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Fish Diversity in Relation to Salinity Gradient in the Meghna River Estuary, Bangladesh

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Abstract: Variation in salinity is one of the major environmental factors influencing the species diversity of fish in an estuary. Therefore, evaluating the relationship between salinity and species diversity is important. In this study, fish diversity was assessed by fish sampling and visiting local fish markets from February to November 2021. Mean salinity was 10.59 psu (Practical Salinity Unit) and 0.46 psu during the dry and wet seasons, respectively. *Harpadon nehereus*, *Odontamblyopus rubicundus* and *Pseudapocryptes elongatus* species were found as polyhaline (0.06~18.1 psu) species. *Anguilla japonica* and *Arius gagora* were abundant in brackish water conditions (0.35~14.2 psu). However, *Acanthopagrus latus* and *Setipinna phasa* were found in freshwater conditions (0.06~0.11 psu). The suitability index indicates that commercially important fish species such as *Liza parsia*, *Macrobrachium rosenbergii*, *Mugil cephalus*, *Penaeus monodon* and *Scylla serrata* can be used for mariculture during the dry season, and *Acanthopagrus latus*, *Pethia canius* and *Setipinna phasa* during the wet season. Overall, these findings suggest that salinity, water temperature, and chlorophyll-a had a significant ($p < 0.05$) effect on the fish distribution and assemblage composition in the study area. This finding will be helpful in developing policies for the conservation and management of the aquatic resources in the coastal zone to enrich the blue economy.

Keywords: salinity; fish diversity; mariculture; season; water quality parameter

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1. Introduction

An estuary is a semi-enclosed body of water with open or intermittently open connections to the ocean [1]. A healthy estuary can be considered as an ecosystem with multiple components (physical, chemical and biological) functioning effectively to maintain the ecosystem within the limits of natural change. The coastal region of Bangladesh has been experiencing a complicated situation regarding freshwater and saline water interactions. Changes in tide and freshwater flow result in the advance and retreat of the salinity limit. Under this process, during the wet season, local rainfall associated with flooding flows from upstream and keeps the salinity limited near the coastline. In contrast, salinity starts increasing and intruding towards upstream from the beginning of November due to reducing river flows which reached maximum values of ~22 psu (Practical Salinity Unit) in June 2014 [2]. The freshwater flowing from the Ganges through the Padma River governs the state of the salinity of the Meghna River basin. But the Ganges' outflow during the dry season has been decreasing due to commissioning of the Farakka barrage (18 km from the western border of Bangladesh) in 1975 [3]. As a consequence, salinity intrusion occurs during the dry season in the lower Meghna River estuary (MRE). This disparity in salinity intrusion is because of a vast flow of freshwater into the MRE from the upstream that results from three rivers: the Padma, the Brahmaputra, and the Kalni River. As a result of the reduced freshwater flow to the coastal region, the intrusion of saline water towards upstream has made the region vulnerable to increasing impacts of salinity [4]. Hence, the salinity pattern of Bangladesh is highly dependent on the volume of the freshwater flow coming from upstream.

The freshwater of rivers, ponds or lakes has a salinity of 0.5 psu or less. Within an estuary, salinity levels are known as oligohaline (0.5–5.0 psu), mesohaline (5.0–18.0 psu), or polyhaline (18.0–30.0 psu) [5]. Adjacent to the open sea, estuarine waters may be euryhaline, in which area salinity levels are similar to the sea (>30 psu). Different fish species have different salinity tolerance levels and show significant responses to slight changes in the salinity of their surrounding water. Over the years, inland open water fisheries of the coastal region have faced increasing threats from over-exploitation of fishery resources, indiscriminate fishing with inappropriate fishing gears, increased water pollution and intrusion of salinity [6]. Human activities, like agriculture or salt mining along with climatic acidification and rising sea levels, are increasing salt concentrations in inland freshwaters and coastal regions [7], which produces severe, negative economic and biological effects [8]. Among climate-related threats, increasing salinity from sea level rise and climate-induced changes in temperature, rainfall, and riverine flows are the most important [9].

Fisheries makes an important contribution to the economy of the coastal region of Bangladesh [6]. Marine fisheries, inland open water or capture fisheries, and closed water fisheries offer an essential source of livelihood for tens of thousands of poor people and supply a significant portion of their protein intake [10]. Because of salinity intrusion, significant changes have taken place in the fisheries sector. In the case of the fishery, increased salinity affects spawning grounds, leading to substantial reductions in the inland open water fishery [11]. The changes in salinity gradient will adversely affect the diversity and availability of many fish species. However, fish diversity, a major portion of biodiversity, is correlated with the stability and resilience of an ecosystem which would have a positive relationship with the well-being of the existing species structure including the humans. As a result, reduced fish diversity is a serious threat to the environment and local people's foodstuff. Consequently, adverse impacts are anticipated for the incomes of small-scale fishermen (SSF) dependent on the captured fishery of the whole coastal region due to increased salinity in these areas. However, an increase in brackish water will enhance opportunities for brackish water aquaculture, for example, farming of *Lates calcarifer, Liza parsia, Macrobrachium rosenbergii, Mugil cephalus, Penaeus indicus, Penaeus monodon* and *Scylla serrata* etc.

Fish assemblage structure in the estuaries of Bangladesh has not been well studied; although there are some scattered works on different biological aspects of the coastal estuarine system of Bangladesh [12–14], none of them examined the species assemblage structure in relation to salinity gradients. The Meghna River estuary (MRE) is the largest estuarine ecosystem of Bangladesh, which is still unknown, unmanaged, and unmonitored. In this study we investigated the changes in the diversity of finfish and crustaceans with changing salinity gradient in the MRE, assessed the salinity tolerance level for individual finfish and crustaceans, and identified the commercially important fish species for mariculture based on the salinity gradient.

2. Materials and Methods

2.1. Study Area

The Meghna River is directly connected to the freshwater source of the Ganges. The Ganges was unregulated prior to the construction of the Farakka Barrage in India in 1975. This diversion diminished the average dry season flow in the Ganges from 3114 m^3 s^{-1} during the pre-Farakka period to 2010 m^3 s^{-1} in the post-Farakka period [15,16].

The Ganges–Brahmaputra–Meghna River system is the third largest freshwater outlet in the world. This system brings immense river discharge ($\sim$1.5 $\times$ 1012 m^3 $year^{-1}$) with billions of tons of associated sediment load into the Bay of Bengal; salinity structure is correlated with this river discharge and other atmospheric variables like rainfall [17]. River discharge is driven by the Indian Monsoon, with a maximum discharge of about 82,000 m^3 s^{-1} in rainy season, a minimum of <10,000 m^3 s^{-1} in winter season, and an annual average of about 32,000 m^3 s^{-1}. Huge river discharge and rainfall during the summer monsoon and the small ones during the winter largely control water temperature, current, density and salinity, nutrients export, and primary of the Meghna River basin. Consequently, saltwater intrusion has extended from the estuarine mouth to the upstream during the spring tide in the dry season in the MRE (Figure 1).

