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RESEARCH PAPER

A comprehensive enumeration of seaweed species diversity from Gulf of Kutch Marine National Park, India: suggestions for sustainable management and conservation

Parth J. Depani[1] · Satej Bhushan[1] · Shivang Acharya[1] · Vaibhav A. Mantri[1,2]

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Abstract
A marine renewable resource, seaweed, is gaining considerable attention due to its multifarious applications. About 865 species from 234 genera have been reported till date from Indian waters; the Gulf of Kutch (GoK) is a Marine Protected Area (MPA) that harbors considerable seaweed diversity. The sporadic publications have recorded floristic accounts, but the most comprehensive enumeration of seaweed is still lacking. Based on the literature, we attempted to provide (i) systematic enumeration documenting seaweeds of GoK Marine National Park (GoKMNP); and (ii) diversity data analysis (Simpson's index of diversity, Shannon Wiener (Shannon Weaver) diversity index, Species Richness, and Species Evenness). The seaweed diversity of GoKMNP when compared with island systems in India viz. Gulf of Mannar (GoM), Andaman, and Nicobar Islands; and from Indian Ocean island systems viz. Rodrigues, Mauritius and Sri Lanka; long with main-land-coast of Gujarat revealed specific differences. A total of 220 seaweed species with 9 varieties and a form were enumerated from GoKMNP. Simpson's index was 0.65; Shannon Weiner index was 1.07; Species Richness was 5.39 and Species Evenness was 0.20. The region holds considerable potential for sustainable management and conservation, for which we provided comprehensive recommendations.

Keywords Conservation · Diversity indices · Gulf of Kutch · Seaweeds diversity · Sustainable management

Introduction

The concept of Marine Protected Areas (MPAs) is widely established, as the conservation of natural resources becomes a growing global priority. In India, there are twenty-five MPAs in the peninsular region and 130 MPAs in the Islands, declared under the wildlife protection act which includes both marine national parks and sanctuaries (Tiwary and Bajaj 2021). Although mangroves, sponges, and corals have been investigated to some extent, other important taxonomic groups such as benthic marine algae, seagrasses, etc. have not been given due consideration (Wafar et al. 2011). Gulf of Kutch Marine National Park (GoKMNP) has been demarcated along the southern coast of gulf, spreading over 400 sq. km, in 1982. This area falls in a bio-geographical zone 'Western coast' of the Indo-Malayan Realm which is classified under IUCN Protected Area Category II (Singh 1997). The marine ecosystem in this area is extremely productive due to the geomorphologic and climatic distinction. The gulf harbors unique biodiversity of marine organisms with a high degree of endemism (Venkataraman and Wafar 2005). About forty-two un-inhabited coral islands, located near or sometimes quite far from the peninsula are protected to conserve their rich and unique marine life.

The phycological collection efforts in the GoKMNP are relatively sporadic. Historically, the distribution and diversity of benthic marine algae of the northern west coast of the Arabian Sea has been studied by Børgesen during his synoptical survey of the Indian coast (Børgesen 1933). The subsequent studies are mostly confined to the adjacent main-land-coast of Gujarat and near-shore islands, leaving interior ones inadequately explored (Murthy et al. 1978; Thivy and Sharma 1966; Krishnamurthy and Baluswami 1984;

✉ Vaibhav A. Mantri
vaibhav@csmcri.res.in

[1] Applied Phycology and Biotechnology Division, CSIR-Central Salt & Marine Chemicals Research Institute, Gijubhai Badheka Marg, Bhavnagar 364002, India

[2] Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

Mantri et al. 2003; Mantri 2004). The records such as *Ulva beytensis*, *Boodlea composita* f. *robusta*, *Willeella ordinata*, *Codium dwarkense*, *Turbinaria indica*, *Porphyra indica*, *P. okhaensis*, *Helminthocladia calvadosii* f. *indica*, *Grateloupia indica*, *Predaea feldmannii* var. *indica*, *Myriogramme okhaensis*, *Polysiphonia kappannae*, *P. parthasarathyi* and *Spirocladia barodensis* essentially represent new algae taxa described over past half century from several localities along the GoKMNP. The recent studies carried out by researchers are mainly on floristic enumeration. Despite of apparently high potential for new discoveries due to the vastness of the geographic area coupled with the diversity of habitats, marine algal flora of GoKMNP remained under-documented.

This communication deals with comprehensive compiling of existing floristic and seaweed biodiversity records made available from the scientific literature. Further, we have evaluated similarities and differences of seaweed flora of GoKMNP with other island systems of Indian waters, namely Gulf of Mannar (GoM) and Andaman and Nicobar Islands; from Indian Ocean island systems, namely Rodrigues, Mauritius and Sri Lanka as well as main-land-coast of Gujarat. The recommendations for sustainable management and conservation of seaweeds in GoKMNP were also provided.

Materials and methods

As stated before, the aim of the present study was to attempt comprehensive compiling of floristic and seaweed biodiversity records of GoKMNP. We have used "Checklist" approach based on secondary data. The seaweed species diversity for islands of GoKMNP (Latitudes 22° 15 N to 23° 40 N and Longitudes 68° 20 E to 70° 40 E) was collected from the following publications: (Kamboj et al. 2017; Anonymous 2012; Nair 2002; Dodia and Joshi 2012) (Supplementary Table 1). The valid and currently accepted scientific names were confirmed as per the entries in AlgaeBase (Guiry and Guiry 2022). The seaweed enumerated were classified into three group's viz. Chlorophyta, Phaeophyta, and Rhodophyta. The various diversity indices were calculated based on the available references e.g. Simpson's index value ranges between 0 and 1 (the higher value denoted higher diversity) (Simpson 1949); Shannon Wiener index (the higher value denoted higher diversity) (Shannon and Weaver 1949); Species Richness and Species Evenness (Baleta and Nalleb 2016; Mitbavkar and Anil 2002). The reports available for our scruitny were carried out by different sampling strategies, different seasons and different locations and area etc., thus conventional analysis of diversity indices was not possible. Neverthels,, to get the more meaningful anlaysis we have considered three groups namely Chlorophyta, Phaeophyta, and Rhodophyta. Thus the diversity indices were employed among these groups. The rationale to use the Simpson index was to know the evenness of the recorded biodiversity besides the dominant cover types; while the rationale to use Shannon index was to understand the richness of the recorded biodiversity besides rare cover types. The comparative analysis of seaweed diversity of GoKMNP was made with seaweed diversity reported in the literature for different regions namely, the main-land-coast of Gujarat (Latitudes 20° 1 to 24° 7 N and Longitudes 68° 4 to 74° 4 E) (Jha et al. 2009), GoM (Latitudes 8° 35 N to 9° 25 N and Longitudes 78° 08 E to 79° 30 E) (Veeragurunathan et al. 2022) and Andaman and Nicobar Islands (Latitudes 6° N to 14° N and Longitudes 92° E to 94° E) (Karthick et al. 2021). In addition to that, comparison was also drawn between GoKMNP versus Rodrigues, Mauritius (Latitudes 19° 40 N to 19° 48 N and Longitudes 63° 20 E to 63° 30 E) (Schils et al. 2004) and Sri Lanka (Latitudes 5° 55 N to 9° 51 N and Longitudes 79° 41 E and 81° 53 E) (Coppejans et al. 2009). The analysis provided over all species diversity of seaweeds at GoKMNP, while the phylum-wise distribution of seaweeds from all the regions was also provided for better understating of major hierarchical taxonomic ranks. The color coding was used in the tabulated data to significantly enhance the understanding of trends, patterns of seaweed biodiversity in GoKMNP and other locations at a glance.

