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Environmental controls on zooplankton community composition across the Bangladesh coast: integrating hydrochemistry, multivariate ordination, and threshold indicator analysis

Syeda Maksuda Yeasmin[1,2,3] • Md Habibur Rahman[1,2,3] • Mamun Abdullah Al[4,5] • Md. Abu Kawsar[6,7] • Syed Tanvir Woalid[8] • Rion Islam Fardin[9] • Md. Hasan[1]

[1] *Department of Fisheries and Marine Bioscience, Jashore University of Science and Technology, Jashore 7408, Bangladesh*
[2] *State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China*
[3] *University of Chinese Academy of Sciences, Beijing 100049, China*
[4] *Aquatic Microbial Ecology (AME-Research Group), Laboratory of Marine and Freshwater Research, Department of Fisheries and Marine Resources Technology (FMRT), Rangamati Science and Technology University (RMSTU), Rangamati 4500, Bangladesh*
[5] *Marine Synthetic Ecology Research Center (MSER), Southern Marine Science and Engineering Guangdong Laboratory (SML), School of Marine Sciences, Sun Yat-sen University, Zhuhai 519082, China*
[6] *State Key Laboratory of Breeding Biotechnology and Sustainable Aquaculture, Guangdong Provincial Key Laboratory of Applied Marine Biology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China*
[7] *Department of Aquaculture, Sylhet Agricultural University, Sylhet 3100, Bangladesh*
[8] *Department of Zoology, National University of Bangladesh, Gazipur 1704, Bangladesh*
[9] *Department of Mathematics, Jamalpur Science and Technology University, Jamalpur 2012, Bangladesh*

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TABLE S1 Sampling sites and their geographic coordinates in the western, central, and eastern coastal zones of Bangladesh.

Sampling sites	Area	Latitude (DMS)	Longitude (DMS)
W1	Upper Shibsa river	22°26′33.18″N	89°25′56.95″E
W2	Upper Shibsa river	22°15′34.33″N	89°28′15.70″E
W3	Middle Shibsha river	22°04′55.31″N	89°30′54.86″E
W4	Lower Shibsa river, estuary	21°54′37.36″N	89°30′16.28″E
W5	Lower Shibsa river, estuary	21°42′35.47″N	89°29′00.88″E
C1	Elisha, lower Meghna River	22°44′46.16″N	90°39′53.91″E
C2	Daulatkhan, lower Meghna River estuary	22°36′00.82″N	90°45′25.75″E
C3	Tazumuddin, lower Meghna River estuary	22°25′01.01″N	90°51′56.56″E
C4	Char Fasson, lower Meghna River estuary	22°11′28.31″N	90°49′33.59″E
C5	Char Nizam, lower Meghna River estuary	21°52′39.05″N	90°50′27.15″E
E1	Ship breaking zone	22°33′21.36″N	91°37′10.12″E
E2	Karnaphuli river mouth	22°12′10.29″N	91°48′31.69″E
E3	Matarbari Project area	21°40′15.40″N	91°50′38.19″E
E4	Inani Beach	21°13′37.70″N	92°02′13.82″E
E5	Dakhinpara	20°45′57.81″N	92°17′44.07″E

TABLE S2 Instruments and analytical methods used for hydrochemical measurements and laboratory analyses.

Parameter	Instrument	Model	Manufacturer	Method
Water temperature	Multiparameter meter	HI 9829	Hanna Instruments, Woonsocket, RI, USA	*In situ*
Salinity	Multiparameter meter	HI 9829	Hanna Instruments, Woonsocket, RI, USA	*In situ*
pH	Digital pH meter	HI 98107	Hanna Instruments, Woonsocket, RI, USA	*In situ*
Dissolved oxygen (DO)	DO meter	PDO-519	Lutron Electronic Enterprise Co., Taipei, Taiwan	*In situ*
Electrical conductivity (EC)	Multiparameter meter	HI 9829	Hanna Instruments, Woonsocket, RI, USA	*In situ*
Total dissolved solids (TDS)	TDS tester	AD31	Adwa Instruments, Szeged, Hungary	*In situ*
Water transparency	Secchi disk	–	–	*In situ*
Nitrate (NO_3–N)	Spectrophotometer	DR/2020	HACH Company, Loveland, CO, USA	APHA (2017)
Phosphate (PO_4)	Spectrophotometer	DR/2020	HACH Company, Loveland, CO, USA	APHA (2017)
Chemical oxygen demand (COD)	Spectrophotometric analysis	DR/2020	HACH Company, Loveland, CO, USA	Potassium permanganate method
Biochemical oxygen demand (BOD)	BOD analyzer	HI 98193	Hanna Instruments	APHA (2017), 5-day BOD method
Chlorophyll-a (Chl-*a*)	Fluorometer	Cyclops-7F	Turner Designs, San Jose, CA, USA	Fluorometric analysis

