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An overview of dinoflagellate cysts in recent sediments along the west coast of India

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Distribution and abundance of dinoflagellate cysts in recent sediments along the west coast of India (26 coastal stations and 3 ports) is presented. A total of 47 different types of cysts and a maximum abundance of 1076 cysts g^{-1} dry sediment were recorded. Highest cyst abundance was recorded at coastal station Mangalore (801 cysts g^{-1} dry sediment) and Kochi port (1076 cysts g^{-1} dry sediment). Lowest cyst abundance was observed at coastal stations from Kochi to Trivandrum. This difference may be attributed to the composition of sediment, since sandy stations had lower abundance and diversity of cysts. Heterotrophic dinoflagellate cysts, mainly *Protoperidinium* species, were the most diversified, predominating at most of the stations sampled. Cysts of potential Harmtul Algal Bloom (HAB) species capable of forming blooms were also detected in the sediment. Effect of the environmental settings of the study area such as upwelling, South West monsoon and anthropogenic pressures on the dynamics of these HAB species in Indian waters needs to be elucidated.

[**Keywords:** dinoflagellate cysts, heterotrophic, harmful, sediment texture, west coast of India]

Introduction

Dinoflagellates are emerging as an important group due to their role in Harmful Algal Blooms (HABs), toxin–producing abilities, varying modes of nutrition and reproduction. Of approximately 100 species of HAB–producing phytoplankton, 75% are dinoflagellates[1]. Reproduction in dinoflagellates is primarily asexual whereas some species are also known to undergo sexual reproduction. Those species capable of sexual reproduction, form gametes that fuse into a swimming cell (planozygote), which, in most cases, transforms into a resting cyst stage (hypnozygote). These cysts are morphologically distinctive and differ from the motile planktonic stage[2]. Of the 2000 marine dinoflagellate species identified, approximately 10% are known to produce resting cysts as part of their life cycle[3]. Cysts play an important role in species dispersal[2], survival under unfavourable conditions[4,5], termination of blooms[6] and initiation of future blooms[7–9].

In recent years, the incidence of HABs has increased in frequency and intensity worldwide[10,11]. This has adversely affected the ecosystems in coastal regions resulting in economic losses to fishing industries, threat to aquatic life, water quality and human health. Global factors, such as climatic changes, eutrophication and increased international shipping traffic are suspected to be the main contributory forces. India, being one of the major maritime countries is also susceptible to ship–mediated bioinvasion[12].

Although many quantitative and semi–quantitative studies on phytoplankton have been carried out in the coastal waters of India, most studies have focused on diatoms and less emphasis has been given to dinoflagellates. Inspite of their importance in understanding bloom dynamics, studies on dinoflagellate cysts are limited and restricted to few regions along the west coast of India[13–15]. Studies on dinoflagellate cysts will provide integrated information on vegetative dinoflagellates present in the water column but which may not be detected due to being rare, short–lived, fragile or difficult to identify[16]. Since they occur in sediment during the dormant part of their life cycle, the study of cysts is important in elucidating bloom dynamics. There has been extensive work carried out on dinoflagellate cysts in other parts of the world[17]. Present study consist the spatial distribution of dinoflagellate cysts

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in recent sediments from coastal and port stations along the west coast of India. It also consists of the information related to the potential HAB species to predict the potential risks of future blooms.

Materials and Methods

Sediment samples were collected at 26 coastal stations from Mumbai to Trivandrum during different cruises onboard CRV *Sagar Sukti* (SaSu 18, 89 and 125). Besides the coastal stations, samples were also collected from 3 ports: Mumbai, Mormugao and Kochi (Fig. 1, Table 1). Undisturbed sediment cores (PVC cores with 2.5 cm diameter and 20 cm length) were collected in triplicates through the top windows of a van Veen grab. Subsequently, the cores were sectioned at 2 cm intervals, mixed well and stored in airtight plastic bags in the dark at 4°C until further analysis.

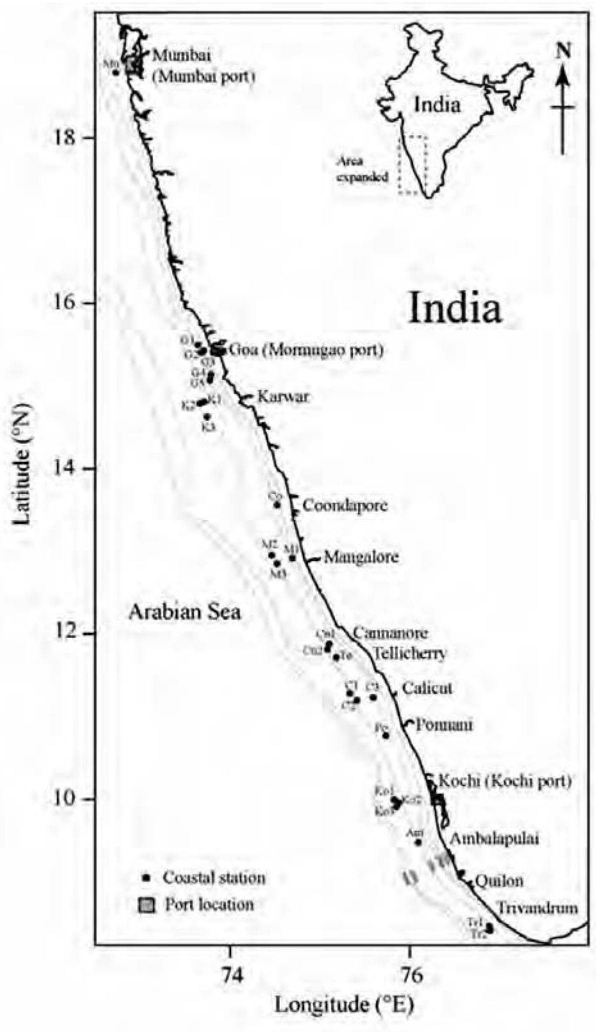

Fig. 1—Location map of sampling stations (26 coastal stations and 3 port areas) along the west coast of India.