Results

A total of 220 seaweed species with 9 varieties and a form were recorded from GoKMNP (Table 1). They belong to 95 genera of 42 families and 21 orders (Table 2a). The class-wise species distribution was found to be Chlorophyta 67, Phaeophyta 55, and Rhodophyta 98. Total of 192 seaweed species with 12 varieties and a form were recorded from the main-land-coast of Gujarat. They belong to 97 genera of 46 families and 22 orders (Table 2b). The class-wise species distribution was found to be Chlorophyta 52, Phaeophyta 35, and Rhodophyta 105 (Supplementary Table 2). A total of 136 seaweed species with 7 varieties and a form were recorded from GoM. They belong to 59 genera of 35 families and 16 orders (Table 2c). The class-wise species distribution was found to be Chlorophyta 47, Phaeophyta 41, and Rhodophyta 48 (Supplementary Table 3). A total of 234 seaweed species with 8 varieties and a form were recorded from Andaman and Nicobar Islands. They belong to 92 genera of 50 families and 21 orders (Table 2d). The class-wise species distribution was found to be Chlorophyta 76, Phaeophyta 54, and Rhodophyta 104 (Supplementary Table 4). A total of 133 seaweed species with 6 varieties and a form were recorded from Sri Lanka seaweeds. They belong to 78 genera of 41 families and 20 orders (Table 2e). The class-wise

Table 1 Species diversity of seaweed present at the GoKMNP

Sr. No	Name of Seaweeds species	Order	Family
1	*Monostroma latissimum* Wittrock	Ulotrichales	Monostromataceae
2	*Acrosiphonia orientalis* (J.Agardh) P.C.Silva	Acrosiphoniales	Acrosiphoniaceae
3	*Ulva compressa* Linnaeus	Ulvales	Ulvaceae
4	*Enteromorpha intestinalis* (Linnaeus) Nees (as *Ulva intestinalis* Linnaeus)	Ulvales	Ulvaceae
5	*Ulva lactuca* Linnaeus	Ulvales	Ulvaceae
6	*Ulva flexuosa* Wulfen	Ulvales	Ulvaceae
7	*Ulva linza* Linnaeus	Ulvales	Ulvaceae
8	*Ulva prolifera* O.F.Müller	Ulvales	Ulvaceae
9	*Ulva reticulata* Forsskål	Ulvales	Ulvaceae
10	*Ulva rigida* C.Agardh	Ulvales	Ulvaceae
11	*Ulva beytensis* Thivy & Sharma	Ulvales	Ulvaceae
12	*Ulva conglobata* Kjellman	Ulvales	Ulvaceae
13	*Ulva clathrata* (Roth) C.Agardh	Ulvales	Ulvaceae
14	*Ulva erecta* (Lyngbye) Fries (as *Ulva paradoxa* C.Agardh)	Ulvales	Ulvaceae
15	*Ulva pertusa* Kjellman (as *Ulva australis* Areschoug)	Ulvales	Ulvaceae
16	*Ulva stenophylla* Setchell & N.L.Gardner	Ulvales	Ulvaceae
17	*Ulva taeniata* (Setchell) Setchell & N.L.Gardner	Ulvales	Ulvaceae
18	*Chaetomorpha antennina* (Bory) Kützing	Cladophorales	Cladophoraceae
19	*Chaetomorpha crassa* (C.Agardh) Kützing (as *Chaetomorpha aerea* (Dillwyn) Kützing)	Cladophorales	Cladophoraceae
20	*Chaetomorpha spiralis* Okamura	Cladophorales	Cladophoraceae
21	*Cladophora herpestica* (Montagne) Kützing (as *Lychaete herpestica* (Montagne) M.J.Wynne)	Cladophorales	Cladophoraceae
22	*Cladophora vagabunda* (Linnaeus) Hoek	Cladophorales	Cladophoraceae
23	*Chaetomorpha indica* (Kützing) Kützing	Cladophorales	Cladophoraceae
24	*Cladophora glomerata* (Linnaeus) Kützing	Cladophorales	Cladophoraceae
25	*Boodlea composita* (Harvey) F.Brand	Cladophorales	Boodleaceaea
26	*Cladophoropsis javanica* (Kützing) P.C.Silva (as *Acrocladus herpesticus* (Montagne) Boedeker)	Cladophorales	Boodleaceaea
27	*Phyllodictyon anastomosans* (Harvey) Kraft & M.J.Wynne	Cladophorales	Boodleaceaea
28	*Dictyosphaeria cavernosa* (Forsskål) Børgesen	Cladophorales	Siphonocladaceae
29	*Struvea anastomosans* (Harvey) Piccone & Grunow ex Piccone (as *Phyllodictyon anastomosans* (Harvey) Kraft & M.J.Wynne)	Cladophorales	Boodleaceae
30	*Chamaedoris auriculata* Børgesen	Cladophorales	Siphonocladaceae
31	*Valonia aegagropila* C.Agardh	Cladophorales	Valoniaceae
32	*Valonia utricularis* (Roth) C.Agardh	Cladophorales	Valoniaceae
33	*Valoniopsis pachynema* (G.Martens) Børgesen	Cladophorales	Valoniaceae
34	*Avrainvillea erecta* (Berkeley) A.Gepp & E.S.Gepp	Bryopsidales	Dictomosiphonaceae
35	*Bryopsis plumosa* (Hudson) C.Agardh	Bryopsidales	Bryopsidaceae
36	*Bryopsis hypnoides* J.V.Lamouroux	Bryopsidales	Bryopsidaceae
37	*Bryopsis maxima* Okamura ex Segawa	Bryopsidales	Bryopsidaceae
38	*Bryopsis pennata* J.V.Lamouroux	Bryopsidales	Bryopsidaceae
39	*Bryopsis indica* A.Gepp & E.S.Gepp	Bryopsidales	Bryopsidaceae
40	*Bryopsis ramulosa* Montagne	Bryopsidales	Bryopsidaceae
41	*Pseudobryopsis mucronata* Børgesen (as *Trichosolen mucronatus* (Børgesen) W.R.Taylor)	Bryopsidales	Pseudobryopsidaceae
42	*Caulerpa microphysa* (Weber Bosse) Feldmann	Bryopsidales	Caulerpaceae
43	*Caulerpa peltata* J.V.Lamouroux (as *Caulerpa chemnitzia* (Esper) J.V.Lamouroux)	Bryopsidales	Caulerpaceae
44	*Caulerpa racemosa var. corynephora* (Montagne) Weber Boss (as *Caulerpa corynephora* Montagne)	Bryopsidales	Caulerpaceae
45	*Caulerpa racemosa* var. *macrophysa* (Sonder ex Kützing) W.R.Taylor	Bryopsidales	Caulerpaceae
46	*Caulerpa racemosa* var. *occidentalis* (J.Agardh) Børgesen (as *Caulerpa chemnitzia* (Esper) J.V.Lamouroux)	Bryopsidales	Caulerpaceae

Table 1 (continued)