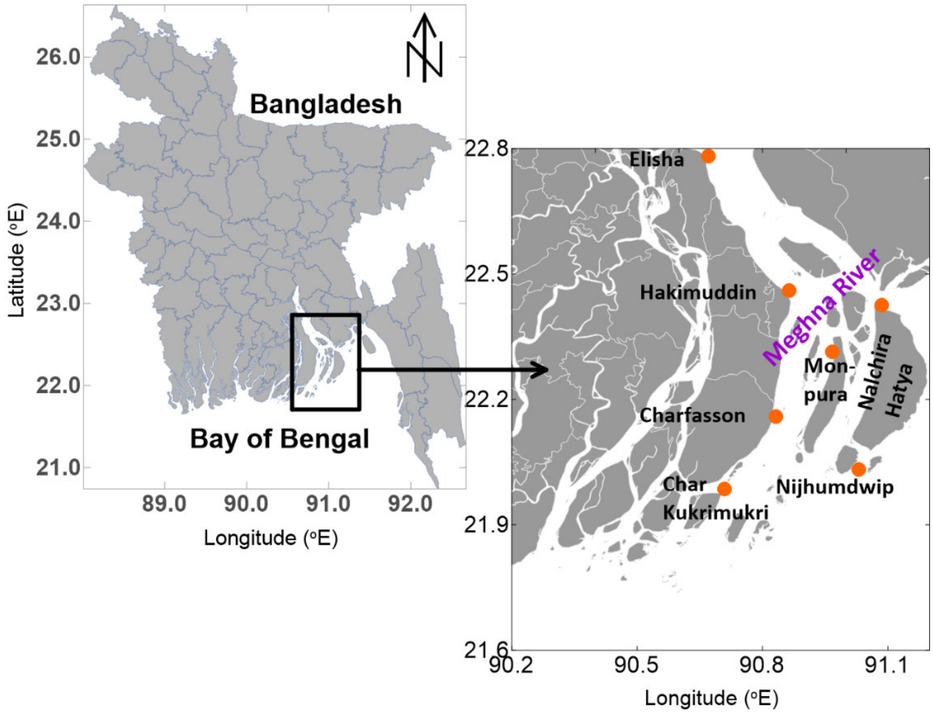

Figure 1. Map of the study area.

2.2. Spatio-Temporal Salinity Observation

Seven stations in the Meghna River estuary were selected for sampling of the salinity and other water quality parameters. The use of a global positioning system (GPS) ensured that precise data were obtained at the sampling stations. Salinity and temperature profile were taken using a conductivity-temperature-depth (CTD) profiler (Model: In-situ Aqua TROLL 500, In-Situ Inc., Fort Collins, CO, USA) at the sampling stations of the Meghna River estuary. A mechanized boat was used to collect data during the dry and wet seasons from February 2021 to November 2021 in the MRE. Five transects were taken during the dry and wet seasons. In addition, water samples were taken using a Kemmerer water sampler (Wildco Instruments, Wildlife Supply Company, Gene Lasserre Blvd., Yulee, FL, USA) for water quality measurement. Dissolve oxygen (DO) concentrations were determined by a DO meter (HACH HQ30d) and pH determined by a pH meter (sensION + EC71).

2.3. Fish Sampling

Data were collected from an artisanal catch of the local fishermen. In addition, local fish markets (Hatya fish market, Monpura fish market, Char fasson fish market, Elisha fish market and Koccopia fish market) were surveyed for collected riverine fish species to enhance the species checklists at each section. Where possible, fish were identified on collection then released. Where not possible, they were preserved in 10% formalin solution and taken to the laboratory for identification. Fishermen interviews and a focused group discussion (FGD) were completed for the collection of information on vulnerable, endangered, and disappeared fish species. Collected fish species were identified up to species level using the morphometric study. All fish specimens and the scientific name was corrected were identified according to [18,19].

2.4. Laboratory Analysis

Nutrients analyses, including the estimation of nitrite, nitrate, ammonia, inorganic phosphate, and silicate, were carried out in the laboratory [20] and the values were determined by spectrophotometric method (HACH, DR-6000, Germany, S/N: 1824775). Nitrite was analyzed by the USEPA diazotization method, ammonia was analyzed by the USEPA Nessler method, and phosphorus was analyzed by the USEPA Ascorbic acid method. Nitrate was analyzed by the HACH cadmium reduction method and silica was analyzed by the HACH Heteropoly blue method. Chlorophyll-a anlaysis followed the Parson's method [21].

2.5. Fish Diversity Indices

This study evaluates the diversity of fish species using three diversity analysis tools: Shannon Weaver diversity index (H′), Evenness by Pielou's index (J′) and Species richness index (d) [22,23].

2.6. Site Suitability Index

Every species needs a standard range of various environmental parameters for their growth and survival. If salinity and most of the other water quality parameters of an estuary are found within a standard range for a species, then it can be said that the species is feasible for mariculture in that estuary. In this study, we have calculated the site suitability index in order to identify suitable sites for different mariculture species. According to the salinity and other water quality parameters, this study concludes that some species are feasible during the dry season, and some are feasible during the wet season for mariculture in the MRE region of Bangladesh. The suitability index is a count of the number of 'optimal' variables divided by the number of variables taken into account. The index ranges between 0 (no variables are in the optimal range) and 1 (all variables in optimal range). A maximum of 8 variables were used [24]. For example, in one zone of the study area, 6 variables were in an optimal range, and so the suitability index score was 6/8 = 0.75. The value greater than 0.5 was taken as suitable for that individual for mariculture. If the value was 0.5 or less than 0.5 for a species during a particular season in a specific area, then that species was considered as unsuitable for mariculture in that area during that season.

2.7. Statistical Analysis

The R program version 4.0.3 [25] was used for performing multivariate statistical analysis for variation in the Meghna River estuarine habitat. In this present study, nine water quality parameters and thirteen fish orders were considered for multivariate statistical analysis. As a complement, boxplot analysis was performed using the 'heatmaply' package [26]. The relations among the environmental factors (physical and chemical parameters, dissolved nutrients, and chlorophyll a) in the study area were analyzed using the principal component analysis (PCA). A PCA was performed on the correlation matrix. In order to confirm the existence of variation among water quality parameters and fish orders, the principal component analysis (PCA) and cluster analysis (CA), using the Euclidean distance method, were employed in the present study. The PCAs were executed using the 'FactoMineR' package [26,27]. Furthermore, the contributions of variables to principal components (PCs) were also examined to determine which environmental factors were most varied among the different compartments of the MRE habitat. The cluster analysis was completed using the 'dendextend' package [26].

3. Results

3.1. Water Quality Parameter

Dissolved oxygen (DO) values ranged from 6.72 to 9.99 mg/L with an average of 7.94 mg/L during the dry season and 6.64 to 7.94 mg/L with an average value of 7.32 mg/L during the wet season. Temperatures ranged from 19.68–29.89 °C with an average of 24.67 °C during the dry season and 26.24–31.16 °C with an average of 28.39 °C during the wet season in the Meghna River estuary (Table 1).

Table 1. Water quality parameter of the Meghna River estuary.

Parameter	Dry Season	Wet Season	*p* Value
Temperature °C	24.67 ± 5.34	28.39 ± 1.24	$p < 0.05$
Salinity (psu)	10.59 ± 6.37	0.46 ± 0.12	$p < 0.05$
DO (mg/L)	7.94 ± 1.23	7.32 ± 0.26	$p < 0.05$
pH	7.87 ± 0.23	7.98 ± 0.17	$p > 0.05$
Chlorophyll-a (µg/L)	3.81 ± 1.08	7.57 ± 3.27	$p < 0.05$
Nitrate (mg/L)	0.03 ± 0.002	0.14 ± 0.001	$p < 0.05$
Nitrite (mg/L)	0.01 ± 0.001	0.01 ± 0.003	$p > 0.05$
Ammonia (mg/L)	0.52 ± 0.20	0.20 ± 0.04	$p < 0.05$
DIN (mg/L)	0.55 ± 0.23	0.35 ± 0.05	$p < 0.05$
DIP (mg/L)	0.43 ± 0.05	0.36 ± 1.24	$p > 0.05$

During the dry season, mean salinity was 10.59 psu with a maximum value of 18.07 psu and a minimum value of 0.12 psu in the Meghna River estuary. During the wet season, the mean salinity was 0.46 psu, where maximum salinity was 3.16 psu and the minimum value was 0.06 psu (Table 1). DO, temperature, chlorophyll-a, dissolved inorganic nitrogen (DIN = Nitrate + Nitrite + Ammonia), and salinity were significantly ($p < 0.05$) varied between the dry and wet seasons. However, pH showed insignificant ($p > 0.05$) variation between the dry and wet seasons. In this study, the pH value ranged from 6.30 to 9.09 with an average of 7.87 during the dry season and 7.10 to 8.79 with an average of 7.98 during the wet season (Table 1).

