomberomorus commerson, S. quttatus, Psettodes erumei, Pseudorhombus arius, P. elevatus, P. malayanus, Synaptura pan, S.orientalis, Zebreas altipinnis, Cynoglossus bilineatus, C. cynoglossus, C. lingua, C. macrolepidotus, C. versicolor, Paraplagusia bilineata, Triacanthus brevirostris, Abalistis stellatus, Arothron stellaris, Tetradon cutcutia, Chelonodon fluviatilis, C. patoca, Colisa fasciata, Cirrhinus cirrhinus, Trypauchen vagina*
Teleostei (1 spp.)	*Lethrinus ornatus*
Elamobranchii (1 spp.)	*lchthyscopus inermis*

TABLE 10 Diversity of avifauna (121 spp.) in the estuarine waters of Bangladesh.

Family	Species
Aves (121 spp.)	*Dendrocygna bicolor, Dendrocygna javanica, Anser indicus, Tadorna ferruginea, Tadorna tadorna, Sarkidiornis melanotos, Nettapus coromandelianus, Anas strepera, Anas falcate, Anas Penelope, Anas platyrhynchos, Anas poecilorhyncha, Anas clypeata, Anas acuta, Anas querquedula, Anas crecca, Netta rufina, Aythya nyroca, Aythya nyroca, Aythya fuligula, Aythya marila, Amaurornis phoenicurus, Porzana pusilla, Porzana fusca, Gallicrex cinerea, Porphyrio porphyrio, Gallinula chloropus, Fulica atra, Porzana porzana, Rallus aquaticus, Gallinago stenura, Gallinago Gallinago, Rostratula bengalensis, Limosa melanuroides, Limosa lapponica, Numenius phaeopus, Numenius arquata, Tringa erythropus, Tringa tetanus, Tringa stagnatilis, Tringa nebularia, Tringa guttifer, Tringa ochropus, Tringa glareola, Xenus cinereus, Actitis hypoleucos, Tringa guttifer, Tringa ochropus, Tringa glareola, Xenus cinereus, Actitis hypoleucos, Arenaria interpres, Limnodromus semipalmatus, Calidris canutus, Cakidris tenuirostris, Calidris alba, Calidris pygmea, Calidris minuta, Calidris ruficollis, Calidris temminckii, Calidris subminuta, Calidris ferruginea, Limicola falcinellus, Philomachus pugnax, Rostratula benghalensis, Hydrophasianus chirurgus, Metopidius indicus, Himantopus himantopus, Recurvirostra avosetta, Pluvialis fulva, Pluvialis squatarola, Charadrius hiaticula, Charadrius dubius, Charadrius alexandrines, Charadrius mongolus, Charadrius leschenaultia, Vanellus cinereus, Vanellus indicus, Vanellus malabaricus, Vanellus duvauceli, Glareola lacteal, Rynchops albicollis, Larus heuglini, Larus barabensis, Larus ichthyaetus, Larus brunnicephalus, Larus ridibundu, Gelochelidon nilotica, Sterna casp.ia, Sterna aurantia, Sterna bengalensis, Sterna bergii, Sterna sandvicensis, Sterna hirundo, Sterna albifrons, Chlidonias hybridus, Chlidonias leucopterus, Sterna acuticauda, Sterna sumatrana, Anous tenuirostris, Anous minuts, Phalacrocorax niger, Phalacrocorax carbo, Egretta garzetta, Ardea cinerea, Ardea goliath, Ardea purpurea, Casmerodius albus, Mesophoyx intermedia, Bubulcus coromandus, Ardeola grayii*s *Butorides striatu, Nycticorax nycticorax, Ixobrychus cinnamomeus Ixobrychus minutus, Ixobrychus sinensis, Dupetor flavicollis, Threskiornis melanocephalus, Platalea leucorodia, Anastomus oscitans, Leptoptilos javanicus*

3.5.5 Avifaunal biodiversity

Birds are important food chain members of food webs, especially in estuaries. The marshes, reeds, and mangroves provide sheltered breeding grounds for swamp birds such as the bittern, marsh crake, banded rail, fern bird, *etc.* A total of 690 avifauna species have been recorded from Bangladesh (Khan,