Sr. No	Name of Seaweeds species	Order	Family
47	*Caulerpa racemosa* var. *turbinata* (J.Agardh) Eubank (as *Caulerpa chemnitzia* var. *turbinata* (J.Agardh) Fernández-García & Riosmena-Rodríguez in J.N.Norris & al.)	Bryopsidales	Caulerpaceae
48	*Caulerpa scalpelliformis* var. *denticulata* (Decaisne) Weber Bosse (as *Caulerpa denticulata* Decaisne)	Bryopsidales	Caulerpaceae
49	*Caulerpa scalpelliformis* f. *dwarkensis* Børgesen	Bryopsidales	Caulerpaceae
50	*Caulerpa sertularioides* (S.G.Gmelin) M.Howe	Bryopsidales	Caulerpaceae
51	*Caulerpa taxifolia* (M.Vahl) C.Agardh	Bryopsidales	Caulerpaceae
52	*Caulerpa veravalensis* Thivy & V.D.Chauhan	Bryopsidales	Caulerpaceae
53	*Caulerpa verticillata* J.Agardh	Bryopsidales	Caulerpaceae
54	*Caulerpa scalpelliformis* (R.Brown ex Turner) C.Agardh	Bryopsidales	Caulerpaceae
55	*Caulerpa mexicana* Sonder ex Kützing	Bryopsidales	Caulerpaceae
56	*Caulerpa crassifolia* (C.Agardh) J.Agardh (as *Caulerpa mexicana* Sonder ex Kützing)	Bryopsidales	Caulerpaceae
57	*Caulerpa cupressoides* (Vahl) C.Agardh	Bryopsidales	Caulerpaceae
58	*Caulerpa prolifera* (Forsskål) J.V.Lamouroux	Bryopsidales	Caulerpaceae
59	*Codium decorticatum* (Woodward) M.Howe	Bryopsidales	Codiaceae
60	*Codium dwarkense* Børgesen	Bryopsidales	Codiaceae
61	*Codium geppiorum* O.C.Schmidt	Bryopsidales	Codiaceae
62	*Codium sursum* Kraft & A.J.K.Millar	Bryopsidales	Codiaceae
63	*Halimeda macroloba* Decaisne	Bryopsidales	Helimedaceae
64	*Halimeda tuna* (J.Ellis & Solander) J.V.Lamouroux	Bryopsidales	Helimedaceae
65	*Udotea indica* A.Gepp & E.S.Gepp	Bryopsidales	Halimedaceae
66	*Chlorodesmis fastigiata* (C.Agardh) S.C.Ducker	Bryopsidales	Halimedaceae
67	*Acetabularia calyculus* J.V.Lamouroux	Dasycladales	Polyphysaceae
68	*Ectocarpus siliculosus* (Dillwyn) Lyngbye	Ectocarpales	Ectocarpaceae
69	*Ectocarpus confervoides* Le Jolis (as *Ectocarpus siliculosus* (Dillwyn) Lyngbye)	Ectocarpales	Ectocarpaceae
70	*Hincksia mitchelliae* (Harvey) P.C.Silva (as *Feldmannia mitchelliae* (Harvey) H.-S.Kim)	Ectocarpales	Acinetosporaceae
71	*Giffordia mitchelliae* (Harvey) Hamel (as *Feldmannia mitchelliae* (Harvey) H.-S.Kim)	Ectocarpales	Acinetosporaceae
72	*Hydroclathrus clathratus* (C.Agardh) M.Howe	Ectocarpales	Scytosiphonaceae
73	*Iyengaria stellata* (Børgesen) Børgesen	Ectocarpales	Scytosiphonaceae
74	*Colpomenia sinuosa* (Mertens ex Roth) Derbès & Solier	Ectocarpales	Scytosiphonaceae
75	*Hydroclathrus stephanosorus* Kraft (as *Hydroclathrus tilesii* (Endlicher) Santiañez & M.J.Wynne)	Ectocarpales	Scytosiphonaceae
76	*Rosenvingea intricata* (J.Agardh) Børgesen (as *Rosenvingea endiviifolia* (Martius) M.J.Wynne)	Ectocarpales	Scytosiphonaceae
77	*Rosenvingea nhatrangensis* E.Y.Dawson	Ectocarpales	Scytosiphonaceae
78	*Scytosiphon lomentaria* (Lyngbye) Link	Ectocarpales	Scytosiphonaceae
79	*Levringia boergesenii* Kylin	Ectocarpales	Chordariaceae
80	*Nemacystus decipiens* (Suringar) Kuckuck	Ectocarpales	Chordariaceae
81	*Myriogloea sciurus* (Harvey) Kuckuck ex Oltmanns	Ectocarpales	Chordariaceae
82	*Canistrocarpus cervicornis* (Kützing) De Paula & De Clerck	Dictyotales	Dictyotaceae
83	*Dictyota atomaria* (Woodward) Greville (as *Taonia atomaria* (Woodward) J.Agardh)	Dictyotales	Dictyotaceae
84	*Dictyota bartayresiana* J.V.Lamouroux	Dictyotales	Dictyotaceae
85	*Dictyota cervicornis* Kützing (as *Canistrocarpus cervicornis* (Kützing) De Paula & De Clerck)	Dictyotales	Dictyotaceae
86	*Dictyopteris australis* (Sonder) Askenasy	Dictyotales	Dictyotaceae
87	*Dictyopteris delicatula* J.V.Lamouroux	Dictyotales	Dictyotaceae
88	*Dictyota ciliolata* Sonder ex Kützing	Dictyotales	Dictyotaceae
89	*Dictyota dichotoma* (Hudson) J.V.Lamouroux	Dictyotales	Dictyotaceae
90	*Dictyota divaricata* J.V.Lamouroux (as *Dictyota implexa* (Desfontaines) J.V.Lamouroux)	Dictyotales	Dictyotaceae
91	*Dictyota pinnatifida* Kützing	Dictyotales	Dictyotaceae
92	*Lobophora variegata* (J.V.Lamouroux) Womersley ex E.C.Oliveira	Dictyotales	Dictyotaceae

Table 1 (continued)

Sr. No	Name of Seaweeds species	Order	Family
93	*Padina boergesenii* Allender & Kraft	Dictyotales	Dictyotaceae
94	*Padina boryana* Thivy	Dictyotales	Dictyotaceae
95	*Padina tetrastromatica* Hauck	Dictyotales	Dictyotaceae
96	*Padina gymnospora* (Kützing) Sonder	Dictyotales	Dictyotaceae
97	*Spatoglossum asperum* J.Agardh	Dictyotales	Dictyotaceae
98	*Stoechospermum marginatum* (C.Agardh) Kützing (as *Stoechospermum polypodioides* (J.V.Lamouroux) J.Agardh)	Dictyotales	Dictyotaceae
99	*Dictyota fasciola* (Roth) J.V.Lamouroux	Dictyotales	Dictyotaceae
100	*Dictyopteris woodwardia* (R.Brown ex Turner) C.Agardh	Dictyotales	Dictyotaceae
101	*Dictyopteris acrostichoides* (J.Agardh) Bornet	Dictyotales	Dictyotaceae
102	*Dictyopteris muelleri* (Sonder) Reinbold	Dictyotales	Dictyotaceae
103	*Lobophora variegata* var. *indica* Umamaheswara Rao	Dictyotales	Dictyotaceae
104	*Spatoglossum variabile* Figari & De Notaris	Dictyotales	Dictyotaceae
105	*Cystoseira indica* (Thivy & Doshi) Mairh (as *Polycladia indica* (Thivy & Doshi) Draisma, Ballesteros, F.Rousseau & T.Thibaut)	Fucales	Sargassaceae
106	*Cystoseira trinodis* (Forsskål) C.Agardh (as *Sirophysalis trinodis* (Forsskal) Kützing)	Fucales	Sargassaceae
107	*Hormophysa cuneiformis* (J.F.Gmelin) P.C.Silva	Fucales	Sargassaceae
108	*Hormophysa triquetra* (C.Agardh) Kützing	Fucales	Sargassaceae
109	*Sargassum cinctum* J.Agardh	Fucales	Sargassaceae
110	*Sargassum cinereum* J.Agardh	Fucales	Sargassaceae
111	*Sargassum johnstonii* Setchell & N.L.Gardner	Fucales	Sargassaceae
112	*Sargassum plagiophyllum* C.Agardh	Fucales	Sargassaceae
113	*Sargassum prismaticum* V.D.Chauhan	Fucales	Sargassaceae
114	*Sargassum swartzii* C.Agardh	Fucales	Sargassaceae
115	*Sargassum wightii* Greville	Fucales	Sargassaceae
116	*Sargassum tenerrimum* J.Agardh	Fucales	Sargassaceae
117	*Turbinaria conoides* (J.Agardh) Kützing	Fucales	Sargassaceae
118	*Turbinaria ornata* (Turner) J.Agardh	Fucales	Sargassaceae
119	*Sargassum aquifolium* (Turner) C.Agardh	Fucales	Sargassaceae
120	*Sargassum carpophyllum* J.Agardh	Fucales	Sargassaceae
121	*Sargassum linearifolium* (Turner) C.Agardh	Fucales	Sargassaceae
122	*Hydroclathrus tenuis* C.K.Tseng & Lu Baroen	Ectocarpales	Scytosiphonaceae
123	*Scinaia carnosa* (Kützing) J.Agardh	Nemaliales	Scinaiaceae
124	*Scinaia complanata* (Collins) Cotton	Nemaliales	Scinaiaceae
125	*Scinaia hatei* Børgesen	Nemaliales	Scinaiaceae
126	*Scinaia moniliformis* J.Agardh	Nemaliales	Scinaiaceae
127	*Tricleocarpa fragilis* (Linnaeus) Huisman & R.A.Townsend	Nemaliales	Galaxauraceae
128	*Scinaia fascicularis* (Børgesen) Huisman	Nemaliales	Scinaiaceae
129	*Galaxaura oblongata* (J.Ellis & Solander) J.V.Lamouroux (as *Tricleocarpa fragilis* (Linnaeus) Huisman & R.A.Townsend)	Nemaliales	Galaxauraceae
130	*Dermonema virens* (J.Agardh) Pedroche & Ávila Ortíz	Nemaliales	Liagoraceae
131	*Liagora ceranoides* J.V.Lamouroux	Nemaliales	Liagoraceae
132	*Ahnfeltia plicata* (Hudson) E.M.Fries	Ahnfeltiales	Ahnfeltiaceae
133	*Gelidiella acerosa* (Forsskål) Feldmann & Hamel	Gelidiales	Gelidiellaceae
134	*Gelidium micropterum* Kützing	Gelidiales	Gelidiellaceae
135	*Gelidium pusillum* (Stackhouse) Le Jolis	Gelidiales	Gelidiellaceae
136	*Gracilaria canaliculata* Sonder	Gracilariales	Gracilariaceae
137	*Gracilaria corticata* var. *cylindrica* Umamaheswara Rao	Gracilariales	Gracilariaceae
138	*Gracilaria debilis* (Forsskål) Børgesen	Gracilariales	Gracilariaceae
139	*Gracilaria dura* (C.Agardh) J.Agardh	Gracilariales	Gracilariaceae