For dinoflagellate cyst analysis, surface sediments (0–2 cm interval) were processed by the palynological method[18]. Each sediment sample (approx. 1gm) was weighed in a beaker and washed with distilled water to remove the salt content. Further the samples were acid–digested, sonicated and sieved through 100 and 10 µm mesh–sizes to remove coarse and fine materials. The residue retained on the 10 µm mesh was transferred into a vial and suspended in 10 mL distilled water. Aliquot of 0.5–1 mL of the processed sample was diluted with distilled water and observed under an Olympus BH–2 light microscope (LM) at 100, 200 and 400 times magnification. Subsequently, photomicrographs of dinoflagellate cysts were captured using an Olympus digital camera. Dinoflagellate cysts were identified based on published descriptions[13,18–25]. When species–level identification was not possible, identification was done at genus level. The cyst abundance is expressed as cysts g^{-1} dry sediment. The water content was calculated according to the formula given by Matsuoka and Fukuyo[18].

For Scanning Electron Microscopy (SEM), the cyst samples were collected on Nucleopore polycarbonate filters (3 µm), dehydrated in increasing concentrations of ethanol series and freeze–dried. The filter was mounted on stubs, sputter–coated with gold and observed with JEOL, JSM 5800 LV Scanning Electron microscope.

The percentage composition of sediment (sand, silt and clay) was determined by standard wet sieving and pipette analysis[26]. The size classification used is sand > 63 µm, silt 2–62 µm and clay < 2 µm.

Data analyses

Univariate measures [Shannon–Wiener's diversity index (*H′*) and Margalef's species richness (*d*)] were calculated. For multivariate analysis, the fourth root (√√)–transformed abundance data of coastal stations was used to construct a lower triangular similarity matrix using Bray–Curtis similarity coefficients[27]. The similarity matrix was then subjected to station and species clustering by group average method. These analyses were carried out using PRIMER software (version 5).

Spatial variation in dinoflagellate abundance, Shannon–Wiener's diversity index (*H′*), Margalef's species richness (*d*); and relative contribution of autotrophic, heterotrophic and potential HAB dinoflagellate cysts were presented using SURFER plots (SURFER 8 program). The relative contribution of cyst species are plotted using pollen diagrams (POLPAL 2004 program[28]). Linear regression analysis was performed on dinoflagellate cyst abundance (log–transformed) and sediment texture (arcsine–transformed) data.

Results

Overall, 47 cyst types representing 18 genera were recorded along the west coast of India (Table 2). The LM and SEM photomicrographs of some dinoflagellate cysts are provided in Fig. 2.

At the 26 coastal stations, a total of 37 cyst types representing 16 genera (Table 2) were observed. The highest cyst abundance (801 cysts g^{-1} dry sediment) was recorded at Mangalore (M1) and lowest abundance (6 cysts g^{-1} dry sediment) was observed at Trivandrum (Tr1) station (Fig. 3a). Further characterization of these identified cysts based on their mode of nutrition indicates the dominance of heterotrophic dinoflagellate at almost all the coastal stations. They contributed 29–100% to the total cyst assemblages (Fig. 4a) except for 3 stations where autotrophic forms dominated (Fig. 4b).

Considering the univariate measures, Shannon–Wiener diversity (H') was highest at Mangalore (M3) and lowest at Kochi (Ko3) (Fig. 3b) whereas margales`s species richness (d) was highest at Goa (G4) and lowest at Kochi (Ko3) (Fig. 3c).

The cluster analysis of coastal stations at 50% Bray–Curtis similarity revealed 3 groups and 5 dissimilar stations (Fig. 5). Group I comprised of 2 stations that supported low cyst abundance; cysts of *Gonyaulax scrippsae* dominated these stations.

Table 1—Details of station, position, sampling period, cruise number, water depth, temperature and salinity

Station name	Station code	Latitude (°N)	Longitude (°E)	Sampling period	Cruise no./Programme	Water depth (m)	Temperature (°C)	Salinity (psu)
Coastal								
Mumbai	Mu	18.79	72.72	November 2001	Globallast programme	14	28.80	35.60
Goa	G1	15.50	73.64	March 2005	SaSu 89	18	28.30	36.00
	G2	15.43	73.70	"	"	16	28.40	36.00
	G3	15.41	73.68	"	"	20	28.00	35.60
	G4	15.14	73.78	"	"	19	28.20	36.10
	G5	15.07	73.77	"	"	25	28.50	36.20
Karwar	K1	14.79	73.66	March 2002	SaSu 14	40	28.27	35.20
	K2	14.81	73.71	December 2006	SaSu 125	38	28.83	34.97
	K3	14.63	73.74	"	"	39	28.21	34.99
Coondapore	Co	13.57	74.52	March 2002	SaSu 14	16	28.75	35.12
Mangalore	M1	12.92	74.69	March 2002	SaSu 14	17	28.84	35.50
	M2	12.95	74.46	January 2007	SaSu 125	30	28.30	34.84
	M3	12.85	74.52	"	"	28	28.70	35.18
Cannanore	Cn1	11.88	75.10	January 2007	SaSu 125	28	28.60	34.86
	Cn2	11.81	75.08	"	"	30	27.89	34.76
Tellicherry	Te	11.72	75.18	March 2002	SaSu 14	28	29.09	34.98
Calicut	C1	11.23	75.59	March 2002	SaSu 14	22	29.10	35.50
	C2	11.28	75.33	January 2007	SaSu 125	31	28.79	35.37
	C3	11.20	75.41	"	"	29	28.76	35.11
Ponnani	Po	10.77	75.73	March 2002	SaSu 14	23	29.00	34.86
Kochi	Ko1	10.00	75.82	January 2007	SaSu 125	33	28.87	35.25
	Ko2	9.97	75.87	"	"	30	28.91	35.11
	Ko3	9.92	75.85	"	"	31	28.88	35.16
Ambalapulai	Am	9.48	76.09	"	SaSu 125	31	28.58	35.02
Trivandrum	Tr1	8.47	76.88	"	"	33	27.90	34.35
	Tr2	8.42	76.89	"	"	34	27.73	34.38
Port								
Mumbai	–	18.9	72.66	November 2001, May 2002 & October–November 2002	Globallast programme	3 to 18	–	–
Mormugao	–	15.4	73.78	May & December 2005, September 2006 & 2007	Ballast programme	3 to 15	–	–
Kochi	–	9.97	73.25	March 2002	SaSu 14	2 to 12	–	–

Table 2—List of dinoflagellate cysts recorded in recent sediments along the west coast of India