TABLE S3 Linear mixed-effects model results for the effects of coastal zone, season, and their interaction on hydrochemical parameters across the Bangladesh coast.

Parameter	Effect	df1	df2	F-value	*p*-value
Temperature (°C)	Zone	2	36	20.67	<0.001
	Season	2	36	998.61	<0.001
	Zone × Season	4	36	23.88	<0.001
Transparency (cm)	Zone	2	12	96.70	<0.001
	Season	2	24	315.08	<0.001
	Zone × Season	4	24	103.84	<0.001
Salinity (ppt)	Zone	2	12	11.54	0.002
	Season	2	24	172.39	<0.001
	Zone × Season	4	24	13.57	<0.001
pH	Zone	2	12	38.08	<0.001
	Season	2	24	399.27	<0.001
	Zone × Season	4	24	21.38	<0.001
Dissolved oxygen (mg L^{-1})	Zone	2	12	86.11	<0.001
	Season	2	24	92.03	<0.001
	Zone × Season	4	24	103.85	<0.001
TDS (mg L^{-1})	Zone	2	12	34.83	<0.001
	Season	2	24	5.55	0.010
	Zone × Season	4	24	2.66	0.057
EC (dS m^{-1})	Zone	2	12	6.56	0.012
	Season	2	24	136.55	<0.001
	Zone × Season	4	24	20.79	<0.001
BOD (mg L^{-1})	Zone	2	12	14.44	<0.001
	Season	2	24	8.70	0.001
	Zone × Season	4	24	1.05	0.401
COD (mg L^{-1})	Zone	2	12	9.81	0.003
	Season	2	24	36.98	<0.001
	Zone × Season	4	24	0.02	0.999
Chlorophyll-*a* (mg m^{-3})	Zone	2	12	46.24	<0.001
	Season	2	24	1185.89	<0.001
	Zone × Season	4	24	45.31	<0.001
NO_3–N (mg L^{-1})	Zone	2	12	24.14	<0.001
	Season	2	24	39.37	<0.001
	Zone × Season	4	24	3.15	0.032
PO_4 (mg L^{-1})	Zone	2	12	168.82	<0.001
	Season	2	24	185.60	<0.001
	Zone × Season	4	24	39.36	<0.001

Note: Linear mixed-effects models included coastal zone, season, and their interaction as fixed effects, with sampling site included as a random intercept to account for repeated seasonal observations. Type III F-tests with Satterthwaite approximation were used. Where Zone × Season interactions were significant, simple-effect comparisons were performed using Tukey-adjusted estimated marginal means. The temperature model showed a singular fit because the estimated site-level random-effect variance was effectively zero

TABLE S4 Checklist, relative abundance, and seasonal–spatial occurrence of zooplankton genera recorded across the Bangladesh coast.