Table 1 (continued)

Sr. No	Name of Seaweeds species	Order	Family
140	*Gracilaria foliifera* (Forsskål) Børgesen	Gracilariales	Gracilariaceae
141	*Gracilaria salicornia* (C.Agardh) E.Y.Dawson	Gracilariales	Gracilariaceae
142	*Gracilaria textorii* (Suringar) Hariot	Gracilariales	Gracilariaceae
143	*Gracilaria corticata* (J.Agardh) J.Agardh	Gracilariales	Gracilariaceae
144	*Asparagopsis taxiformis* (Delile) Trevisan	Bonnemaisoniales	Bonnemaisoniaceae
145	*Peyssonnelia obscura* var. *bombayensis* Børgesen (as *Peyssonnelia obscura* Weber Bosse)	Peyssonneliales	Peyssonneliaceae
146	*Cryptonemia undulata* Sonder	Halymeniales	Halymeniaceae
147	*Halymenia porphyriformis* P.G.Parkinson	Halymeniales	Halymeniaceae
148	*Halymenia porphyroides* Børgesen	Halymeniales	Halymeniaceae
149	*Halymenia venusta* Børgesen	Halymeniales	Halymeniaceae
150	*Halymenia dilatata* Zanardini	Halymeniales	Halymeniaceae
151	*Halymenia floresii* (Clemente) C.Agardh	Halymeniales	Halymeniaceae
152	*Grateloupia filicina* (J.V.Lamouroux) C.Agardh	Halymeniales	Grateloupiaceae
153	*Corynomorpha prismatica* (J.Agardh) J.Agardh	Halymeniales	Halymeniaceae
154	*Grateloupia indica* Børgesen	Halymeniales	Grateloupiaceae
155	*Gracilaria verrucosa* (Hudson) Papenfuss (as *Gracilariopsis longissima* (S.G.Gmelin) Steentoft, L.M.Irvine & Farnham)	Gracilariales	Gracilariaceae
156	*Amphiroa anceps* (Lamarck) Decaisne	Corallinales	Corallinaceae
157	*Amphiroa fragilissima* (Linnaeus) J.V.Lamouroux	Corallinales	Corallinaceae
158	*Cheilosporum spectabile* Harvey ex Grunow (as *Jania spectabilis* (Harvey ex Grunow) J.H.Kim, Guiry & H.-G.Choi)	Corallinales	Corallinaceae
159	*Jania rubens* (Linnaeus) J.V.Lamouroux	Corallinales	Corallinaceae
160	*Corallina officinalis* Linnaeus	Corallinales	Corallinaceae
161	*Chondracanthus acicularis* (Roth) Fredericq	Gigartinales	Cystocloniaceae
162	*Hypnea esperi* Bory	Gigartinales	Cystocloniaceae
163	*Hypnea musciformis* (Wulfen) J.V.Lamouroux	Gigartinales	Cystocloniaceae
164	*Hypnea pannosa* J.Agardh	Gigartinales	Cystocloniaceae
165	*Hypnea spinella* (C.Agardh) Kützing	Gigartinales	Cystocloniaceae
166	*Hypnea valentiae* (Turner) Montagne	Gigartinales	Cystocloniaceae
167	*Hypnea cervicornis* J.Agardh	Gigartinales	Cystocloniaceae
168	*Kappaphycus alvarezii* (Doty) L.M.Liao	Gigartinales	Solieriaceae
169	*Sarconema filiforme* (Sonder) Kylin	Gigartinales	Solieriaceae
170	*Solieria chordalis* (C.Agardh) J.Agardh	Gigartinales	Solieriaceae
171	*Solieria robusta* (Greville) Kylin	Gigartinales	Solieriaceae
172	*Sebdenia flabellata* (J.Agardh) P.G.Parkinson	Sebdeniales	Sebdeniaceae
173	*Champia compressa Harvey*	Rhodymeniales	Champiaceaea
174	*Champia globulifera* Børgesen	Rhodymeniales	Champiaceaea
175	*Champia indica* Børgesen	Rhodymeniales	Champiaceaea
176	*Champia parvula* (C.Agardh) Harvey	Rhodymeniales	Champiaceaea
177	*Champia somalensis* Hauck	Rhodymeniales	Champiaceaea
178	*Gastroclonium iyengarii* K.Srinivasan	Rhodymeniales	Champiaceaea
179	*Botryocladia leptopoda* (J.Agardh) Kylin	Rhodymeniales	Rhodymeniaceae
180	*Botryocladia skottsbergii* (Børgesen) Levring	Rhodymeniales	Rhodymeniaceae
181	*Coelarthrum opuntia* (Endlicher) Børgesen	Rhodymeniales	Rhodymeniaceae
182	*Halopeltis australis* (J.Agardh) G.W.Saunders	Rhodymeniales	Rhodymeniaceae
183	*Rhodymenia sonderi* P.C.Silva (as *Halopeltis australis* (J.Agardh) G.W.Saunders)	Rhodymeniales	Rhodymeniaceae
184	*Rhodymenia dissecta* Børgesen	Rhodymeniales	Rhodymeniaceae
185	*Gelidiopsis repens* (Kützing) Weber Bosse (as *Ceratodictyon repens* (Kützing) R.E.Norris)	Rhodymeniales	Lomentariaceae
186	*Gelidiopsis gracilis* (Kützing) Feldmann (as *Ceratodictyon variabile* (J.Agardh) R.E.Norris)	Rhodymeniales	Lomentariaceae
187	*Griffithsia corallinoides* (Linnaeus) Trevisan	Ceraminales	Wrangeliaceae

Table 1 (continued)