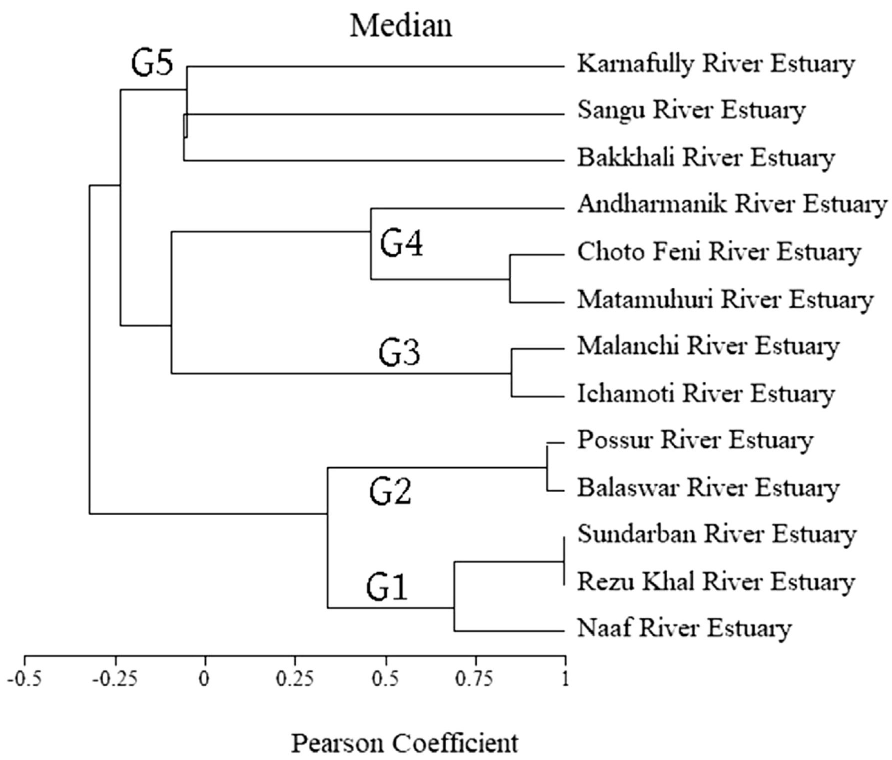

FIGURE 7
Cluster analysis of all estuaries in different groups (G) by considering different hydrobiological variables with Pearson coefficient.

2008); however, only 121 species have been reported from BEC environments, as shown in Table 10 (Kamal and Khan, 2009). Common bird species were *Dendrocygna bicolor, Dendrocygna javanica*, *Sarkidiornis melanotos, Gallinula chloropus Fulica atra, Tringa ochropus, Tringa glareola, Xenus cinereus, Actitis hypoleucos, Rynchops albicollis, Larus heuglini, Larus barabensis, Sterna hirundo, Sterna aurantia, Phalacrocorax carbo, Casmerodius albus, Anastomus oscitans,* and *Leptoptilos javanicus*. It covered all estuaries of Bangladesh accordingly. Tidal flats hold a bounty of food for different aquatic birds (Table 10). Previous reports show that the *Scolopacidae* family is the most common, and *Rostratulidae* and *Glareolidae* are less diverse in this area (Kamal and Khan, 2009). For example, Mud probers, Wrybills, Herons, Caspian terns, Ducks, *etc.* (Hossain and Lin, 2001). In addition, mangroves of SRE acted as food sources for *Avifauna* (Gopal and Chauhan, 2006). Additionally, migratory birds travel thousands of kilometers from their Siberian and Alaskan breeding grounds each year, arriving at estuaries (Maheswaran and Rahmani, 2001; Albores and Siguenza, 2011). Tropical weather provided suitable cruising places (Gopal and Chauhan, 2006). Hunting down migratory birds in BEC was a potential threat to biodiversity, which the government mitigated through proper law and action during the winter. This model can apply worldwide for protecting avifaunal biodiversity as well.