Biological name	Paleontological name	Species code
Autotrophic		
Alexandrium affine (Inoue *et* Fukuyo) Balech*	–	Ale.aff
Alexandrium minutum Halim*	–	Ale.min
Alexandrium tamarense (Lebour) Balech*	–	Ale.tam
Alexandrium spp.	–	Ale.sp
Cochlodinium cf. *polykrikoides* Margalef*	–	Coc.cf.poly
Cochlodinium sp.	–	Coc.sp
Gonyaulax digitalis (Pouchet) Kofoid	*Spiniferites bentori* (Rossignol) Wall *et* Dale	Gon.dig
Gonyaulax scrippsae Kofoid	*Spiniferites bulloideus* (Deflandre *et* Cookson) Sarjeant	Gon.scri
Gonyaulax spinifera (Claparède *et* Lachmann) Diesing complex*	*Spiniferites membranaceus* (Rossingnol) Sarjeant, *Spiniferites ramosus (*Rossingnol) Sarjeant, *Spiniferites mirabilis*(Ehrenberg) Mantell	Gon.spi
Gonyaulax spp.	–	Gon.sp
Gymnodinium cf. *catenatum* Graham*	–	Gym.cf.cat
Gyrodinium impudicum Fraga *et* Bravo	–	Gyr.imp
Lingulodinium polyedrum (Stein) Dodge*	*Lingulodinium machaerophorum* (Deflandre *et* Cookson) Wall	Lin.poly
Pentapharsodinium dalei Indelicato *et* Loeblich III	–	Pen.dal
Phaeopolykrikos hartmannii (Zimmermann) Matsuoka *et* Fukuyo	–	Phae.har
Protoceratium reticulatum (Claparède *et* Lachmann) Bütschli*	*Operculodinium centrocarpum* Deflandre *et* Cookson	Pro.ret
Pyrodinium bahamense var. *compressum* (Böhm) Steidinger*	*Polysphaeridium zoharyi* Wall	Pyro.bah
Pyrophacus steinii (Schiller) Wall *et* Dale	*Tuberculodinium vancampoae* Rossignol	Pyr.ste
Pyrophacus sp.	*Tuberculodinium rossignolae* Drugg	Pyro.sp
Scrippsiella trifida Lewis *et* Head	–	Scr.tri
Scrippsiella trochoidea (Stein) Loeblich III*		Scr.tro
Scrippsiella spp.	–	Scr.sp
Heterotrophic		Dip.par
Diplopelta parva (Abé) Matsuoka	–	
Diplopsalis lenticula Bergh	–	Dipl.len
Lebouraia minuta Abé	–	Leb.min
Polykrikos kofoidii Chatton	–	Poly.koi
Polykrikos schwartzii Bütschli	–	Poly.sch
Polykrikos sp.		Poly.sp
Protoperidinium claudicans (Paulsen) Balech	*Votadinium spinosum* Reid	Prot.cla
Protoperidinium compressum (Abé) Balech	*Stelladinium stellatum* (Wall *et* Dale) Reid	Prot.com
Protoperidinium conicoides (Paulsen) Balech	*Brigantedinium simplex* (Wall) Reid	Prot.co
Protoperidinium conicum (Gran) Balech	*Selenopemphix quanta* (Bradford) Matsuoka	Prot.con
Protoperidinium denticulatum (Gran *et* Braarud) Balech	*Brigantedinium irregulare* Matsuoka	Prot.den
Protoperidinium divaricatum (Meunier) Balech	*Xandarodinium variable* Bujak	Prot.div
Protoperidinium latissimum (Kofoid) Balech	–	Prot.lat
Protoperidinium leonis (Pavillard) Balech	*Quinquecuspis concreta* (Reid) Harland	Prot.leo
Protoperidinium oblongum (Aurivillius) Balech	*Votadinium calvum* Reid	Prot.obl
Protoperidinium pentagonum (Gran) Balech	*Trinovantedinium applanatum*(Braford) Bujak *et* Davies	Prot.pen
Protoperidinium cf. *pentagonum* Gran	*Trinovantedinium capitatum* Reid	Prot.cf.pen
Protoperidinium subinerme (Paulsen) Loeblich III	*Selenopemphix nephroides* Benedeck	Prot.sub
Protoperidinium sp.1	*Stelladinium robustum* Zonneveld	Prot.sp1
Protoperidinium sp.2	*Trinovantedinium palidifluvum* Matsuoka	Prot.sp2
Protoperidinium sp.3	–	Prot.sp3
Protoperidinium sp.4	–	Prot.sp4
Protoperidinium sp.5	*Lejeunecysta* sp1	Prot.sp5
Protoperidinium spp.	–	Prot.spp
Zygabikodinium lenticulatum (Paulsen) Pavillard	*Dubridinium caperatum* Reid	Zyg.len