Sr. No	Name of Seaweeds species	Order	Family
188	*Griffithsia rhizophora* Grunow ex Weber Bosse	Ceraminales	Wrangeliaceae
189	*Wrangelia argus* (Montagne) Montagne	Ceraminales	Wrangeliaceae
190	*Haloplegma duperreyi* Montagne	Ceraminales	Ceramiaceaea
191	*Centroceras clavulatum* (C.Agardh) Montagne	Ceraminales	Ceramiaceaea
192	*Ceramium tenerrimum* (G.Martens) Okamura	Ceraminales	Ceramiaceaea
193	*Ceramium cruciatum* Collins & Hervey	Ceraminales	Ceramiaceaea
194	*Ceramium rubrum* C.Agardh (as *Ceramium virgatum* Roth)	Ceraminales	Ceramiaceaea
195	*Wrangelia tanegana* Harvey	Ceraminales	Wrangeliaceae
196	*Spyridia alternans* Børgesen (as *Spyridia horridula* F.Schmitz ex J.Agardh)	Ceraminales	Callithamniaceae
197	*Spyridia filamentosa* (Wulfen) Harvey	Ceraminales	Callithamniaceae
198	*Dasya punicea* (Zanardini) Meneghini	Ceraminales	Delesseriaceae
199	*Heterosiphonia crispella* (C.Agardh) M.J.Wynne	Ceraminales	Delesseriaceae
200	*Heterosiphonia muelleri* (Sonder) De Toni	Ceraminales	Delesseriaceae
201	*Hypoglossum heterocystideum* (J.Agardh) J.Agardh	Ceraminales	Delesseriaceae
202	*Platysiphonia delicata* (Clemente) Cremades	Ceraminales	Delesseriaceae
203	*Acanthophora dendroides* Harvey	Ceraminales	Rhodomelaceae
204	*Acanthophora nayadiformis* (Delile) Papenfuss	Ceraminales	Rhodomelaceae
205	*Acanthophora spicifera* (M.Vahl) Børgesen	Ceraminales	Rhodomelaceae
206	*Acanthophora delilei* J.V.Lamouroux (as *Acanthophora nayadiformis* (Delile) Papenfuss)	Ceraminales	Rhodomelaceae
207	*Chondria armata* (Kützing) Okamura	Ceraminales	Rhodomelaceae
208	*Digenea simplex* (Wulfen) C.Agardh	Ceraminales	Rhodomelaceae
209	*Laurencia dendroidea* J.Agardh	Ceraminales	Rhodomelaceae
210	*Laurencia glandulifera* (Kützing) Kützing	Ceraminales	Rhodomelaceae
211	*Laurencia obtusa* (Hudson) J.V.Lamouroux	Ceraminales	Rhodomelaceae
212	*Laurencia platyclada* Børgesen	Ceraminales	Rhodomelaceae
213	*Palisada cruciata* (Harvey) K.W.Nam	Ceraminales	Rhodomelaceae
214	*Palisada perforata* (Bory) K.W.Nam	Ceraminales	Rhodomelaceae
215	*Leveillea jungermannioides* (Hering & G.Martens) Harvey	Ceraminales	Rhodomelaceae
216	*Lophocladia lallemandii* (Montagne) F.Schmitz	Ceraminales	Rhodomelaceae
217	*Polysiphonia denudata* (Dillwyn) Greville ex Harvey in Hooker (as *Carradoriella denudata* (Dillwyn) Savoie & G.W.Saunders)	Ceraminales	Rhodomelaceae
218	*Laurencia cruciata* Harvey (as *Palisada cruciata* (Harvey) K.W.Nam)	Ceraminales	Rhodomelaceae
219	*Laurencia papillosa* (C.Agardh) Greville (as *Palisada perforata* (Bory) K.W.Nam)	Ceraminales	Rhodomelaceae
220	*Chondria dasyphylla* (Woodward) C.Agardh	Ceraminales	Rhodomelaceae

species distribution was found to be Chlorophyta 51, Phaeophyta 21, and Rhodophyta 61 (Supplementary Table 5). A total of 67 seaweed species with 2 varieties and a form were recorded from Rodrigues Islands. They belong to 55 genera of 32 families and 16 orders (Table 2f). The class-wise species distribution was found to be Chlorophyta 23, Phaeophyta 14, and Rhodophyta 30 (Supplementary Table 6). The over-all comparison of the diversity of unique and common seaweed species in GoKMNP and other locations using different color codes was presented to identify the unique and common species (Supplementary Tables 7–12).

The Simpson's index of the diversity of the six different places ranged between 0.59 and 0.67. Among all GoM registered highest value (0.67) followed by GoKMNP (0.65), Andaman and Nicobar Islands (0.64), Rodrigues Islands (0.64), Sri Lanka (0.62), and the lowest was for the main-land-coast of Gujarat (0.59). The Shannon Weiner diversity index of the six different places ranged between 0.99 and 1.10. Among all GoM registered highest value (1.10) followed by GoKMNP (1.07), Andaman and Nicobar Islands (1.06), Rodrigues Islands (1.05), Sri Lanka (1.02), and the lowest was for the main-land-coast of Gujarat (0.99). The Species Richness of the six different places ranged between 4.20 and 5.46. Among all Andaman and Nicobar Islands registered the highest value (5.46) followed by GoKMNP (5.39), the main-land-coast of Gujarat (5.26), GoM (4.91), Sri Lanka (4.89), and lowest was for Rodrigues Islands (4.20). The Species Evenness of the six different places

Table 2 Phylum-wise distribution of seaweeds

Class	Order	Family	Genera	Species (including varieties and forms)
(a) GoKMNP				
Chlorophyta	6	14	23	67 (6)
Phaeophyta	3	6	22	55 (1)
Rhodophyta	12	22	50	98 (2)
Total	21	42	95	220 (9)
(b) Main-land-coast of Gujarat				
Chlorophyta	6	14	23	52 (8)
Phaeophyta	3	5	16	35 (0)
Rhodophyta	13	27	58	105 (4)
Total	22	46	97	192 (12)
(c) GoM				
Chlorophyta	4	11	14	47 (5)
Phaeophyta	3	3	14	41 (0)
Rhodophyta	9	21	31	48 (2)
Total	16	35	59	136 (7)
(d) Andaman and Nicobar Islands				
Chlorophyta	5	14	20	76 (4)
Phaeophyta	5	7	16	54 (2)
Rhodophyta	11	29	56	104 (2)
Total	21	50	92	235 (8)
(e) Sri Lanka				
Chlorophyta	3	11	18	51 (5)
Phaeophyta	6	6	13	21 (0)
Rhodophyta	11	24	47	61 (1)
Total	20	41	78	133 (6)
(f) Rodrigues Island				
Chlorophyta	3	10	17	23 (2)
Phaeophyta	3	3	10	14 (0)
Rhodophyta	10	19	28	30 (0)
Total	16	32	55	67 (2)

ranged between 0.19 tand 0.25. Among all Rodrigues Island registered the highest value (0.25) followed by GoM (0.22), Sri Lanka (0.21), GoKMNP (0.20), and the lowest was for main-land-coast of Gujarat (0.19) and Andaman and Nicobar Islands (0.19) (Table 3).

The analysis revealed that 63 seaweed species were unique to GoKMNP and 35 were unique to the main-land-coast of Gujarat. Further, 157 seaweed species were common in both places (Table 4a). The analysis revealed that 126 seaweed species were unique to GoKMNP and 142 were unique to Andaman and Nicobar Islands. And 92 seaweed species were common in both places (Table 4b). The analysis revealed that 127 seaweed species were unique to GoKMNP and 47 were unique to GoM. And 90 seaweed species were common in both places (Table 4c). The analysis revealed that 167 seaweed species were unique to GoKMNP and 81 were unique to Sri Lanka. And 53 seaweed species were common in both places (Table 4d). The analysis revealed that 190 seaweed species were unique to GoKMNP and 37 were unique to Rodrigues Islands. And 30 seaweed species were common in both places (Table 4e).