Group	Genus	RA (%)	Pre-monsoon			Monsoon			Post-monsoon		
			W	C	E	W	C	E	W	C	E
Protozoa	*Tintinnopsis*	5.65	+	+	+	+	+	+	+	+	+
	Eutintinnus	2.43	+	+	+	+	+	+	+	+	+
Rotifera	*Brachionus*	11.24	+	+	+	+	+	+	+	+	+
	Keratella	3.40	+	+	–	+	+	–	+	+	–
	Asplanchna	2.50	+	+	–	+	+	–	+	+	–
	Hexarthra	2.17	+	+	–	+	+	–	+	+	–
	Filinia	2.03	+	+	–	+	+	–	+	+	–
	Colurella	1.57	+	+	–	+	+	–	+	+	–
	Polyarthra	1.56	+	+	–	+	+	–	+	+	–
	Lecane	1.24	+	+	–	+	+	–	+	+	–
	Trichocera	0.86	+	+	–	+	–	–	+	+	–
Copepoda	*Acartia*	13.29	+	+	+	+	+	+	+	+	+
	Oithona	9.00	+	+	+	+	+	+	+	+	+
	Pseudodiaptomus	3.35	+	+	+	+	+	+	+	+	+
	Paracalanus	2.98	+	+	+	+	+	+	+	+	+
	Centropages	2.86	+	+	+	+	+	+	+	+	+
	Diaptomus	2.09	+	+	–	+	+	–	+	+	–
	Euterpina	2.05	+	+	+	+	+	+	+	+	+
	Temora	2.03	+	+	+	+	+	+	+	+	+
	Cyclops	1.83	+	+	–	+	+	+	+	+	–
	Merocyclops	1.29	+	+	–	+	+	–	+	+	–
	Calanopia	1.12	+	+	+	+	+	+	+	+	+
	Mesocyclops	1.11	+	+	–	+	+	–	+	+	–
	Microsetella	1.01	+	+	+	–	+	+	+	+	+
	Labidocera	1.00	+	+	+	–	+	+	+	+	+
	Canthocalanus	0.85	+	+	+	+	+	+	+	+	+
	Oncaea	0.79	+	+	+	+	+	+	+	+	+
	Candacia	0.57	+	+	+	–	+	+	+	+	+
	Tigriopus	0.38	+	–	+	–	+	+	+	+	+
	Calanus	0.20	+	+	+	–	–	+	+	+	+
	Subeucalanus	0.16	+	+	+	–	+	–	+	+	+
	Eucalanus	0.11	+	–	+	+	–	+	+	–	+
	Microcalanus	0.09	+	–	+	–	–	+	+	–	+
Cladocera	*Bosmina*	4.30	+	+	–	+	+	–	+	+	–
	Evadne	3.02	+	+	+	+	+	+	+	+	+
	Daphnia	2.75	+	+	–	+	+	–	+	+	–
	Alona	2.03	+	+	+	+	+	–	+	+	–
	Chydorus	1.66	+	+	–	+	+	–	+	+	–
	Diaphanosoma	1.21	+	+	–	+	+	–	+	+	–
	Bosminopsis	1.04	+	+	–	+	+	–	+	+	–
	Moina	0.99	+	+	–	+	–	+	+	+	–
	Simocephalus	0.18	+	–	–	–	+	–	+	+	–

RA = relative abundance. '+' indicates presence and '–' indicates absence within the corresponding season–zone combination. W=Western, C=Central, E=Eastern

TABLE S5 Linear mixed-effects model results for the effects of coastal zone, season, and their interaction on zooplankton community metrics.

Community metric	Effect	df1	df2	F-value	p-value
Total abundance	Zone	2	12	37.14	<0.001
	Season	2	24	373.28	<0.001
	Zone × Season	4	24	23.85	<0.001
Taxa richness	Zone	2	12	279.33	<0.001
	Season	2	24	67.57	<0.001
	Zone × Season	4	24	16.82	<0.001
Shannon diversity (H')	Zone	2	12	707.84	<0.001
	Season	2	24	14.50	<0.001
	Zone × Season	4	24	18.93	<0.001
Margalef richness (D)	Zone	2	12	199.70	<0.001
	Season	2	24	24.95	<0.001
	Zone × Season	4	24	15.15	<0.001
Pielou's evenness (J')	Zone	2	12	749.15	<0.001
	Season	2	24	5.29	0.012
	Zone × Season	4	24	4.23	0.010

Note: Models were specified as response ~ zone × season + (1 | site). Fixed effects were tested using Type III F-tests with Satterthwaite-adjusted denominator degrees of freedom. Significant interactions were followed by Tukey-adjusted estimated marginal means.

TABLE S6 Codes and identities of the 15 zooplankton genera displayed in the RDA ordination, with corresponding species scores, RDA rank, and total abundance.