*potential HAB species

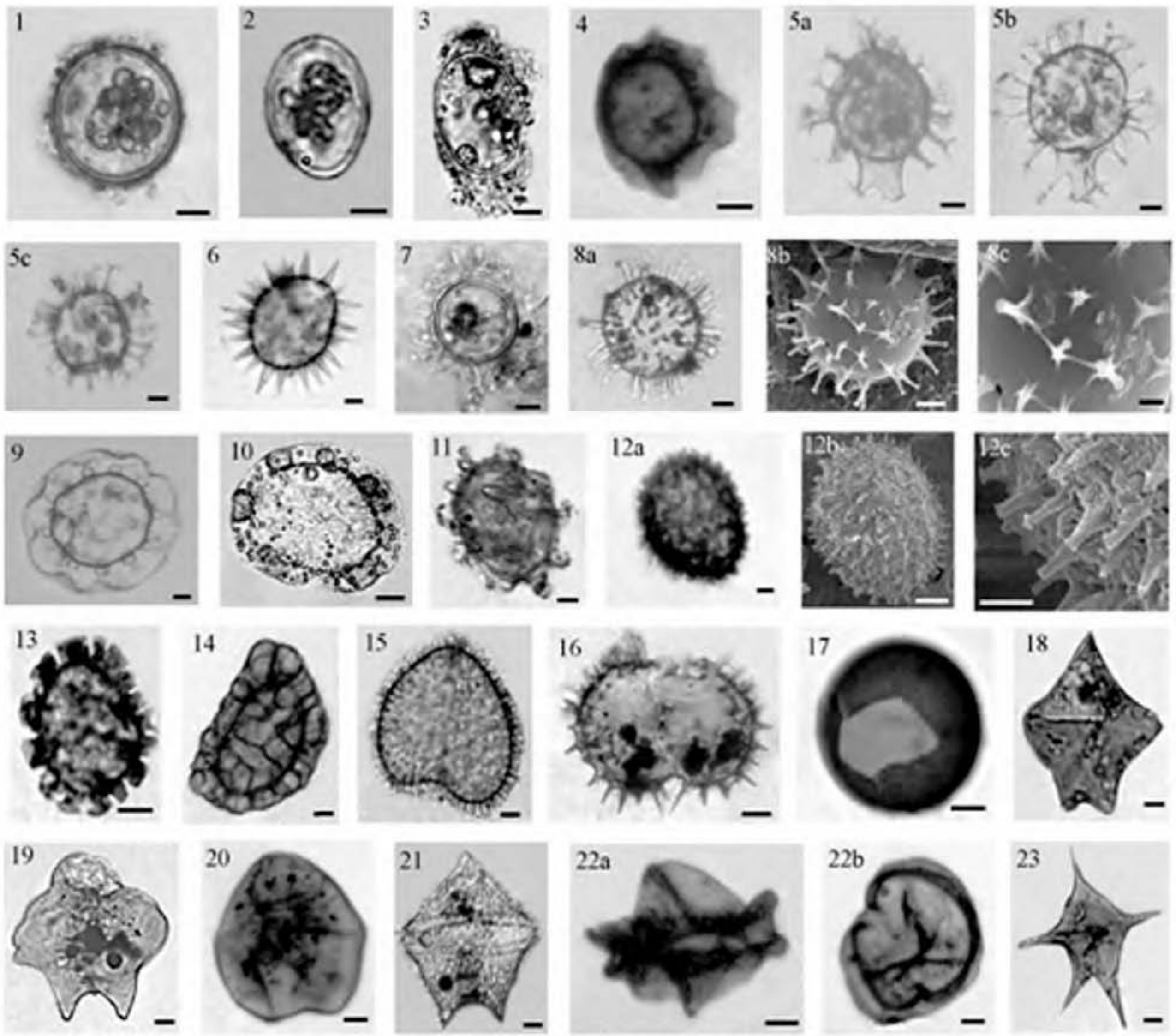

Fig. 2—Photomicrographs of dinoflagellate cyst types recorded in recent sediments along the west coast of India. (1) *Alexandrium affine*. (2) *Alexandrium minutum*. (3) *Alexandrium tamarense*. (4) *Cochlodinium* cf. *polykrikoides*. (5a–c) *Gonyaulax spinifera* complex – (5a) *Spiniferites membranaceus*. (5b) *Spiniferites mirabilis* and (5c) *Spiniferites ramosus*. (6) *Lingulodinium polyedrum*. (7) *Pentapharsodinium dalei*. (8a–c) *Protoceratium reticulatum*. (8a) LM. Cyst showing slender capitate processes (8b) SEM. Cysts showing slender capitate processes and (8c) SEM. Details of capitates processes. (9) *Pyrophacus steinii*. (10) *Pyrophacus* sp. (11) *Scrippsiella trifida*. (12a–b) *Scrippsiella trochoidea* – (12a) LM. Cyst showing calcareous processes. (12b) SEM. Cyst showing calcareous processes and (12c) SEM. Details of the processes. (13) *Polykrikos kofoidii*. (14) *Polykrikos schwartzii*. (15) *Protoperidinium claudicans*. (16) *Protoperidinium conicum.* (17) *Protoperidinium denticulatum*. (18) *Protoperidinium latissimum*. (19) *Protoperidinium leonis*. (20) *Protoperidinium oblongum*. (21) *Protoperidinium* cf. *pentagonum*. (22a–b) *Protoperidinium subinerme*: (22a) lateral and (22b) apical view. (23) *Protoperidinium* sp1. (24) *Protoperidinium* sp3. (25) *Protoperidinium* sp4. (26a–b) *Protoperidinium* sp5 – (26a) lateral view and (26b) apical view. (27a–b) *Zygabikodinium lenticulatum* – (27a) lateral view and (27b) apical view. All scale bars are 10µm.

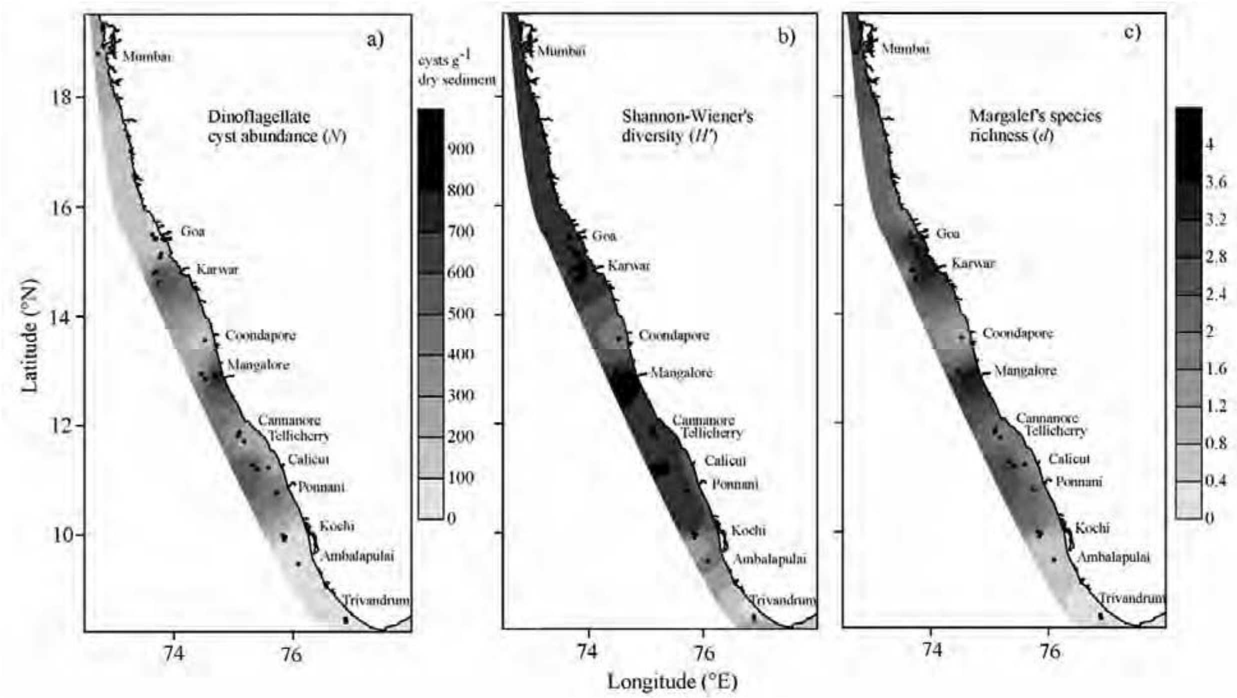

Fig. 3—Spatial variation of (a) dinoflagellate cyst abundance, (b) Shannon–Weiner's diversity and (c) Margalef's species richness in recent sediments at 26 coastal stations along the west coast of India.