Discussions

Of the 118 taxa of benthic marine algae reported earlier from GoKMNP (Nair 2002), 30 were collected during the present investigation. Nevertheless, this comprehensive enumeration added 102 new taxa, expanding the species list to 220 from this region. The new finding clearly points out to the inadequacy in taxonomic work on benthic marine algae of GoKMNP. The critical salient feature of the present study was the fact that some of the widespread tropical species that would be expected from the island waters were completely absent. Among the Chlorophyceae, *Caulerpa racemosa* [var. *typical*] was not encountered and represented, although this genus is well represented by 13 other species and interestingly four varieties of *C. racemosa*. The genus *Halimeda* with a record of only two species was certainly under-represented. The absence of genera *Boergesenia* and *Trichosolen* is striking. However, the species of Indian origin such as *Codium dwarkense* and *Ulva beytensis* were reported. It seems that the *U. beytensis* expanded its range of distribution to the eastern side of the Gulf waters. The record of *Ulva pertusa* represented a new nothernmost limit of distribution of this species in the Indian sea. The brown algal flora was well represented in the island. Three conspicuous species

Table 3 Comparative seaweed diversity analysis

References	Simpson's index of diversity	Shannon Weiner diversity index	Species richness	Species evenness
GoKMNP	0.65	1.07	5.39	0.20
Main-land-coast of Gujarat	0.59	0.99	5.26	0.19
GoM	0.67	1.10	4.91	0.22
Andaman and Nicobar Islands	0.64	1.06	5.46	0.19
Rodrigues Island	0.64	1.05	4.20	0.25
Sri Lanka	0.62	1.02	4.89	0.21

Table 4 Phylum-wise comparison of seaweed diversity

	Chlorophyta	Phaeophyta	Rhodophyta	Total
(a) GoKMNP vs Main-land-coast of Gujarat				
Unique to GoKMNP	23	23	17	63
Common	44	32	81	157
Unique to Main-land-coast of Gujarat	8	3	24	35
(b) GoKMNP vs Andaman and Nicobar Islands				
Unique to GoKMNP	32	36	58	126*
Common	33	19	40	92*
Unique to Andaman and Nicobar Islands	43	35	64	142*
(c) GoKMNP *vs* GoM				
Unique to GoKMNP	37	27	63	127*
Common	28	28	34	90*
Unique to GoM	20	13	14	47*
(d) GoKMNP vs Sri Lanka				
Unique to GoKMNP	40	48	79	167*
Common	27	7	19	53*
Unique to Sri Lanka	25	14	42	81*
(e) GoKMNP vs Rodrigues Islands				
Unique to GoKMNP	57	45	88	190
Common	10	10	10	30
Unique to Rodrigues Island	13	4	20	37

*(b) Variations in the total number reported earlier in the manuscript is because 3 taxa have been synonymized

*(c) Variations in the total number reported earlier in the manuscript is because 3 taxa have been synonymized

*(d) Variations in the total number reported earlier in the manuscript is because 2 taxa have been synonymized

Levringia boergesenii, *Colpomenia sinuosa*, and *Turbinaria ornata* which are easily noticeable and identifiable in the field and common along the main-land-coast of Gujarat were not encountered and represented. The record of *Rosenvingea nhatrangensis* was the first record from the West coast of India. The genus *Dictyota* and *Cystoseira* were well represented with seven and two species respectively. Jagtap and Untawale reported *Hydroclathrus tenuis* from this island as a new record to the Indian coast (Jagtap and Untawale 1996). This species also was re-reported. Interestingly, over the past two decades this species did not expanded its distribution range to the main-land-coast of Gujarat. The red algal flora of GoKMNP was diverse and represented by several widespread species. However, several common species namely, *Hypnea flagelliformis*, *Bostrychia tenella*, *Scinaia fascularis* Huisman were conspicuously absent. The genus *Grateloupia* having widespread distribution and is represented by over 15 species in the Indian Ocean and 9 species from Indian waters was only represented by two species. The genus *Gracilaria* with a record of 8 species and one variety was the only genus represented fairly well. The absence of some of these common species growing along the exposed shores on the hard substrata might be related to the nature and the geography of the islands. The islands are surrounded by extensive growth of corals that might have limited the availability of preferred exposed rocky substratum essential for the recruitment of some of these benthic algal populations. The other convincing justification could be the presence of unfavorable current patterns that might be hindering the entry of certain species in to the Gulf impeding their colonization process. Similar, observations were also recorded by Schils (Schils et al. 2004) for Rodrigues Island in the Indian Ocean.

The geographic affinities of benthic marine algae of confined locations in the Southern Arabian Sea are well documented (Schils and Wilson 2006; Schils and Coppejans 2003a, 2003b; Wynne 2000), while such information for the northern region is limited. Børgesen pointed out the characteristic flora of this region and commented on its affinities with several distant floras such as Australia, Japan, and northern Atlantic Ocean countries (Børgesen 1935). Despite these initial observations, no further studies have been focused on floristic similarity and biogeography of benthic algae of this area. Schils and Coppejans also stated that the Hadramout coast of Yemen and Dhofar coast of Oman of the southern Arabian Peninsula are a center of high endemism, and thus represented distinct floristic composition (Schils and Coppejans 2003b). The record of

Bryopsis maxima Okamura, *Dictyopteris divaricata* from GoKMNP further accentuates the observations made by Børgesen and Wynne of an interesting affinity between the benthic algal floras of Japan and the northern Arabian Sea (Wynne 2000; Børgesen 1934). The occurrence of *Codium sursum* from the GoKMNP region represented interesting record with disjunct distribution pattern. However, disjunct distribution of other benthic marine algae from Arabian Sea was also reported by Schils and Coppejans and Wynne and needs further studies to unravel complicated distribution patterns (Schils and Coppejans 2003a; Wynne 2000).

Comparison with the seaweed diversity of the main-land-coast of Gujarat

With respect to the species found at both GoKMNP and the main-land-coast of Gujarat, *Caulerpa* and *Ulva* shared the highest diversity at both places amongst the green algal genera, whereas their brown counterpart *Sargassum* was found to be most abundant in terms of the species. Contrastingly, the brown algal genera *Ectocarpus* which is represented by two different species in GoKMNP, had zero representative species in the main-land-coast of Gujarat. Among the taxa belonging to class Rhodophyceae, *Gracilaria* was one of the most abundant from both GoKMNP as well as the main-land-coast of Gujarat. The geography of GoKMNP makes it a unique habitat which remains, to some extent, invulnerable to inclement conditions of the open sea. It provides ambient and stable conditions in terms of nutrients, tidal waves, and anthropogenic interference, which are important for the survival of diverse flora and fauna including seaweeds (Roy et al. 2015). The main-land-coast of Gujarat on the other hand is directly exposed to various extreme conditions which can affect the seaweed diversity of the region. Our literature survey found a total of 192 species of seaweeds from the main-land-coast of Gujarat as compared to 220 from GoKMNP. The main-land-coast of Gujarat represented open sea conditions, while GoKMNP is situated in protected gulf area. The former has very few habitats suitable for seaweed growth (Jha et al. 2009); comparatively gulf area provides several amenable habitats (Biswas 2009). Besides waters of gulf are nutrient-rich and productive environment might have prevailed for diverse seaweed growth (Joshi et al. 2017).