The multivariate analysis showed a seasonal gradient for the water quality parameters, forming two different groups for the dry and wet seasons (Figure 2). The measured water quality parameter is summarized in Table 1. Dissolved inorganic nitrogen (DIN) concentrations were significantly ($p < 0.05$) higher during the dry season (0.55 mg/L) than during the wet season (0.35 mg/L) (Table 1). On the other hand, dissolved inorganic phosphate (DIP) concentrations were also insignificantly ($p > 0.05$) higher during the dry season (0.43 mg/L) than during the wet season (0.36 mg/L). The mean chlorophyll-a concentrations in the dry season and wet season were 3.81 µg/L and 7.57 µg/L, respectively. That means that chlorophyll-a concentrations were significantly higher ($p < 0.05$) in the wet season than the dry season (Table 1). Principal components 1 and 2 contributed about 69.4% of the variability, where salinity, chlorophyll-a, and temperature contributed most, indicating seasonal variation of salinity, chlorophyll-a and temperature in water. On the contrary, component 3 and 4 contributes 25.5% of the variation in water, where the contribution of NO_3^- and pH was highest. Dry season showed a higher variation than the wet season where salinity, NO_2^- and NH_4^+ were dominant during the dry season. By contrast, Chl-a, NO_3^- and pH dominated during the wet season.

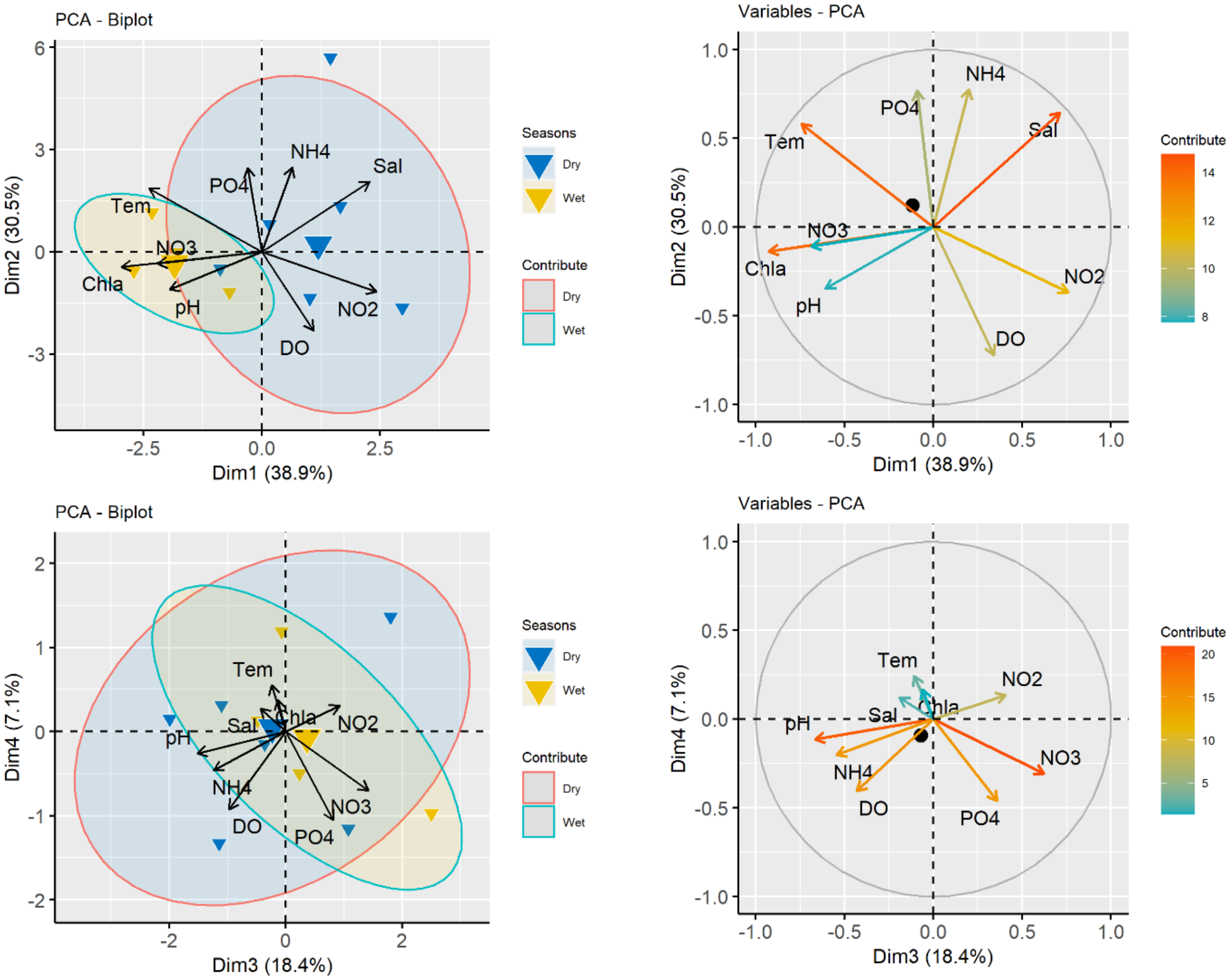

Figure 2. Principal component analysis (PCA) showed that water temperature, salinity and chlorophyll-a had a significant effect on fish distribution and assemblage composition.

Cluster analysis grouped the nine water quality parameters (Temperature, NO_3^-, Chl-a, pH, PO_4^{3-}, NH_4^+, salinity, NO_2^- and DO) and thirteen fish orders (Clupeiformes, Aulopiformes, Scombriformes, Gadiformes, Anguiliformes, Myliobatiformes, Gobiiformes, Siluriformes, Mugiliformes, Pleuronectiformes, Scorpaeniformes, Beloniformes, Synbranchiformes, Anabantiformes, Perciformes and Decapoda) into two different clusters (Figure 3). The first cluster included temperature, NO_3^-, Chl-a and pH which showed their correlation with the rest of the parameters and the various fish orders. The second cluster included the thirteen fish orders and the rest of the parameters. The second cluster was divided into two subclasses, where the first subclass included all the fish orders and three water quality parameters salinity, PO_4^{3-} and NH_4^+ where the salinity was the dominant factor. The second subclass included a correlation of DO with the first subgroup (Figure 3). Overall, these findings suggest that water temperature, salinity and chlorophyll-a had a significant effect on the fish distribution and assemblage composition in the study area ($p < 0.05$).