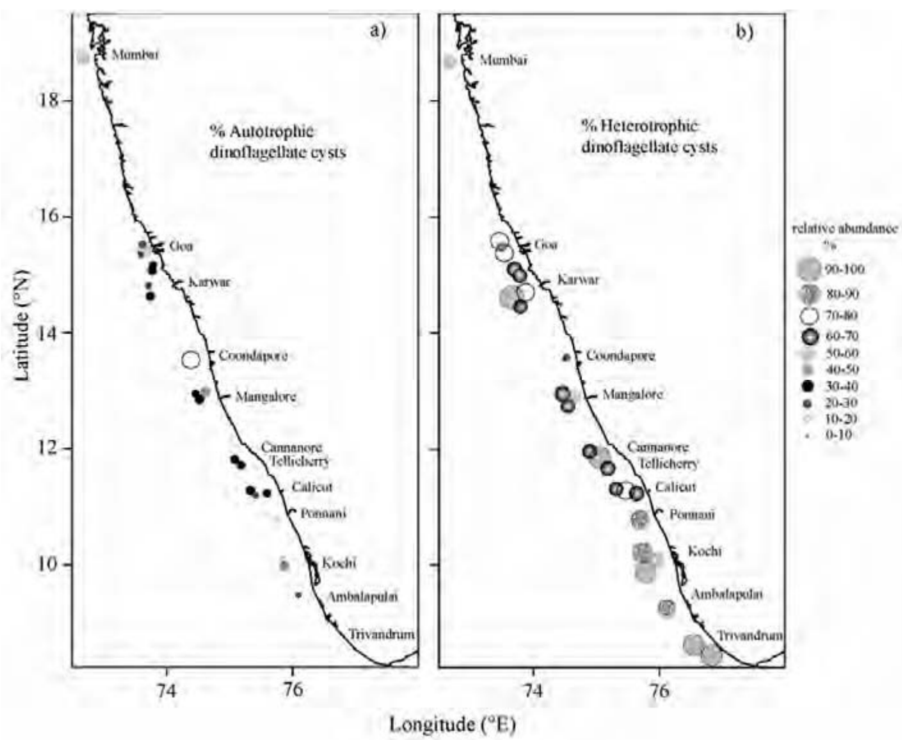

Fig. 4—Relative contribution (%) of (a) autotrophic and (b) heterotrophic dinoflagellates to the total cyst assemblages in recent sediments at 26 coastal stations along the west coast of India.

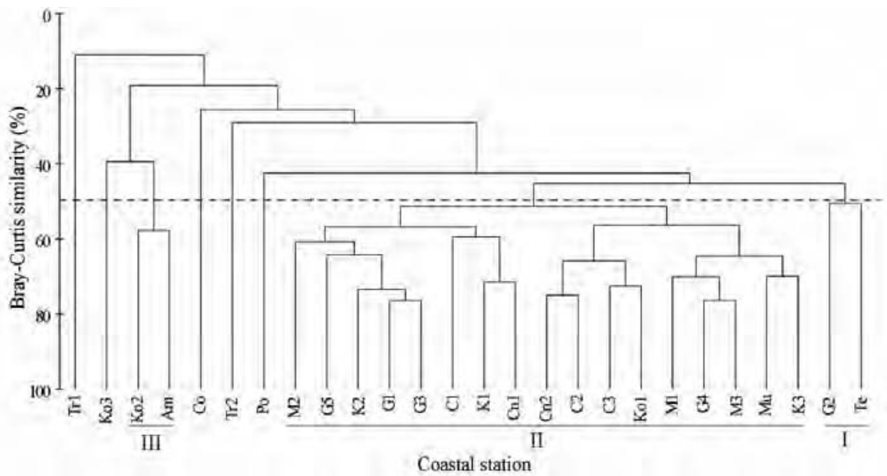

Fig. 5—Cluster dendrogram of coastal stations based on dinoflagellate cyst abundance using Bray–Curtis similarity coefficient and group average method; grouping done at 50% similarity (------). The station codes are provided in Table 1.

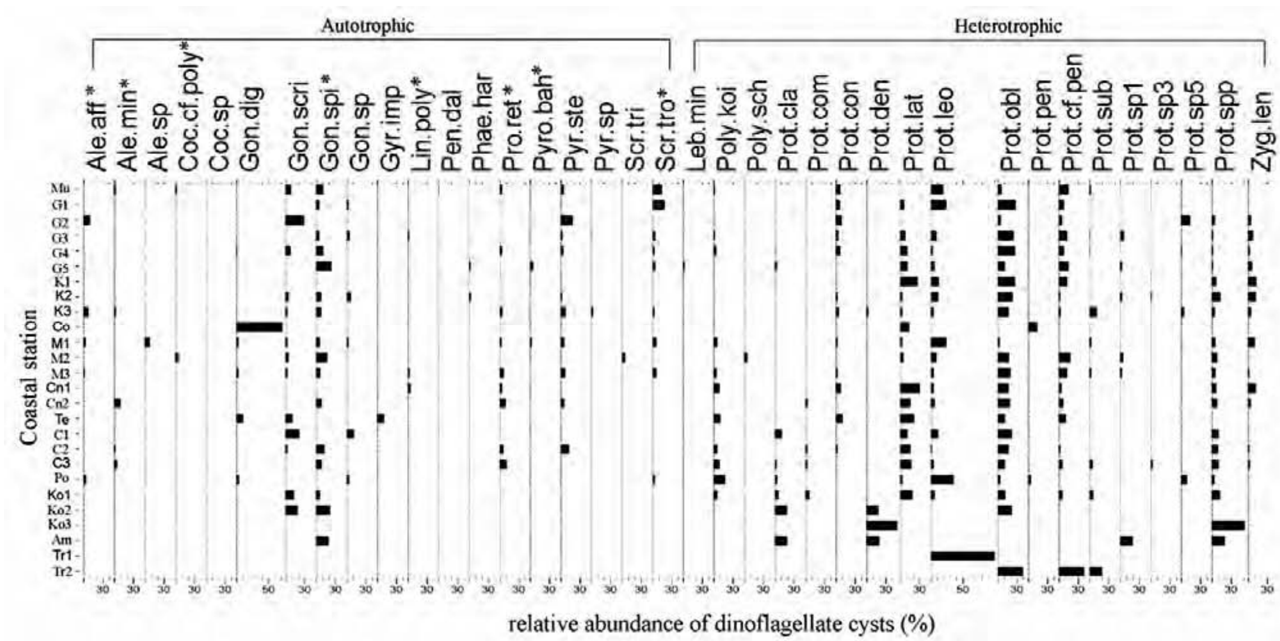

Fig. 6—Species composition of autotrophic and heterotrophic dinoflagellate cysts in recent sediments at 26 coastal stations along the west coast of india. The species codes are provided in Table 2 and potential HAB species are marked*.