Comparison with the seaweed diversity of the Andaman and Nicobar Islands

With respect to the species found at both GoKMNP and the Andaman and Nicobar Islands, *Caulerpa* and *Ulva* shared highest diversity at both the places among the green algal genera, whereas their brown counterpart *Sargassum* was found to be most abundant in terms of the species. Contrastingly, the brown algal genera *Dictyota* which is represented by eight different species in GoKMNP, had only one representative species, *Dictyota implexa* in the Andaman and Nicobar Islands. The trend, in fact, was consistent with most of the common species of the family Dictyotaceae e.g., *Lobophora*, *Padina*, *Spatoglossum*, etc., with none to very few representations as compared to the GoKMNP. Among the taxa belonging to class Rhodophyceae, *Gracilaria* was one of the most abundant from both GoKMNP as well as the Andaman and Nicobar Islands. It is worth mentioning that the report of carrageenophyte *Kappaphycus alvarezii* from GoKMNP by Kamboj from some of the islands needs critical attention (Kamboj et al. 2017). The species diversity data set we used in this study by Karthick and Ramesh did not mention its presence (Karthick et al. 2021). But *K. alvarezii* was reported from the Red Skin Island by Rao and Rao (Rao and Rao 1999). To the best of our knowledge the most important factor which can affect the diversity of seaweeds at any place is anthropogenic in origin. Both these places have seen very low to below average human footfall which might help in the exceptionally rich diversity of the seaweeds. It is important to mention that the onset of the monsoon season along the Andaman and Nicobar Islands, is related with the Bay of Bengal branch, whereas, while for GoKMNP (with is the part of Peninsular India) the same depends on the Arabian Sea branch. The former receives the highest rainfall, while the later receives the least, delayed and short spell rainfall (Guhathakurta and Rajeevan 2007; Kumar et al. 2012). Further diversity of marine organism along the Andaman and Nicobar coast has been found to be impacted by both South West monsoon and North East monsoon (Jeeva et al. 2018). Although both the areas displayed high species diversity of seaweeds the difference in species composition could be attributed to monsoon and other climatological differences.

Comparison with the seaweed diversity of GoM

With respect to the species found at both GoKMNP and GoM *Caulerpa* and *Ulva* shared the highest diversity at both places amongst the green algal genera, whereas their brown counterparts *Sargassum* and *Dictyota* were found to be most abundant in terms of the species. Also, the brown algal genera *Iyengaria* is represented by one species in GoKMNP and GoM. The trend, in fact, was consistent with most of the common species of the family Scytosiphonaceae e.g., *Hydroclathrus*, *Colpomenia*, *Rosenvingea*, and *Scytosiphon*, with none to very few representations as compared to the GoKMNP. Among the taxa belonging to class Rhodophyceae, *Gracilaria* and *Hypnea* were the most

abundant from both GoKMNP as well as GoM. The GoM being surrounded by the main-land-coast of Tamil Nadu should ideally be harboring rich diversity but compared to the GoKMNP the diversity is less. The Simpson's index of the diversity of 0.67 was highest for GoM, suggesting that there is a 67% chance of two randomly collected species, belonging to a different class of seaweeds which is more, although marginally, than GoKMNP.

Although, the GoM is home to 18 different *Caulerpa* species and 14 different *Sargassum* species which is more than those found in GoKMNP. But the red seaweeds have been observed to favour the west coast in comparison to the east. Around 100 different red seaweed species have been reported from GoKMNP whereas red seaweeds accounted for only 50 species in the GoM. Furthermore, it was interesting to note that the Florideophycean red algae like *Scinaia*, *Solieria*, *Kappaphycus,* and *Galaxaura* were not reported from Mannar whereas their representative species were present in GoKMNP. It has been established that the R: P Index (ratio of the number of red algal species to those of brown algal species) increases while moving from the cold regions to the warm tropical regions (Lüning 1991), implying that red seaweeds prefer comparatively warmer conditions. This could be one of the major factors influencing the current seaweed distribution. Both the costs are classified under-protected habitats, but there are differences in tidal ranges. At GoKMNP it varies 3 m to over 6 m at the upstream locations; while at GoM it is found to be only 1.5 m. The former experiences high tidal currents. Similarly, the current patters are different at both the south-eastern coast and the west coast (Amol et al. 2014; Jain et al. 2021). These parameters might have a critical bearing on site-specific diversity of seaweeds and distribution, despite having similaries in habitats.

Comparison with the seaweed diversity of Sri Lanka

With respect to the species found at both GoKMNP and Sri Lanka *Caulerpa* and *Ulva* shared the highest diversity at both places amongst the green algal genera, whereas their brown counterpart *Sargassum* was found to be most abundant in terms of the species. Also, the brown algal genera *Dictyota* which is represented by eight different species in GoKMNP, had only three representative species in Sri Lanka. Among the taxa belonging to class Rhodophyceae, *Gracilaria* was one of the most abundant from both GoKMNP as well as Sri Lanka. Diversity of seaweeds along the 1600 km Sri Lanka coasts is mainly the attribute of the same common factors like wave action, salinity and temperature of seawater, and anthropogenic interference in addition to the North-West and South-East monsoon (Coppejans et al. 2009). Owing to this, there is a difference in the distribution of various seaweeds and some of the seaweeds found on opposite coasts of the country.

Among the green algae, the Sri Lanka coasts are rich in *Caulerpa*, and *Ulva* just like GoKMNP. Moreover, seaweeds like *Acetabularia* and *Acrosiphonia* were represented in GoKMNP, whereas zero reports of these algae from Sri Lanka were found. Furthermore, unicellular siphonous alga *Boergesenia forbesii* was reported from Sri Lanka only. Among the brown algae, *Sargassum*, and *Dictyota* dominated the Sri Lankan coasts. Even though Sri Lankan coasts were not inhabited by seaweeds like *Cystoseira*, *Ectocarpus*, and *Spatoglossum* which is not the case for GoKMNP, some Phaeophycean species, *Ralfsia*, *Chnoospora* and *Sphacelaria* were only reported from Sri Lanka. Many of the common red algal species like *Corallina, Gelidium, Griffithsia, Heterosiphonia* etc. have not been reported from Sri Lanka. Interestingly, the red algal species dominating the Sri Lanka coasts is calcareous seaweed *Jania* along with *Gracilaria*. The diversity of seaweeds of Sri Lanka when compared to that of GoKMNP does not show much difference in terms of diversity indices, as is the case with GoM. The Simpson's Index of diversity and Shannon Weiner diversity index of Sri Lanka were found to be 0.62 and 1.02 whereas these values for GoKMNP were 0.65 and 1.07. Moderate climate, especially temperature that is suitable for thriving tropical species and shallow waters might be responsible for similarity patterns that was reported (Coppejans et al. 2009). Besides, floristic affinities could be other reason.

Comparison with the seaweed diversity of Rodrigues Island

With respect to the species found at both GoKMNP and Rodrigues Island, *Ulva*, although under-represented at Rodrigues Island, shared the highest diversity at both places amongst the green algal genera. The brown algal genus *Padina* which was represented by four different species in GoKMNP, had three representative species in Rodrigues Island. Of the four *Padina* species observed at GoKMNP, only one species, *P. boergesenii*, was found absent in Rodrigues Island. Among the taxa belonging to class Rhodophyceae, *Hydrolithon* was present in Rodrigues Island but absent in GoKMNP.

Rodrigues Island in Mauritius has a very peculiar kind of coastal environment. The diversity of seaweeds in comparison to highly diverse GoKMNP was found to be significantly lower with under representation of almost all commonly found seaweeds like *Ulva, Caulerpa, Sargassum, Gracilaria* etc. In spite of very limited diversity at Rodrigues Island, some unique taxa were present which were not reported from GoKMNP. These include *Boergesenia forebesii*, *Neomeris vanbosseae*, and *Portieria hornemannii*. A total of 67 species were reported from Rodrigues Island,

the comparison of seaweed diversity with GoKMNP revealed obvious patterns with Simpson's index of diversity and Shannon Weiner diversity index of 0.64 and 1.05 respectively. Interestingly, at Rodrigues Island, the Species Evenness was highest among the other geographic regions under consideration. Ideally, tropics have been reported to possess high seaweed diversity (Bolton 1994), which does not do justice to the reported diversity of Rodrigues Islands. It could very well be because of the fact that the seaweed diversity reported from Rodrigues Island was very less (Schils et al. 2004) and warrants more extensive floristic investigations in and around the island.