3.5.6 Hydrobiological correlations of estuaries

A cluster analysis was used on available estuarine data by applying Pearson correlation after considering environmental and physical parameters (Figures 3A, B) as variables (Figure 7). Rezu and Naf River estuaries are situated in the southern part of Bangladesh. Considering environmental conditions (e.g., temperature, salinity, nutrients, *etc.*), Sundarban, Rezu, and Naf River estuaries clustered together in group 1. Temperature influenced by salinity and dissolved oxygen correlates with Sangu, Bakkhali, and KR in group 5, which were located near the hilly area of BEC (Figure 3). On the other hand, Balaswar and Possur river estuary demonstrated similarity in Group 2. Despite having different geographical positions, close water temperature acted as clustering variables for MRE and IR (Group 3), followed by Matamuhuri, Choto Feni, and AR too (Group 4) (Figure 7). This review found that no research is available to generalize the hydro-biographic conditions of these estuaries due to proper planning and research. All research is scattered with different purposes, which made a complex demography to understand the factual composition and their comparisons across these estuaries (Jiyu et al., 2001). A combined project on soil texture and nutrients of all main estuaries with their countable biodiversity tabulation is recommended to deploy soon for an in-depth assessment of the estuarine ecosystem and their interactions. Future researchers should concentrate on these to fulfill the dataset about all important estuaries of BEC for better scientific development and review.

Accordingly, possible recommendations should be considered by recording sand composition, angiosperm, birds, animals, fishes, weeds, and related environmental parameters. Data deficient areas, i.e., GE, BRE, and SR, need to be surveyed accordingly. Monitoring cells on wildlife conservation should be regulated to pursue existing biodiversity with proper protections. Strict laws, sync preservation, and maintenance of proper past records can help enhance the local biotic community. Explicit lab equipment to examine these data is also necessary at each bio-research institution. Fundamental regulations with modern technology can also develop such situations.

4 Concluding remarks and future recommendations

This is the first comprehensive review to unify all the available information on the ecological quality and biodiversity status of the estuarine environment in Bangladesh. The study demonstrates that the estuarine environment of Bangladesh is quite diverse and dynamic, like other tropical countries, due to the tropical climate and strong monsoonal influence. Ecological drivers varied daily and even hourly in Bangladesh. In these diverse and dynamic environments, for example, water temperature, salinity, and pH varied 15–34°C, 0.5–33 ppt, and 6.2–8.53, respectively. The total dissolved solids concentration was found to be very high, especially during monsoon, causing low water transparency/visibility (24 cm only) in the estuaries.

Additionally, higher concentrations of silicates and lower levels of ammonium ions were also observed. Despite having low chlorophyll assemblage caused by low dissolved oxygen (5.19 mg/L), 85 phytoplankton species were reported from the estuarine water of Bangladesh. Over 830 faunal and floral species of 273 genera were recorded from the estuaries. Considering the abundance of biota, *Scylla serrate* of crabs, *Shrimp*, Tubificidae and *Nereidiae* of benthos group, *Copepoda* of zooplankton, Zygnemataceae family from phytoplankton, *Rhodophyta* division from seaweed, and Scolopacidae family of birds were most abundant in these coastal estuaries. Among them, the International Union for Conservation of Nature (ICUN) red-listed organisms should be given the highest priorities for conservation, and close habitat monitoring should be deployed. To protect the estuarian ecosystems, the government, policymakers, scientists, non-governmental organizations (NGOs), researchers, *etc.*, need to have an overall dataset to protect and manage the Bangladeshi estuarine ecosystem. This review reveals a paucity of available biotic data for major estuaries, and more research is needed on these aspects to record the current biodiversity status and understand interrelations among them. This research unraveled the need for the national database archiving system to closely monitor the subtle changes in this dynamic ecosystem.

Author contributions

MJ: Conceptualization; data collection; Formal analysis; Investigation; Resources; Writing—original draft, editing and review. MI: Formal analysis; Writing-editing, and review. MH: Conceptualization, editing, and review. IH: Data collection. MR: Writing-editing, and review. RK: Formal analysis; Writing-editing, and review PS: Writing-editing, and review.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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