Group II consisted of 17 stations with moderate to high cyst abundance and were dominated by cysts of *Protoperidinium oblongum*. Group III comprised of 2 stations with low cyst abundance and were dominated by cysts of *Gonyaulax spinifera* and *Protoperidinium denticulatum*. Ponnani station, supporting moderate cyst abundance (497 cysts g^{-1} dry sediment) did not cluster together with the other groups. This station was dominated by cysts of *Protoperidinium leonis* and *Polykrikos kofoidii*.

The species composition of dinoflagellate cysts has been presented as pollen diagrams for the 26 coastal stations (Fig. 6). The most frequently occurring and dominant dinoflagellate cysts were *G. spinifera*, *P. latissimum*, *P. leonis*, *P. oblongum*, *P.* cf. *pentagonum, Protoperidinium* spp and *Zygabikodinium lenticulatum*. Cluster analysis of the species was performed to segregate the species based on their contribution to total cyst assemblages (Table 3). At 50% Bray–Curtis similarity level,

Table 3—Abundance of dinoflagellate cyst species (cysts g^{-1} dry sediment) recorded in recent sediments at 26 coastal stations along the west coast of India

Species code	Cyst abundance (cysts g^{-1} dry sediment) Coastal station																								
	Mu	G1	G2	G3	G4	G5	K1	K2	K3	Co	M1	M2	M3	Cn1	Cn2	Te	C1	C2	C3	Po	Ko1	Ko2	Ko3	Am	Tr1	Tr2
Autotrophic																										
Ale.aff*			2						47		22		8							22						
Ale.min*	8								16						33			16	24							
Ale.tam*																										
Ale.sp											67															
Coc.cf.poly*	4											13														
Coc.sp					1																					
Gon.dig					3					90	22		17			15				22						
Gon.scri	23		6		15			31	16		22	13	16			15	44	21			19	6				
Gon.spi*	27	5		7	22	36		50	47		45	53	33		31			83	44		10	8		7		
Gon.sp		3		7	1			42			22						22			22						
Gym.cf.cat*																										
Gyr.imp																15										
Lin.poly*				3									17	10												
Pen.dal	4																									
Phae.har						4		17																		
Pro.ret*	11				9				31		22		32	10	34			42	59							
Pyro.bah*						9					22															
Pyr.ste	12		4	4	7	1		14	47		45		33		21			83								
Pyro.sp				1					16																	
Scr.tri												13														
Scr.tro*	40	20		6	6	9			16		45		31							22						
Heterotrophic																										
Dip.par																										
Dipl.len																										
Leb.min						4																				
Poly.koi	4			3	9						45		24	26		15		42	44	86	9					
Poly.sch					1	1						13														
Poly.sp																										
Prot.cla					2	6											22		15	22	10	6		7		
Prot.com															12			21	15		10					
Prot.co																										
Prot.con	19	6	2	5	14	1		17	31		22		16	24		15		21								
Prot.den									16													6	6	7		
Prot.div																										
Prot.lat		6		10	23	20	75	28	16	18	22	13		89	54	29	22	104	92	22	28					
Prot.leo	49	25		12	5	10	37	78	31		200	26	25	13	21		22	16	27	173	10				6	
Prot.obl	15	28	1	32	52	18	75	150	109		22	53	97	47	64	15	44	109	59	22	19	8				14
Prot.pen										18										22						
Prot.cf.pen	37	8	1	17	17	23	37	14	16			53	64	10	22	15		16	29		10					14
Prot.sub	4			1	2				78		22		17						27		9					7
Prot.sp1				8		4		17				13	16											7		
Prot.sp2																										
Prot.sp3								14											15							
Prot.sp4																										
Prot.sp5			3		3				31											43						
Prot.spp			1	3	4	4	19	89	31		45	26	31	21	31		22	63	56	22	19		7	7		
Zyg.len			1	10	6	9	38	75	31		89		8	34	12			16	15							

*potential HAB species

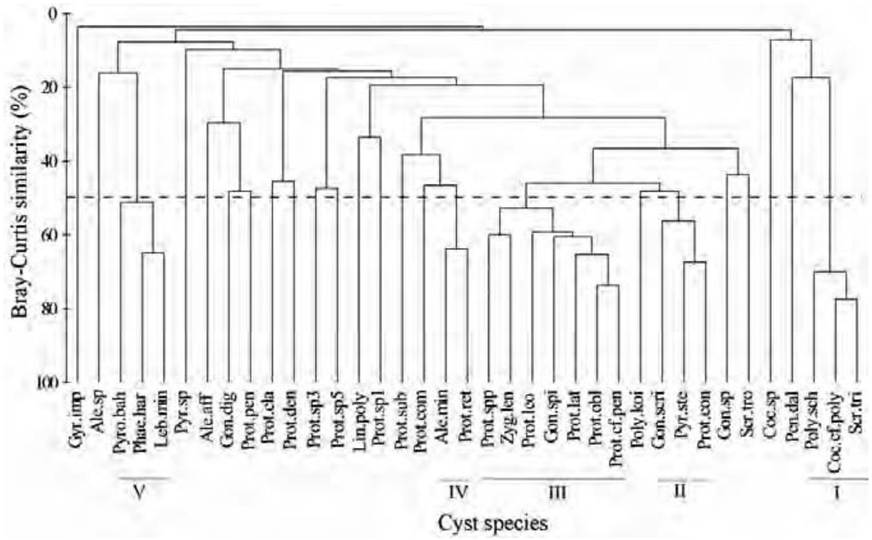

Fig. 7—Cluster dendrogram of species using Bray–Curtis similarity coefficient and group average method; grouping done at 50% similarity (------). The species codes are provided in Table 2.