Code	Genus	RDA rank	RDA1 score	RDA2 score	RDA magnitude	Total abundance
G1	*Acartia*	1	0.5761	−0.0139	0.5763	1387
G2	*Oithona*	2	0.4708	0.0063	0.4709	940
G3	*Brachionus*	3	−0.4235	−0.0545	0.4270	1174
G4	*Bosmina*	4	−0.4108	−0.0035	0.4108	449
G5	*Keratella*	5	−0.3593	−0.0426	0.3618	355
G6	*Daphnia*	6	−0.3261	−0.0281	0.3273	287
G7	*Asplanchna*	7	−0.3115	−0.0254	0.3125	261
G8	*Hexarthra*	8	−0.2903	−0.0356	0.2925	227
G9	*Diaptomus*	9	−0.2837	−0.0446	0.2872	218
G10	*Filinia*	10	−0.2815	−0.0345	0.2836	212
G11	*Alona*	11	−0.2705	−0.0215	0.2713	212
G12	*Cyclops*	12	−0.2584	−0.0156	0.2589	191
G13	*Chydorus*	13	−0.2545	0.0333	0.2567	173
G14	*Colurella*	14	−0.2468	−0.0182	0.2474	164
G15	*Polyarthra*	15	−0.2409	−0.0228	0.2419	163

Note: RDA magnitude was calculated as $\sqrt{RDA1^2 + RDA2^2}$. Genera were ranked according to their species-score magnitude across the first two canonical axes, and the 15 genera with the largest magnitudes were displayed in Fig. 6 to improve figure readability. All 42 genera were retained in the RDA analysis; the selection of 15 genera was performed solely for visualization and did not affect model fitting or statistical inference.

TABLE S7 Community-level Threshold Indicator Taxa Analysis (TITAN) results for salinity, total dissolved solids (TDS), electrical conductivity (EC), and pH gradients across the Bangladesh coast.

Environmental gradient	Unit	z− threshold	5–95% CI	z+ threshold	5–95% CI	z− taxa (n)	z+ taxa (n)
Salinity	ppt	13.85	13.05–25.55	8.90	8.60–10.75	18	13
TDS	mg L^{-1}	827.50	47.95–1031.50	23.80	23.30–1156.78	23	5
EC	dS m^{-1}	1.80	1.55–2.10	1.90	1.30–2.30	20	10
pH	–	–	–	7.00	6.90–7.10	0	9

Note: z− and z+ represent community-level change points based on taxa showing negative and positive responses along each environmental gradient, respectively. Confidence intervals (CI) represent the 5th–95th percentiles of bootstrap change-point estimates. The numbers of z− and z+ taxa represent taxa classified as negative and positive responders, respectively. No community-level z− threshold was identified for pH. Broad confidence intervals, particularly for TDS, indicate greater uncertainty in the corresponding community-level threshold estimates.

TABLE S8 Robustness of community-level TITAN thresholds for salinity, total dissolved solids (TDS), electrical conductivity (EC), and pH under primary and sensitivity analyses.

Environmental gradient	Unit	Primary z− threshold (5–95% CI)	Sensitivity z− threshold (5–95% CI)	Primary z+ threshold (5–95% CI)	Sensitivity z+ threshold (5–95% CI)
Salinity	ppt	13.85 (13.05–25.55)	13.85 (12.90–25.55)	8.90 (8.60–10.75)	8.90 (8.60–10.75)
TDS	mg L^{-1}	827.50 (47.95–1031.50)	827.50 (47.95–1006.00)	23.80 (23.30–1156.78)	24.35 (23.95–1145.00)
EC	dS m^{-1}	1.80 (1.55–2.10)	1.80 (1.55–2.10)	1.90 (1.30–2.30)	1.90 (1.50–2.30)
pH	–	–	–	–	7.00 (6.90–7.10)

Note: Primary and sensitivity analyses were used to evaluate the robustness of community-level TITAN change points to alternative analytical settings. Values are community-level z− and z+ thresholds, with the 5th–95th percentile bootstrap confidence intervals in parentheses. Similar threshold estimates between the primary and sensitivity analyses indicate robust community-level responses. Salinity showed highly consistent z− (13.85 ppt) and z+ (8.90 ppt) thresholds across both analyses. EC and pH thresholds were also stable, whereas TDS showed greater uncertainty, as indicated by its broad bootstrap confidence intervals. No z− threshold was identified for pH in either analysis.