Studies on seaweed diversity of marine protected areas from India

The floristic studies on benthic marine algae of protected areas in India are not exhaustive. Tigga and Rao recorded 39 species belonging to 22 genera of benthic marine algae from Rani Jhansi Marine National Park, Andaman (Tigga and Rao 2004). They further indicated that 5 species namely *Acetabularia crenulata* var. *monodisca*, *Boergesenia forbesii*, *Ulva fasciata*, *Asparagopsis taxiformis*, and *Halymenia venusta* have restricted distribution and rare occurrence thus requires urgent attention. The rare occurrence of *C. racemosa* var. *occiddentalis* has been documented from Samiani Island, GoKMNP (Mantri et al. 2003). The Marine Sanctuary at Malvan, Central West coast recorded the diversity of 70 benthic marine algae (Dhargalkar et al. 2001; Mantri and Subba Rao 2007). The studies further pointed out that the occurrence of *Acetabularia parvula*, *Ulva taeniata*, and *Ernodesmis verticillata* is restricted only to the sanctuary area. About 147 species of benthic algae with several endemic taxa are reported from GoM Biosphere reserve (Achuthankutty et al. 2008). The characteristic algal flora at each protected place representing few species hitherto only known from these locations requires immediate attention for conservation.

The over exploitation of natural resources, environmental as well as anthropogenic driven habitat degradation, growing industrial pollution, climate change and global warming are the major threats for marine diversity (Venkataraman and Wafar 2005). In Indian waters, few studies have highlighted the local extinction of benthic marine algae due to the over harvesting and industrial pollution of coastal waters. Umamaheswara Rao and Chaugule placed *Gelidiella acerosa* under vulnerable species category due to the indiscriminate industrial exploitation from several localities in southeast coast of India (Umamaheswara Rao et al. 2006). Based on the recent surveys three species originally described by Børgesen from Mumbai namely, *Cladophora saracenica*, *Monosporus indicus* and *Myriogramme bombayensis* are considered extinct by these authors (Børgesen 1935). A few species described from GoKMNP such as *Turbinaria indica*, *Porphyra indica*, *P. okhaensis* and *Myriogramme okhaensis* have been not collected during past several years, expressing doubts about their existence. The collection of endemic species *Ulva beytensis* during this study confirmed its presence in gulf waters which was previously thought extinct. This study further lamented the need of having red data book for benthic marine algae of India, which will further enhance the prospects of conserving this neglected marine resource.

The data implies that the Simpson's index of diversity of GoKMNP was higher (0.65) than main-land-coast of Gujarat (0.59), Andaman and Nicobar island (0.64), Rodrigues island (0.64) and Sri Lanka (0.62). Simpson's index represents arithmetic mean of relative diversity and thus this confirms dominance of the species in GoKMNP than other regions mentioned above. Therefore, it might in all likelihood find higher proportion or more individuals among the different groups of seaweeds namely Chlorophyta, Phaeophyta, and Rhodophyta in GoKMNP. Similarly, Shannon Weiner diversity index of GoKMNP was higher (1.07) than main-land-coast of Gujarat (0.99), Andaman and Nicobar island (1.06), Rodrigues island (1.05) and Sri Lanka (1.02). Shannon Weiner index represents diversity richness and rare species types in GoKMNP than other regions mentioned above. This measure accounts for number of taxa, as well as the abundance of each taxa among the different groups of seaweeds namely Chlorophyta, Phaeophyta, and Rhodophyta in GoKMNP. This analysis has provided a clearer understanding of their significance and contribution to the overall interpretation of species diversity in this study. Further, the present study unequivocally confirms the need for sustainable management and conservation of seaweed diversity of the islands of GoKMNP.

Suggestions for sustainable management and conservation

The sustainable management of biological diversity is necessary for the long-term and unceasing utilization of resources. Both human-induced (habitat degradation, over-exploitation, coastal urbanization) and natural (increased seawater temperature, grazing, climate-induced calamities) factors are responsible for the degradation of seaweed biodiversity around the globe. Such studies are also important to understand the functional consequences of biodiversity change to real-world losses of biodiversity (Bracken and Williams 2013). It also has important consequences on ecosystem-based management of seaweed harvesting for commercial operations (Lotze et al. 2019). India globally has only ~ 10% share in seaweed diversity and ~ 0.01% in farming, but assumes considerable importance, due to over 20% of its territorial waters are

bound by island system (Mantri et al. 2019). The recent initiative of the Government of India that ensured the establishment of over 100 protected areas of marine habitats across several islands and coastal union territories is praiseworthy. But the conservation and management focus has overwhelmingly relied on wetlands, mangroves, and coral reefs. Of the total 42 marine species that are protected in Indian waters; 3 are mammals, 6 reptiles, 9 fishes, and 24 mollusks and not a single species of seaweed is included (Rajan 2015). The reason for this is that information on seaweed biodiversity in marine protected areas in India is scattered and not easily accessible to the researchers which can be effectively utilized for drawing comprehensive policy. This study is the first study to address this gap. The comprehensive database of seaweeds of Gulf of Kutch Marine National Park, India is provided.

The second most relevant aspect of the seaweed biodiversity conservation and management program is information on their current status, which is necessary. Further, the information on habitat, population size, overall ecology, and impeding threats is also critical to catalyzing action for protecting them. The overall seaweed species reported in the present communication are data deficient where there is inadequate information present that can be useful to have an assessment of the risk of extinction either directly or indirectly. There two specific pointers those required serious considerations for species that have limited distribution, (i) These species belong to taxonomically difficult groups and specialized expertise is needed to correctly identify them, (ii) dispersal restrictions, phenology, and life-history strategies are not known for these taxa and laboratory-based investigation are required. The comprehensive investigations on population dynamics need to be planned under ex-situ conditions that can aid conservation and management plan. There are different legal and policy considerations which are concurrently acting and govern GoKMNP. For example, most of the area (over 87%) of GoKMNP overlaps with the jurisdiction of the Gujarat Maritime Board (GMB). The port-building and development activities are undertaken by GMB often directly in conflict with conservation measures. The other areas of concern are the increase in activities of polluting industries, pilgrimage at Beyt Dwarka, and fishing grounds for traditional fishermen (Biswas 2009). There has been exploitation of seaweeds from islands of Gulf of Kutch for the production of liquid plant bio-stimulant (Subba Rao and Mantri 2006). State Government has been giving on implementing commercial seaweed farming for providing alternative employment to local fishermen to rejuvenate coastal economy and reducing natural exploitation. The amendment of the Wildlife Protection Act in 2002 has empowered the State Government to empower local communities to create Conservation and Community Reserves. The enhanced participation of local communities who depend on natural resources of GoKMNP for a living would certainly help in better conservation and management of resources in general and seaweeds in particular.

As stated before, not only the current status of species of restricted distribution is needed, but the strategy for long-term monitoring is essential. This will enable the early detection, recognition and evaluation of the direct or indirect effects of natural or human-induced changes. These studies would be very crucial for future generations, reinforcing the importance of education and understanding of the biodiversity of coastal ecosystems.

The present work is not only a comparative study but can be used as a base-line information to prepare the checklist of seaweeds of GoKMNP which is non-existent at the moment despite isolated reports listing seaweeds from in and around GoKMNP made available (Kamboj et al. 2017; Anonymous 2012; Nair 2002; Dodia and Joshi 2012; Roy et al. 2015). This being one of the few coasts of the country with healthy live corals and extensive mangrove forests, the decisions taken to ensure its conservation like giving it a national park status was a step in the right direction which has also provided a plethora of seaweeds a safe haven to thrive. But a lot more efforts will have to be put in not only by government organizations but also by the common public as marine diversity of several taxa has been reported to be reduced recently due to anthropogenic activities.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no conflict of interest and financial or proprietary interests in any material discussed in this article.

Ethical approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

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