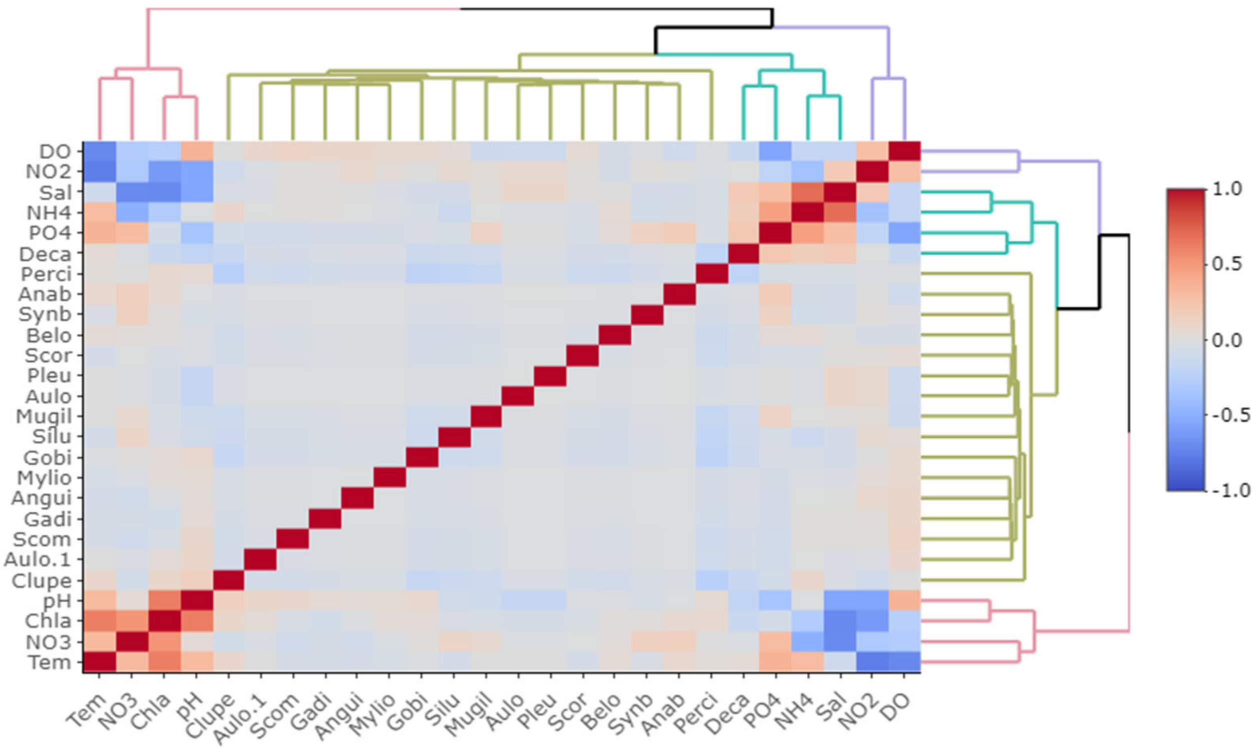

Figure 3. Dendrogram showing clustering of the water quality parameters and fish orders found in the MRE (Tem: Temperature, NO_3^-: Nitrate, Chla: Chlorophyll-a, Clupe: Clupeiformes, Aulo: Aulopiformes, Scom: Scombriformes, Gadi: Gadiformes, Angui: Anguiliformes, Mylio: Myliobatiformes, Gobi: Gobiiformes, Silu: Siluriformes, Mugil: Mugiliformes, Pleu: Pleuronectiformes, Scor: Scorpaeniformes, Belo: Beloniformes, Synb: Synbranchiformes, Anab: Anabantiformes, Perci: Perciformes, Deca: Decapoda, PO_4^{3-}: Phosphate, NH_4^+: Ammonia, Sal: Salinity, NO_2^-: Nitrite and DO: Dissolved oxygen).

3.2. Fish Diversity and Distribution in Relation to Salinity in the Meghna River Estuary

A total of 38 fish species were found under 27 families and 13 orders, where 33 species were found during the dry season and 29 species were found during the wet season in the Meghna River estuary (MRE) (Table 2, Figure 4). Among these, Palaemonidae and Penaeidae were the dominant families during the dry season, and Oxudercidae was the most dominant family during the wet season. Among these orders, Perciformes and Decapoda were dominant during the dry season comprising 23% and 20%, respectively, of the total fish found during the dry season. Perciformes and Siluriformes were dominant during the wet season comprising 27% and 14% of the total fish species, respectively, found during that season. Aulopiformes, Beloniformes, Gadiformes, Mugiliformes and Myliobatiformes were the submissive orders during the wet season. *H. nehereus*, *O. rubicundus* and *P. elongatus* species were found in all the sampling months indicating that these fish are polyhaline (0.06~18.1 psu) species. *A. japonica* and *A. gagora* were abundant in brackish water conditions (0.35~14.2 psu). *A. latus* and *S. phasa* were found in freshwater conditions (0.06~0.11 psu).

Species identified during the wet season in the MRE are as follows: *A. latus*, *B. walga*, *C. ramacarati*, *E. tetradactylum*, *G. morhua*, *G. giuris*, *H. nehereus*, *K. pelamis*, *L. calcarifer*, *M. nobilii*, *M. spinulatus*, *M. cephalus*, *M. gulio*, *O. rubicundus*, *O. pama*, *P. argenteus*, *P. hypophthalmus*, *P. monodon*, *P. indicus*, *P. canius*, *P. elongatus*, *S. argus*, *S. phasa*, *S. panijus*, *S. silondia*, *T. ilisha*, *T. curvirostris*, *T. lepturus* and *X. cancila* (Table 2).

Table 2. Salinity tolerance level of fish species found in the Meghna River estuary (MRE).

SL No	Scientific Name	Local Name	Salinity (psu) of Observed Months and Seasons							Salinity (psu) for Individual Species
			February 21	**March 21**	**June 21**	**September 21**	**November 21**	**Dry**	**Wet**	
			0.35–14.2	**0.6–18.07**	**0.06–9.8**	**0.06–0.11**	**0.14–3.2**	**0.35~18.1**	**0.06~3.2**	
Trichiuridae Family										
01	*Trichiurus lepturus*	Churi	+	+		+		+	+	0.06~18.1
Anguillidae Family										
02	*A. japonica*	Kuchia	+		+			+		0.35~14.2
Ariidae Family										
03	*A. gagora*	Gagra tengra	+					+		0.35~14.2
Palaemonidae Family										
04	*Macrobrachium dolichodactylus*	Goda chingri	+	+	+			+		0.35~18.1
05	*M. rosenbergii*	Golda chingri		+				+		0.6~18.1
06	*Macrobrachium nobilii*	Lal icha			+		+	+	+	0.06~9.8
Bagridae Family										
07	*M. gulio*	Gulia	+			+	+	+	+	0.06~14.2
Clupeidae Family										
08	*Tenualosa ilisha*	Ilish	+			+	+	+	+	0.06~14.2
09	*Escualosa thoracata*	Boccha	+		+			+		0.06~14.2
Belonidae Family										
10	*Xenentodon cancila*	Kakila			+	+	+	+	+	0.06~9.8
Schilbeidae Family										
11	*Silonia silondia*	Shillong				+	+		+	0.06~3.2
Lactariidae Family										
12	*Lactarius lactarius*	Parava	+		+			+		0.06~9.8
Platycephalidae Family										
13	*Platycephalus indicus*	Chota bele	+	+		+	+	+	+	0.06~18.1