Table 4—Range of abundance of dinoflagellate cyst species (cysts g^{-1} dry sediment), total number of stations sampled in each port, total cyst abundance, total number of species, Shannon Wiener's diversity index (H') and Margalef's species richness (d) of cysts recorded in recent sediments of Mumbai, Mormugao and Kochi ports along the west coast of India.

Cyst type	Port			Cyst type	Port		
	Mumbai	Mormugao	Kochi		Mumbai	Mormugao	Kochi
Autotrophic				*Polykrikos kofoidii*	1–7	1–16	22–74
*Alexandrium affine**	0–2	0–2	22–57	*Polykrikos schwartzii*	1–4	0–10	27–148
*Alexandrium minutum**	0–2	1–8	22–80	*Polykrikos* sp.		0–9	
*Alexandrium tamarense**	0–3		26–37	*Protoperidinium claudicans*	1–4	3–14	28–30
Alexandrium spp.			0–27	*Protoperidinium compressum*	1–8	3–9	0–43
Cochlodinium cf. *polykrikoides**		1–9		*Protoperidinium conicoides*	2–10		
Cochlodinium sp.		0–10		*Protoperidinium conicum*	1–39	3–33	18–82
Gonyaulax digitalis	1–11	0–1	27–74	*Protoperidinium denticulatum*		0–8	
Gonyaulax scrippsae	1–45	1–29	22–287	*Protoperidinium divaricatum*	2–4	0–9	
Gonyaulax spinifera complex*	2–72	1–28	18–148	*Protoperidinium latissimum*	1–15	2–44	22–85
Gonyaulax spp.		1–10	25–107	*Protoperidinium leonis*	2–36	1–47	22–241
Gymnodinium cf. *catenatum*	0–2			*Protoperidinium oblongum*	2–49	2–45	18–108
Gyrodinium impudicum		0–8		*Protoperidinium pentagonum*	2–59		26–28
*Lingulodinium polyedrum**	0–22	0–10	25–44	*Protoperidinium cf. pentagonum*	1–37	1–48	26–103
Pentapharsodinium dalei	1–8	7–9	22–40	*Protoperidinium subinerme*	1–10	0–37	26–60
Phaeopolykrikos hartmannii	0–4	1–8		*Protoperidinium* sp.1	2–4	0–8	0–28
*Protoceratium reticulatum**	1–25	0–1	18–120	*Protoperidinium* sp.2	0–2		
Pyrodinium bahamense var. compressum*	2–4			*Protoperidinium* sp.3			
Pyrophacus steinii	1–29	1–17	0–18	*Protoperidinium* sp.4		0–4	
Pyrophacus sp.		0–16		*Protoperidinium* sp.5		5–21	22–37
Scrippsiella trifida				*Protoperidinium* spp.		4–53	22–80
*Scrippsiella trochoidea**	1–19	0–64	0–28	*Zygabikodinium lenticulatum*	1–6	5–51	22–111
Scrippsiella spp.		0–1		Total number of stations sampled	22	17	21
Heterotrophic				Total cyst abundance (cysts g^{-1} dry sediment)	35–262	0–280	214–1076
Diplopelta parva		0–12		Total number of species (N)	32	35	29
Diplopsalis lenticula	0–2			Shannon–Wiener's diversity index (H')	1–2.60	0.50–2.51	1.55–2.47
Lebouraia minuta	1–34		27–50	Margalef's species richness (d)	0.41–3.64	0.30–4.75	0–2.78

* potential HAB species

5 groups were defined (Fig. 7). One of these groups, Group III consisted of the frequently occurring and dominant species of dinoflagellate cysts (Fig. 7). 19 species were dissimilar at 50% Bray–Curtis similarity; some of these were reported on less than 5 occasions and were considered rare species.

Apart from the coastal stations, the cyst assemblages were studied at 3 port locations situated along the west coast of India. At the ports, 44 cyst types representing 18 genera were recorded (Table 4). Compared to the coastal stations, 9 additional cysts types such as *Alexandrium tamarense*, *Gymnodinium* cf. *catenatum*, *Diplopelta parva*, *Diplopsalis lenticula*, *Polykrikos* sp., *Protoperidinium conicoides*, *Protoperidinium divaricatum*, *Protoperidinium* sp.2 and *Protoperidinium* sp.4 were recorded in port areas. The maximum dinoflagellate cyst abundance (314–1076 cysts g^{-1} dry sediment) was observed at Kochi port followed by Mumbai port (Table 4).

The cyst assemblages were further looked into from the HAB perspective. Among of the 47 identified cyst types, 10 potential HAB species were revealed (marked with * in Table 1). Among the coastal stations, the maximum abundance of HAB species was observed at Mumbai station (Mu) and minimum abundance at Kochi station (Ko3) (Fig. 8). Considering the port stations, Mumbai port recorded the maximum number (9 cyst types) of potential HAB species (Table 4). *Gonyaulax spinifera* was the most frequently occurring potential HAB species at most stations (Fig. 6, Table 4) whereas *Alexandrium tamarense* and *Gymnodinium* cf. *catenatum* were recorded only on one occasion in Mumbai port (Table 4).

Discussion

This study provides an overview of distribution of dinoflagellate cysts in recent sediments along the west coast of India. Previous cyst studies in this region were restricted to 3 locations i.e. Mumbai port[15] and coastal station in Zuari river–Goa[14] and Mangalore[13]. In addition to earlier locations, the present study involves 9 more locations from Karwar to Trivandrum (Fig. 1). The dinoflagellate cyst abundance (max. 1076 cysts g^{-1} dry sediment) recorded in the present study was higher than that reported by previous studies along the west coast of India. In comparison to previous studies, *Scrippsiella trifida*, *Protoperidinium denticulatum*, *Protoperidinium* sp.3, *Protoperidinium* sp.4 and P*rotoperidinium* sp.5 are the additional species reported in this study.