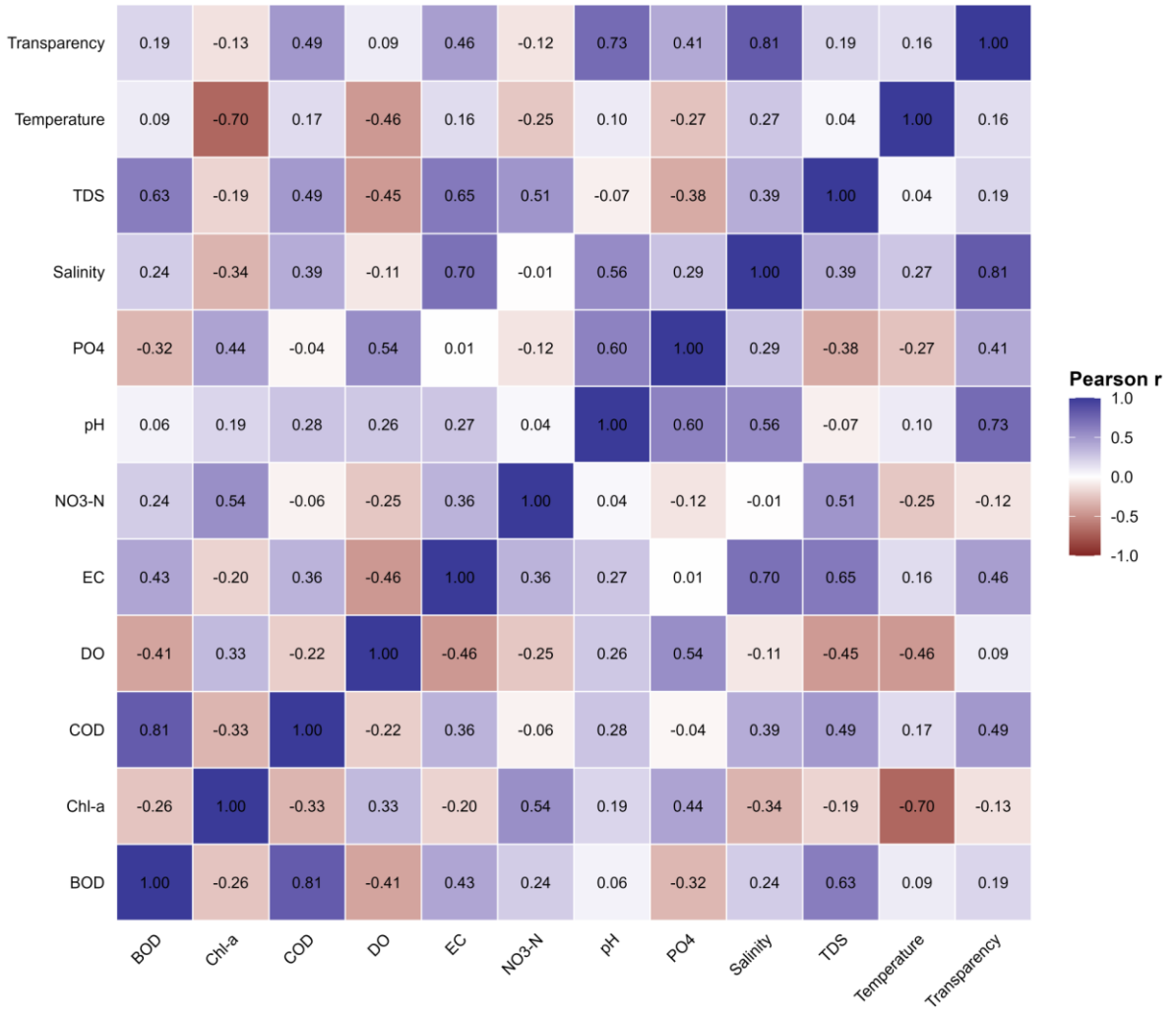

FIGURE S1 Pearson correlation matrix among hydrochemical variables used in the multivariate analyses.