Table 2. *Cont.*

SL No	Scientific Name	Local Name	Salinity (psu) of Observed Months and Seasons							Salinity (psu) for Individual Species
			February 21	**March 21**	**June 21**	**September 21**	**November 21**	**Dry**	**Wet**	
			0.35–14.2	**0.6–18.07**	**0.06–9.8**	**0.06–0.11**	**0.14–3.2**	**0.35~18.1**	**0.06~3.2**	
					Penaeidae Family					
14	*Trachysalambria curvirostris*	Kharkharia chingri	+	+		+		+	+	0.06~18.1
15	*Metapenaeus spinulatus*	Lalia/chama chingri	+	+		+		+	+	0.06~18.1
16	*P. monodon*	Bagda		+	+		+	+	+	0.06~18.1
					Synodontidae Family					
17	*H. nehereus*	Loitta	+	+	+	+	+	+	+	0.06~18.1
					Sciaenidae Family					
18	*Otolithoides pama*	Bhola/Poa	+	+		+		+	+	0.06~18.1
					Polynemidae Family					
19	*Polynemus paradiseus*	Ricksha	+	+				+		0.35~18.1
20	*Eleutheronema tetradactylum*	Tarail		+	+		+	+	+	0.06~18.1
					Mugilidae Family					
21	*M. cephalus*	Bata	+	+			+	+	+	0.14~18.1
					Latidae Family					
22	*L. calcarifer*	Coral		+		+	+	+	+	0.06~18.1
					Sparidae Family					
23	*Acanthopagrus latus*	Datina/Java bhola				+			+	0.06~0.11
					Scombridae Family					
24	*Katsuwonus pelamis*	Rupsha	+	+			+	+	+	0.14~18.1
25	*Scomberomorus guttatus*	Surmai		+				+		0.6~18.1
					Sillaginidae Family					
26	*Sillaginopsis panijus*	Tular dandi		+	+	+	+	+	+	0.06~18.1

Table 2. *Cont.*

SL No	Scientific Name	Local Name	Salinity (psu) of Observed Months and Seasons							Salinity (psu) for Individual Species
			February 21	**March 21**	**June 21**	**September 21**	**November 21**	**Dry**	**Wet**	
			0.35–14.2	**0.6–18.07**	**0.06–9.8**	**0.06–0.11**	**0.14–3.2**	**0.35~18.1**	**0.06~3.2**	
					Gadidae Family					
27	*Gadus morhua*	Tara fish	+	+			+	+	+	0.14~18.1
					Engraulidae Family					
28	*S. phasa*	Phasa				+			+	0.06~0.11
29	*Colia ramacarati*	Oula			+	+	+	+	+	0.06~9.8
					Plotosidae Family					
30	*Pethia canius*	Kain magur					+		+	0.14~3.2
					Pangasiidae Family					
31	*Pangasianodon hypophthalmus*	Samudrik pangas			+		+	+	+	0.06~9.8
					Sactophagidae Family					
32	*Scatophagus argus*	Chitra	+	+		+		+	+	0.06~18.1
					Gobiidae Family					
33	*Glossogobius giuris*	Bailla/Bele				+	+		+	0.06~3.2
					Oxudercidae Family					
34	*O. rubicundus*	Lal chewa	+	+	+	+	+	+	+	0.06~18.1
35	*Apocryptes bato*	Chiring	+	+	+			+		0.06~18.1
36	*P. elongatus*	Chewa/chemu	+	+	+	+	+	+	+	0.06~18.1
					Stromateidae Family					
37	*Pampus argenteus*	Foli chanda	+			+		+	+	0.06~14.2
					Dasyatidae Family					
38	*Brevitrygon walga*	Shapla pata	+			+		+	+	0.06~14.2

The identified 33 fish species during the dry season in the MRE are as follows: *A. japonica*, *A. bato*, *A. gagora*, *B. walga*, *C. ramacarati*, *E. tetradactylum*, *E. thoracata*, *G. morhua*, *H. nehereus*, *K. pelamis*, *L. lactarius*, *L. calcarifer*, *M. dolichodactylus*, *M. rosenbergii*, *M. nobilii*, *M. spinulatus*, *M. cephalus*, *M. gulio*, *O. rubicundus*, *O. pama*, *P. argenteus*, *P. hypophthalmus*, *P. monodon*, *P. indicus*, *P. paradiseus*, *P. elongatus*, *S. argus*, *S. guttatus*, *S. panijus*, *T. ilisha*, *T. curvirostris*, *T. lepturus* and *X. cancila* (Table 2).

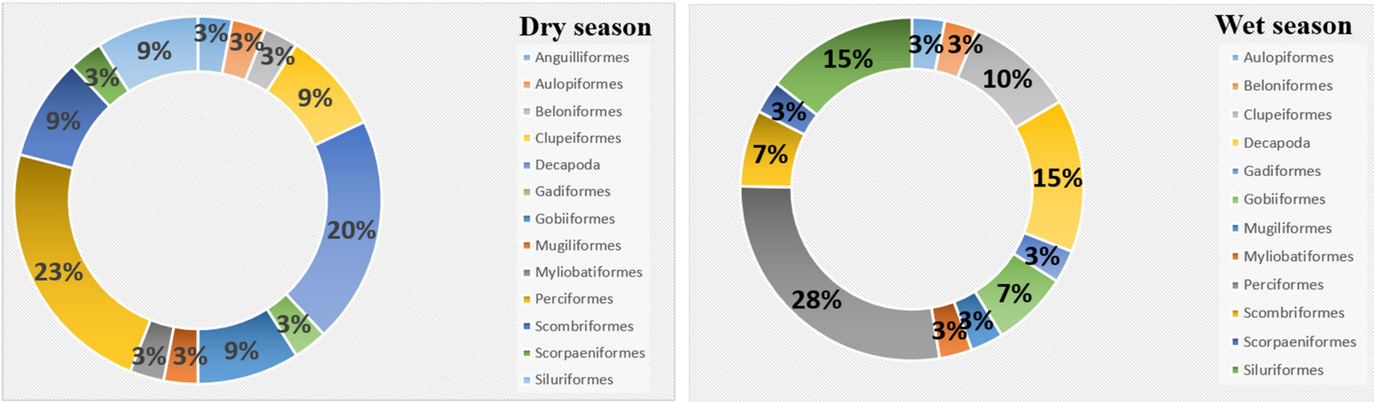

Figure 4. Percentage orders of fish species in the MRE during the dry and wet seasons.

Recorded fish species from the orders Decapoda (4.0–13.5 psu), Mugiliformes (1.0–13.0 psu), Beloniformes (1.0–9.0 psu), Perciformes (1.0–12.5 psu), Clupeiformes (1.0–9.0 psu), Gobiiformes (1.5–9.0 psu), Siluriformes (1.5–8.5 psu), Aulopiformes (2.0–12.0 psu), Scorpaeniformes (2.5–12.5 psu) and Scombriformes (2.5–12.0 psu) were found to tolerate wide ranges of salinity. Meanwhile, fish species from the orders Gadiformes (6.0–11.0 psu) and Myliobatiformes (2.5–7.0 psu) were available in moderate ranges of salinity. However, Pleuronectifomes (14.0–14.5 psu), Anabantiformes (0.0–0.1 psu), Synbranchiformes (1.0–3.0 psu) and Anguiliformes (6.0–7.5 psu), were found in narrow ranges of salinity (Table 3, Figure 5).

Table 3. Number and percent composition of families and species under various orders of fishes recorded in the Meghna River estuary (MRE).