Variation in abundance and diversity of cyst along these coastal stations indicates region–specific distribution. These variations can be attributed to the sediment texture of the coastal stations. The high abundance of dinoflagellate cysts at Mangalore, Karwar and Calicut stations coincides with silt content whereas the low cyst abundance from Kochi to Trivandrum can be attributed to sandy sediment texture (84–85%) (Fig. 9a). The regression analysis between cyst abundance and sediment texture indicates a positive correlation with silt whereas sand showed a negative correlation (Fig. 9b). Dinoflagellate cysts are in the same size range as silt particles i.e. <63 μm, and therefore cysts settle out within the silt fraction. Hence, finer–grained sediment provides richer cyst assemblages than coarser–grained sediment[29,30]. The coastal stations situated along the west coast of India, characterized by silt content

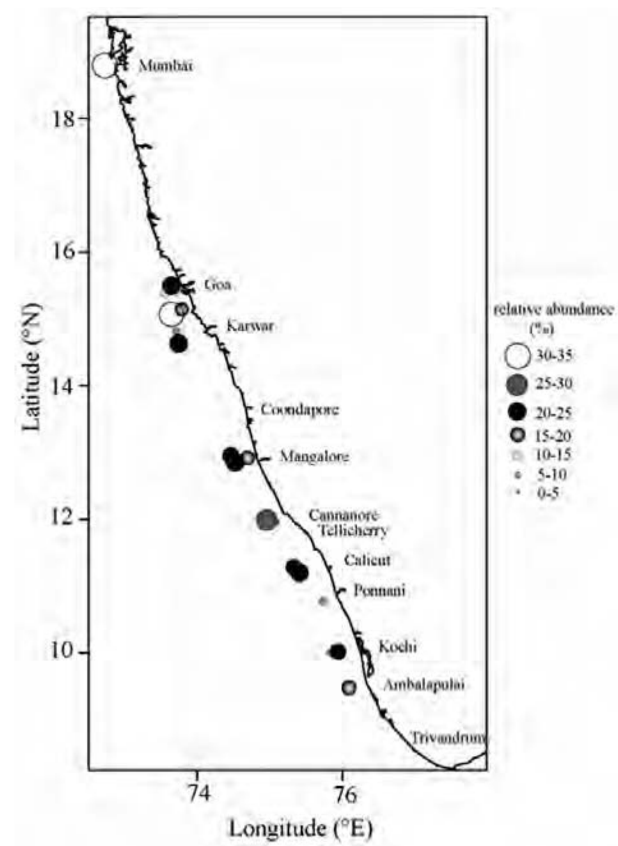

Fig. 8—Relative contribution of potential Harmful Algal bloom (HAB) dinoflagellate cysts in recent sediments at 26 coastal stations along the west coast of India.

supported higher abundance and diversity of cyst species whereas the sandy stations recorded low abundance and diversity of cysts. This observation shows that sediment characteristics of the region play an important role in settlement of dinoflagellate cysts along the inner continental shelf of the west coast of India.

Dominance of heterotrophic dinoflagellate cysts was mainly due to *Protoperidinium* species (Fig. 6). It is well known that cyst assemblages from major coastal upwelling systems (North–West Africa, the Angola/Benguela, South–West Africa, Chile, Peru and southern California) are dominated by heterotrophic *Protoperidinium* species[17,31]. Matsuoka[32] suggested that increasing diatom production was the main reason for increase in heterotrophic dinoflagellates, whereas Dale[3] reported that reduction in light intensity can lead to an increase in heterotrophic forms. Dominance of different heterotrophic taxa reflects different nutrient enrichment levels based on their specific modes of feeding and preferences for prey[33]. Naturally occurring seasonal enrichment in nutrients has been reported in many parts of the world including the west coast of India where upwelling during the South–West monsoon (SWM) results in high nutrient conditions triggering high primary production[34,35]. It is also observed that the coastal stations are mainly dominated by diatom populations[36–40] that may serve as prey organisms for *Protoperdinium* species. These features of the study area such as upwelling, monsoon and prey availability justify the dominance of heterotrophic cyst forms and their abundance in these coastal waters.

The cyst abundance in port areas was found to be high compared to the coastal stations. The higher abundance coincided with increased silt content of sediment and dominance of heterotrophic forms. As discussed above, the dominance of heterotrophic forms indicates the availability of prey organisms, and nutrient–enriched conditions[41]. Port areas are known to be influenced by anthropogenic pressures that may lead to eutrophic conditions. The port environments of Kochi and Mumbai have been classified as eutrophic[42,43] and mesotrophic[44] respectively. Hence, the dominance of *Protoperidinium* species in these port areas can be considered as a resultant effect of elevated nutrient conditions. Since the Mormugao port situated at the mouth of the Zuari estuary, the predominance of heterotrophic forms in this port can most probably be attributed to the availability of prey organisms. Therefore the distribution of cysts in port environments can be influenced by environmental settings, sediment characteristics and anthropogenic pressures.

Overall, cysts of 10 potential HAB species were recorded in the study area, indicating a potential risk for outbreaks or harmful events associated with these in the future. Previous reports on Paralytic Shellfish Poisoning (PSP) outbreaks have been recorded from Mangalore and Kerala coasts[45–47]. Of the 10 identified HAB species, there are 5 potential Paralytic Shellfish Poisoning (PSP) forms (*Alexandrium affine*, *A. minutum*, *A. tamarense*, *Gymnodinium* cf. *catenatum* and *Pyrodinium bahamense* var. *compressum*) recorded in recent sediments from coastal and port locations. In addition to PSP–producers, yessotoxin–producers such as *Lingulodinium polyedrum*, *Protoceratium reticulatum* and *Gonyaulax spinifera* were also recorded in the study area. Although these potential HAB species are present in the sediment, no known blooms or harmful events associated with these species have been observed along the west coast of India till date. However, the study area is also influenced by the SWM and upwelling. The potential of the SWM to influence the dinoflagellate community and shifts in dominance has already been observed in Mumbai port[15]. Upwelling results in increased productivity in coastal waters[48], usually dominated by diatoms along the west coast of India[36–40]. However, a change in nutrient ratios can alter the population from diatom– to flagellate–dominated algal assemblages[49]. Such alteration in nutrient ratios is usually related to eutrophic environments[50]. In view of these factors, the presence of potential HAB species in sediments along the west coast of India is a matter of concern. Therefore regular monitoring of dinoflagellate assemblages in this region is needed.

Conclusions

The west coast of India harbors a wide diversity of cysts and presence of potential HAB species. Some of the potential HAB species that cause PSP outbreaks were recorded in the study area. Further studies on dinoflagellate cysts and vegetative cells will provide useful insights in dinoflagellate biology and ecology. Investigations to delineate the influence of environmental factors responsible for excystment–encystment patterns of dinoflagellate cysts will be useful to understand the bloom dynamics in such tropical environments influenced by monsoon.

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