Note: Values within cells represent Pearson correlation coefficients (*r*). Positive and negative correlations are indicated by contrasting color gradients, with increasing color intensity representing stronger correlations. BOD, biochemical oxygen demand; Chl-*a*, chlorophyll-*a*; COD, chemical oxygen demand; DO, dissolved oxygen; EC, electrical conductivity; NO_3–N, nitrate nitrogen; PO_4, phosphate; TDS, total dissolved solids.

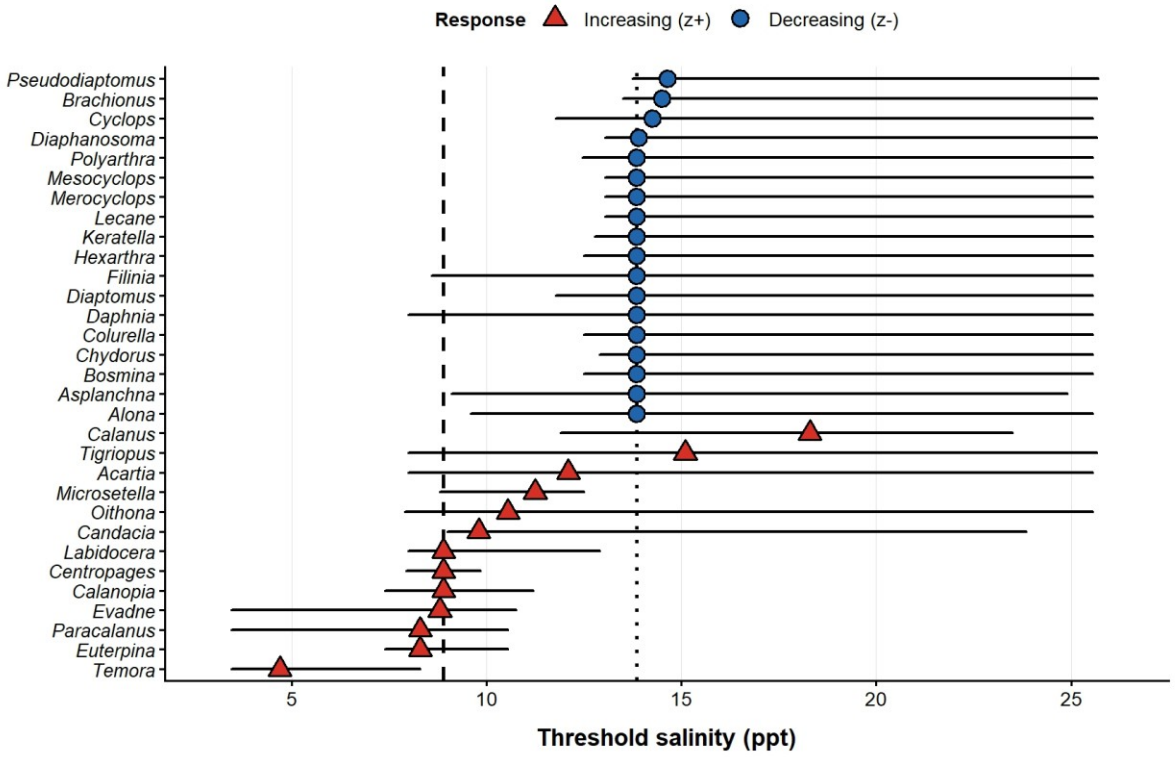

FIGURE S2 Salinity threshold responses of zooplankton genera identified by Threshold Indicator Taxa Analysis (TITAN). Red triangles (z^+) indicate genera that increased in abundance with increasing salinity, whereas blue circles (z^-) indicate genera that declined. Symbols represent the estimated change points, and horizontal lines indicate the 5–95% bootstrap confidence intervals of the threshold estimates. The dashed vertical line denotes the community-level salinity threshold (8.9 ppt), and the dotted vertical line indicates the strongest community transition (13.9 ppt).