Order		No. of Family		No. of Species		% Family		% Species	
Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Anguilliformes	Aulopiformes	1	1	1	1	4	4	3	3
Aulopiformes	Beloniformes	1	1	1	1	4	4	3	3
Beloniformes	Clupeiformes	1	2	1	3	4	7	3	10
Clupeiformes	Decapoda	2	2	3	4	9	7	9	14
Decapoda	Gadiformes	2	1	7	1	9	4	20	3
Gadiformes	Gobiiformes	1	1	1	2	4	4	3	7
Gobiiformes	Mugiliformes	1	1	3	1	4	4	9	3
Mugiliformes	Myliobatiformes	1	1	1	1	4	4	3	3
Myliobatiformes	Perciformes	1	8	1	8	4	31	3	27
Perciformes	Scombriformes	7	2	8	2	29	8	23	7
Scombriformes	Scorpaeniformes	2	1	3	1	8	4	9	3
Scorpaeniformes	Siluriformes	1	4	1	4	4	15	3	14
Siluriformes		3		3		13		9	
Total = 13	11	26	24	33	29	100	100	100	100

Fish species from the orders Beloniformes, Clupeiformes, Decapoda, Gobiiformes, Mugiliformes and Siluriformes were found during the dry season when salinity was near to 18 psu (Figure 6). Fish species from the orders Anguiliformes, Aulopiformes, Gadiformes, Myliobatiformes, Perciformes, Pleuronectifomes, Scombriformes and Scorpaeniformes were also available during the dry season, but at that time salinity was comparatively lower ($\simeq$11 psu). However, Anabantiformes and Synbranchiformes were available mostly in fresh water during the wet season when the salinity was near to 0 psu.

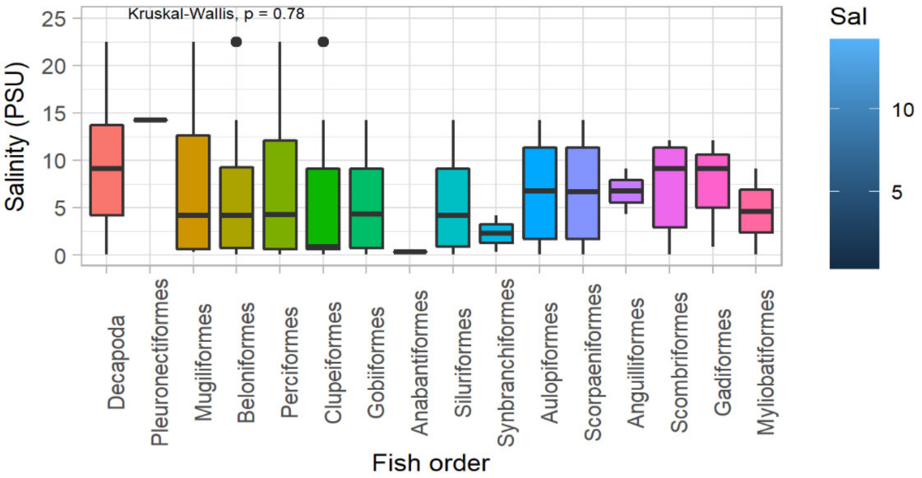

Figure 5. Fish orders availability with salinity variation. Note: the top, bottom and middle lines of the Box plot represent the upper quartile, the lower quartile and the median, respectively; the black spot represents the percentiles; the vertical part of the box body extending upward and downward represents the range of data distribution.

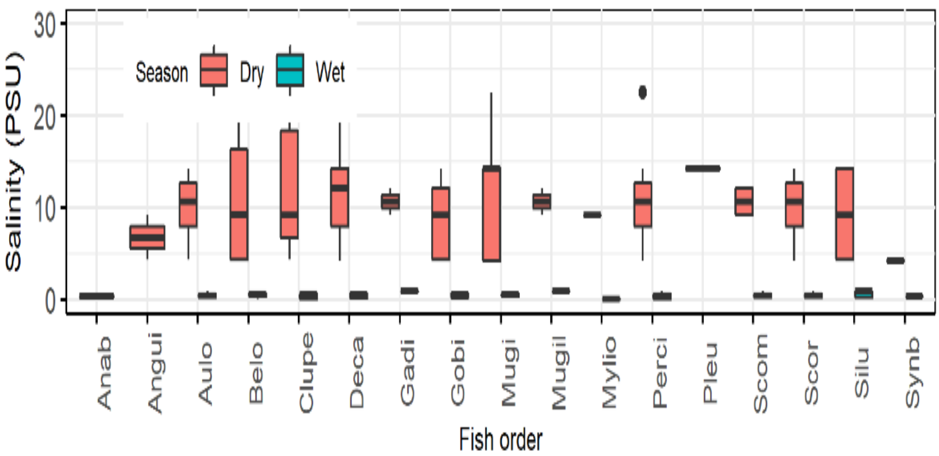

Figure 6. Seasonal distribution of fish orders with salinity variation. Note: the top, bottom and middle lines of the Box plot represent the upper quartile, the lower quartile and the median, respectively; the black spot represents the percentiles; the vertical part of the box body extending upward and downward represents the range of data distribution (Anab: Anabantiformes, Angui: Anguiliformes, Aulo: Aulopi-formes, Belo: Beloniformes, Clupe: Clupeiformes, Deca: Decapoda, Gadi: Gadiformes, Gobi: Gobiiformes, Mugil: Mugiliformes, Mylio: Myliobatiformes, Perci: Perciformes, Pleu: Pleuronectiformes, Scom: Scombriformes, Scor: Scorpaeniformes, Silu: Siluriformes, Synb: Synbranchiformes).

3.3. Suitability Index for Mariculture of the Commercially Important Fisheries Species

Suitability for the mariculture of commercially important fish species was calculated using suitability indices of various environmental parameters (Table 4). The value of the suitability index for the Sea cucumber in the Meghna River estuary (MRE) was calculated; during the dry and wet season, the suitability index value was 0.5 and 0.3, respectively. The suitability index for scallop in the MRE was found to be 0.4 during both the dry and wet seasons, respectively. Clam and coral are important mariculture species. We found that the suitability index value for clam was 1.00 and 0.25 during the dry and wet seasons, respectively. However, the suitability index value for coral species was 1.00 and 0.25 during the dry and wet season, respectively. In the consideration of mussel, the suitability index value was found to be 0.25 during the dry season and 0.4 during the wet season.

Table 4. Suitability index for mariculture of the commercially important fisheries species in the MRE.

	Season	Temp. (°C)	Salinity (psu)	pH	DO (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Inorganic Phosphorus (mg/L)	Suitability of Species for Mariculture		Reference
	Dry	19.68–29.89	0.12–18.07	7.30–9.09	6.72–9.99	0.01–2.84	0.01–0.18	0.00–0.09	0.02–2.08	Value	S * /NS **	This study value
	Wet	26.24–31.16	0.06–3.16	7.10–8.79	6.64–7.94	0.09–0.37	0.10–0.23	0.00–0.01	0.09–1.77			
Sea cucumber		10–30	28–37	4.6–8.6	>6	0.4–0.7			<0.01			[28] [29]
	Dry	S *	NS **	S *	S *	NS **			NS **	0.42	NS **	
	Wet	S *	NS **	NS **	S *	NS **			NS **	0.33	NS **	
Scallop		10–18	23–35	7.5–8.2	>4.5		0.01–0.02					[30] [31]
	Dry	NS **	NS **	S *	S *		NS **			0.40	NS **	
	Wet	NS **	NS **	S *	S *		NS **			0.40	NS **	
Clam		18–26	20–30	9	4.5–6.5							[32] [33] [34]
	Dry	S *	S *	S *	S *					1.00	S *	
	Wet	NS **	NS **	NS **	S *					0.25	NS **	
L. calcarifer (Coral/Sea bass)		15–40	10–30	7.5–8.5	4–9	<1		<0.02				[35] [36]
	Dry	S *	S *	S *	S *	S *		S *		1.00	S *	
	Wet	S *	NS **	NS **	S *	S *		NS **		0.42	NS **	
Mussel		26–32	27–35	7.9–8.2	>8	<0.4						[37] [38] [39]
	Dry	S *	NS **	S *	NS **	NS **				0.40	NS **	
	Wet	S *	NS **	NS **	S *	NS **				0.40	NS **	
Oyster		17–33	10–28	6.3	2–5	<1.2						[40] [41] [42]
	Dry	S *	S *	NS **	NS **	S *				0.60	S *	
	Wet	S *	NS **	NS **	NS **	S *				0.40	NS **	
L. parsia (Grey mullet)		3–35	0–38	6.5–9	>4	0–0.5	0.1–4.5	0.03–0.26	>0.06			[43] [44]
	Dry	S *	S *	S *	S *	S *	S *	S *	S *	1.00	S *	
	Wet	S *	S *	S *	S *	S *	S *	NS **	S *	0.87	S *	
Sea weed		24–32	27–35	7.5–9.13	4–8.5				0.03–0.05			[45] [39]
	Dry	NS **	NS **	NS **	S *				S *	0.40	NS **	
	Wet	S *	NS **	S *	NS **				NS **	0.40	NS **	

Table 4. *Cont.*

	Season	Temp. (°C)	Salinity (psu)	pH	DO (mg/L)	Ammonia (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Inorganic Phosphorus (mg/L)	Suitability of Species for Mariculture		Reference
S. serrata (Mud crab)		21–35	0–30	5–9	4–9		0.31–0.57	0–0.007				[46] [47] [39]
	Dry	S *	S *	S *	S *		NS **	S *		0.83	S *	
	Wet	S *	S *	S *	S *		NS **	S *		0.83	S *	
M. rosenbergii		25–29	0–15	7–8.5	4.4–7.1							[48] [49] [39]
	Dry	S *	NS **	NS **	S *					0.40	NS **	
	Wet	S *	S *	S *	S *					1.00	S *	
M. cephalus		26–29.3	<30	7.8–8.2	5.7–6.1							[50] [51]
	Dry	S *	S *	S *	NS **					0.75	S *	
	Wet	S *	NS **	S *	NS **					0.40	NS **	
P. monodon		26–30.8	10–55	7–8.9	4.5–7.2	0.1–0.3	0.09–0.2	0.01–0.05	0.31			[28] [52] [39]
	Dry	S *	S *	S *	S *	S *	S *	S *	S *	1.00	S *	
	Wet	S *	NS **	S *	S *	NS **	S *	NS **	NS **	0.44	NS **	
P. hypophthalmus		20–35	<20	6.7–8.6	5–8							[53] [54] [55]
	Dry	NS **	NS **	S *	NS **					0.25	NS **	
	Wet	S *	S *	NS **	S *					0.75	S *	
P. indicus		30.3–31.6	10.25–30	7.8–7.9	5.6–5.9							[56] [57] [39]
	Dry	S *	S *	S *	NS **					0.75	S *	
	Wet	S *	NS **	S *	NS **					0.40	NS **	
M. vittatus		26.1–28	<10	7.1–8.2	5.9–6.5							[58] [59]
	Dry	S *	NS **	S *	NS **					0.40	NS **	
	Wet	S *	S *	S *	NS **					0.75	S *	
M. gulio		25.8–29	1.73–3	7.1–7.6	4.9–5.6	0.34–0.36	0.05–0.08	0.02–0.05	0.42			[60]
	Dry	S *	NS **	S *	NS **	S *	S *	NS **	NS **	0.45	NS **	
	Wet	S *	S *	S *	NS **	S *	NS **	NS **	S *	0.73	S *	
T. ilisha		29.3–30.8	<0.1	7.7–8.4	4.8–6.8							[61]
	Dry	S *	NS **	S *	NS **					0.40	NS **	
	Wet	NS **	S *	S *	S *					0.75	S *	

Here, S * = Suitable and NS ** = Not Suitable.

Oyster is one of the most popular mariculture species, and they also have large economic value. In the study area, the suitability index values of oyster were in 0.8 during the dry season, whereas they were 0.4 during the wet season. Grey mullet is the most common and suitable species for culture in both saline water and fresh water. The suitability index value for the mariculture of Grey mullet was found to be 1.00 and 0.9 during the dry and wet seasons, respectively. Seaweed culture is very new culture in the Asian subcontinent. In Bangladesh, seaweed culture is still less popular. The suitability index value was found to be 0.5 during the dry season and 0.25 during the wet season. Mud crab is another common and popular species in Bangladesh, with a value of 0.8 during the wet season. Prawn (*M. rosenbergii*) is called white gold. Prawn is the most popular and demanding species. From the suitability index calculation, we found it to be 0.5 during the dry season in the study area. On the other hand, it was 1.00 during the wet season. Shrimp (*P. monodon*) is another commercially important species which contributes to our economy. The suitability index value was found to be 1.00 during the dry season, whereas it was 0.4 during the wet season. The suitability index value for *M. vittatus* was found to be 0.5 during the dry season and 0.75 during the wet season in the study area.

3.4. Fish Species Diversity Indices

In the study area, the highest Shannon–Weaver diversity index (H′), Pielou's species evenness and Margalef's species richness index value was observed in the dry season, where the lowest values were observed in the wet season (Table 5). Shannon–Weaver diversity index (H′) was measured 0.37 in the MRE (Table 5) which indicates a very poor diversity of fishes. The highest Shannon–Weaver diversity index value (0.33) was found during the dry winter season in the estuary due to low water volume, which results in less dilution.

Table 5. Fish species diversity index values in the MRE during the dry and wet seasons.

	Average	Dry Season	Wet Season	Standard	References
Total number of species (S)	38	33	29		
Total number of individuals (N)	102	62	40		
Shannon-Weaver diversity index (H′)	0.37	0.34	0.25	0–5	[62]
Pielou's species evenness (J′)	0.11	0.09	0.07	0–1	[63]
Margalef species richness (d)	8.00	7.90	7.30	>5	[62]

The lowest value (0.25) was found during the rainy monsoon due to a high volume of water flow which results in more dilution. The lowest evenness value was 0.07 (wet season) and the highest value was 0.09 (dry season), which is exhibited in Table 5. The seasonal mean evenness value in the MRE was 0.11, which also indicates an unbalanced evenness of fish species in the MRE. The seasonal mean richness index (d) value was 8.0 in the MRE, whereas the highest value (7.9) was found during the dry summer due to a high concentration of nutrients. The species richness shows the lowest value (7.3) during the rainy monsoon.

4. Discussion

The rapid increase in human activity in the estuaries and coastal areas has increased the nutrient transport from land to sea in the past decades, resulting in environmental deterioration and changes to biogeochemical processes [64]. The quality of water is defined by its physical, chemical, and biological parameters, and all these characteristics directly or indirectly influence the survival and production of aquatic species [65]. The changes recorded in physico-chemical characteristics of the MRE clearly showed that the variability of the estuarine regime is mostly conditioned by seasonal changes. Seasonality brings about changes in water temperature, pH, salinity, DO and primary production in the estuary. Generally, rainfall plays an important role in seasonal cyclic phenomena in the tropical environment, causing important changes in the hydrology of the estuarine environment. In the present study, rainfall showed a good connection with changes in salinity and water temperature in this estuarine system [65]. Our results indicate two broad patterns of change: the brackish water expanding moderately to upstream during the dry season and the freshwater habitat expanding to downstream during the wet season. These changes will adversely affect many fish species, with significant impacts on their reproductive cycles, reproductive capacities, suitable spawning areas, feeding, breeding and longitudinal migration [6]. The key indicator of an estuary is its salinity profile. A general increase in water temperature in the wet season in the MRE could be the result of high solar radiation and higher atmospheric temperature, whereas the lower temperature in the dry season was due to foggy weather. The presence of higher pH in the wet season is probably induced by the photosynthesizing organisms and high biological activity of aquatic flora and fauna [66]. However, the lower pH during dry season might be linked to the low temperature and organic matter decomposition.

Chlorophyll-a constitutes the chief photosynthetic pigment of phytoplankton and acts as an index that provides the primary production potential, biodiversity, and biomass in an estuarine ecosystem [65]. Higher values of chlorophyll-a were observed during the wet season, which could be due to the high nutrients and higher phytoplankton abundance in the corresponding seasons [67]. A significant negative correlation was observed between chlorophyll-a and salinity ($p < 0.05$). The concentration of chlorophyll-a had a positive correlation with the concentrations of nitrate and temperature, but a negative correlation with salinity in this study, which was also reported by [68–70]. This indicates that if salinity increases, chlorophyll-a concentration decreases. It is natural for chlorophyll-a levels to fluctuate over time. Chlorophyll-a concentrations are often higher after rainfall, particularly if the rain has flushed nutrients into the water. In addition, chlorophyll-a also showed different spatial patterns during the two seasons. Dissolved inorganic nutrients such as nitrite, nitrate, ammonium, and phosphate are the major essential nutrients for the phytoplankton growth [71]. In an aquatic ecosystem, dissolved inorganic nitrogenous (DIN = NH_4^+ + NO_3^- + NO_2^-) substances are therefore very much dependent on biological uptake and regeneration [72]. Among the DIN substances, the ammonia-nitrogen is preferentially used by plants and produced by the bacterial breakdown of organic matter and animal excretion. Dissolved nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+) ions are the three major sources of nitrogen, which are required by phytoplankton; nitrate that is an important source of nitrogen is present in large quantities, and nitrite is present in much lower quantities [73]. In the present study, the higher ammonium concentration in the dry season could be linked to the death and decay of the species that are less tolerant of salinity [65].

However, salinity gradient was found to be a major factor that affects the diversity and distribution of various fish species in the middle coastal region of Bangladesh over different spatial and temporal scales. Fishes are the most studied group of species and the best indicators of geographical patterns. Due to water dynamic changes, salinity intrusion and other human activity limited the flow of nutrients, organisms, matter, energy, and genetic information in aquatic habitats [74]. Further analyses revealed that most species were saline water species. Different fish species prefer different ranges of salinity for growth, survival, feeding, breeding, nursing etc. throughout their life cycle. Similarly, thirteen fish orders were found under this study in the MRE. Among them, some orders of fish were found to tolerate a wide range of salinity, whereas others were found to tolerate moderate or narrow ranges of salinity. Fish species from the orders Anguiliformes, Aulopiformes, Gadiformes, Myliobatiformes, Perciformes, Pleuronectifomes, Scombriformes and Scorpaeniformes were also available during the dry season but, at that time, salinity was comparatively lower ($\simeq$11 psu). However, Anabantiformes and Synbranchiformes were available mostly in fresh water during the wet season when the salinity was near to 0 psu. Many studies have also found that the changes of environmental factors, such as dissolved oxygen, pH, water depth and turbidity, affected fish assemblages [75]. The results indicated that environmental factors also affected fish distributions and assemblage composition. Therefore, the probable decline in the biodiversity of freshwater, low-value, wild fish species with increased river salinity may have significant implications for the nutrition of the rural poor [6].

The suitability index value indicates that both grey mullet and mud crab species are suitable for mariculture in the Meghna River estuary during both the dry and wet seasons. In contrast, the value of suitability index indicates that sea cucumber, scallop, mussel, and seaweed species are unsuitable for mariculture during both the dry and wet seasons in the MRE. Clam, coral, oyster, and *P. monodon* are also an important mariculture species. Similarly, the suitability index value indicating that these species are suitable for mariculture in the MRE during the dry season only. On the other hand, *M. rosenbergii, M. vittatus* and *M. gulio* are also an important mariculture species. The suitability index value indicates that this species is suitable for mariculture in the MRE during the wet season only. The authors will try to consult our relevant ministry by combining the results of the study with our current studies, and by preparing a detailed report developing policies for the conservation and management of the aquatic resources in the coastal zone to enrich the blue economy.

Diversity indices are used to quantify the species diversity of a habitat. The higher the diversity index, the more diverse the site is. In the study area, the highest Shannon–Weaver diversity index (H′), Pielou's species evenness, and Margalef's species richness index value was observed in the dry season, where the lowest values were observed in the wet season. It indicates that fish species abundance was higher in the brackish water (0.35~14.2 psu) compared to freshwater (0.06~0.11 psu). The Shannon–Weaver diversity index value during dry winter resulted in a higher fish abundance in the study area. The lowest evenness value was 0.07 (wet season) and the highest value was 0.09 (dry season). In each case of the highest Shannon–Weaver (dry season), the diversity index was involved with a high number of individuals, and the lowest diversity (wet season) was involved with a low number of individuals. The seasonal mean evenness value in the MRE was 0.11, which also indicates an unbalanced evenness of fish species in the MRE. Our study revealed that the Shannon–Weaver diversity index (H'), Margalef and Pielou indices presented a significant difference between the dry and wet seasons of this study, as fish biodiversity was higher in the dry season compared to the wet season. Fish biodiversity had positively correlated with the Shannon–weaver index, Pielou's evenness and Margalef's index. Margalef's richness is the simplest measure of biodiversity and is simply a count of the number of different species in a given area. Pielou's evenness index (J′) measures the evenness in which individuals are divided among the taxa present [76]. Therefore, the species equitability index in the different months reveals that the distribution of the fish population of the Meghna River estuary is more or less equally distributed. Fish species richness is a good allusion of healthy fish diversity in the waters, which could be conserved. On the contrary, the poor availability status and decreasing trend of many fish species intimates the alarming situation of the fisheries resources. Furthermore, the current study also observed that the freshwater fish species are affected by a range of anthropogenic and natural threats.

5. Conclusions

The Meghna River estuary plays a significant role in maintaining and replenishing the fish resources. The results have further shown that fish composition and diversity have significant differences between the dry and wet seasons. The multivariate analysis showed a seasonal gradient for the water quality parameters, forming two different groups for the dry and wet seasons. The results showed that salinity, chlorophyll-a and water temperature significantly affected fish distribution and assemblage composition. Overall, 31 fish species were identified in the study area where 33 species were found during the dry season and 29 species were found during the wet season. Among them, *H. nehereus, O. rubicundus* and *P. elongatus* were found as polyhaline. *A. japonica* and *A. gagora* were abundant in brackish water conditions. However, *A. latus* and *S. phasa* were found in freshwater conditions (0.06~0.11 psu). Commercially important species such as *L. parsia*, *M. rosenbergii*, *M. cephalus, P. monodon* and *S. serrata*, which prefer higher salinity for their growth, survival, feeding, nursing, and breeding purposes, are feasible for mariculture during the dry season (January–May) when water salinity is comparatively higher. On the contrary, *A. Latus*, *P. canius* and *S. phasa* are feasible during the wet season when water salinity is low. Thus, the conservation of fish has become urgent, and an integrated coastal management plan should be developed and effectively implemented to enrich our blue economy.

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