

Influence of oil and gas exploration activities on the macrobenthic community structure of the Krishna-Godavari basin (Ravva coast), Western Bay of Bengal

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Abstract

The influence of oil and gas exploration activities on the macrobenthic community of an offshore oil and gas drilling site was investigated along the Krishna-Godavari basin (KG), Western Bay of Bengal. In the oil well sites, the enrichment factor of most of the metals (Cu, Zn, Pb, Cr) showed relatively higher values (EF > 10), indicating their anthropogenic origin. The macrobenthic community exhibited a conspicuous reduction in biomass (av. 33.5%), density (av. 20.9%) and diversity (av. 6.7%) in and around the oil well platforms. Polychaetes abundance increased towards the oil well platforms and decreased away from the wells, whereas cumaceans dominated at the coastal stations. The lower density of *Ampelisca* sp. in the oil well platforms and higher density at the locations away from the oil wells indicates the adverse effects of exploration activities. Along with the environmental variables such as depth, sediment texture and composition, trace metal concentration also had a prominent influence on the macrobenthic fauna. The biotic indices (H' index and AMBI) exhibiting slightly disturbed condition at the oil well sites; and M-AMBI exhibiting moderate-good-high condition, reveals the distinct distribution pattern of benthic communities in the region. Slightly disturbed conditions at a distance of 1-1.5 km from the oil wells compared to the undisturbed conditions at regions 3-4 km away from the platforms reveals the impacts of oil and gas exploration activities on the benthic habitat quality.

Keywords: Oil exploration; Trace metals; Bay of Bengal; Ravva coast; AMBI & M-AMBI.

1. Introduction

The exploration and production of oil and gas in marine ecosystems have a crucial role in the economic advancement of any beneficial country and thus forms one of the major industrial activities promoting global economic growth. However, these operations have the potential to elicit a variety of critical environmental impacts on the marine ecosystem worldwide (Cordes et al., 2016; Gordon et al., 2003; Hall-Spencer et al., 2002). Regular oil and gas drilling activities produce direct and indirect effects on the ecosystems during each phase of exploration, production, and decommissioning (Cordes et al., 2016). The discharged waste water and crude oils from the oil drilling activities contain diverse contaminants ranging from trace metals to varying concentrations of polycyclic aromatic hydrocarbons (PAHs); phenols; alkanes; and mono-aromatic compounds having potential toxicological consequences (Schifter et al., 2015). Trace metals often form a major pollutant of the offshore oil explorations as it is produced in considerably high quantities during the drilling processes. Trace metals are toxic, non-biodegradable, and can bio-accumulate in aquatic ecosystems (Censi et al., 2006; Ghani, 2015). Therefore, because of their presence in the crude oil (Dekkers and Daane, 1999) and in sediments around the oil and gas production regions (Kennicutt et al., 1996a; Kennicutt et al., 1996b), it has emerged as a potential threat to the biota of the adjacent environments, in addition to the possible risk imposed by the oil and gas wells itself.

The offshore oil and natural gas explorations and production activities take place in coastal waters of more than half of the nations on the Earth (Speight, 2014), and these activities are found to evoke socio-ecological impacts on their contiguous environment (Baptiste and Nordenstam, 2009). It has been found that the long term releases of many chemicals associated with the hydrocarbon production activities even at low levels, impart significant ecological impacts, even though they do not induce immediate environmental catastrophes (Gray et al., 1990; Lissner et al., 1991; Olsgard and Gray, 1995; Osenberg et al., 1992). Over the past few decades, studies on the impacts of oil and gas exploration activities on the marine ecosystems have garnered well research attentions (Bakke et al., 2013; Currie and Isaacs, 2005; Hartley, 1996), and the potential of these activities in causing critical negative effects on pristine marine ecosystems have received more attention in environmental management practices.

The Ravva coast (16°35'-16°56'N to 82°07'- 82°32'E) is situated in the Krishna-Godavari (KG) basin along the east coast of India (Andhra Pradesh) in Bay of Bengal (BoB). The state-owned Oil and Natural Gas Corporation (ONGC) discovered the Ravva oil field in 1987 and pioneered the exploration activities contributing to the successful production of crude oil in March 1993. Initially, it was estimated to produce about 100 million barrels of crude oil from the Ravva field. However, it was

successful enough to produce more than twice the quantum of oil initially estimated, producing 25,986 barrels of oil equivalent a day at present (<https://www.offshore-technology.com/projects/ravva-field/>). The crude oil produced from the Ravva field is transferred to the Ravva onshore terminal via four pipelines. The output from the field accounts for 8% of the total domestic oil production in India, hence have a crucial role in the growth of the Indian economy.

Macrobenthic communities (>0.5 mm) play a critical role in many ecological processes, and are known to regulate or modify many physical, chemical, biological, and geological processes (Day, 1989 ; Sturdivant et al., 2013). Moreover, the nature of their mobility helps in the accurate assessment of the environmental health of marine and coastal ecosystems (Muniz et al., 2005). It has long been proven that in marine ecosystems, anthropogenic disturbance can be assessed efficiently using macrobenthic communities which characterize the ecological quality of their habitats (Bigot et al., 2008). Many studies in the BoB have elucidated the community structure, and ecology of macrobenthic fauna for the last few decades (Harkantra et al. 1982; Ganesh and Raman 2007; Raman et al. 2015), but studies describing the influence of oil and gas exploration activities on the fauna is still lacking. With respect to benthic communities, the effects of oil and gas explorations mainly arise from the physical disturbances it put forth and also from the pollutants emerging from the drilling and production processes. Hence, many studies attempted on this aspect have reported on the changes in the abundance and diversity of the macrobenthic communities (Currie and Isaacs, 2005; Gray et al., 1990; Hernández-Arana et al., 2005). Furthermore, the reports on the potential acoustic effects on vertebrates (Moore et al., 2012; Southall et al., 2008), and also significant developmental delays and body malformations reported in some invertebrates concurrent to these activities augment the need for continuous and extensive monitoring of the environmental impacts associated with it (De Soto et al., 2013).

In the present study, the ecological changes occurring in the benthic realm of the Ravva waters owing to the oil and gas exploration activities have been closely evaluated through the variability generated in the sediment characteristics, the structural properties of macrobenthic communities, and through assessment using the biotic indices AMBI and M-AMBI. Globally, the macroinvertebrates based biotic indices are widely accepted for assessing the ecological status of coastal marine ecosystems (Borja et al. 2000). The AZTI's Marine Biotic Index (AMBI) (Borja et al., 2000, 2007) and multivariate-AMBI (M-AMBI) (Borja et al., 2004; Muxika et al., 2007), are the extensively used biotic indices for assessing the benthic habitat quality (Sivaraj et al., 2014; Sivadas et al., 2016; Joydas et al., 2017; Santibañez-Aguascalientes et al., 2020). The study mainly focused on (1) the variation in distribution and community structure of the macrobenthos in the oil exploration sites and also in the

reference sites away from the oil wells situated in the KG basin (Ravva coast), and 2) the trace metals distribution and its influence on the macrobenthic community distribution and diversity.

Material and methods

2.1 Study area

The Ravva oil and gas field is located in the coastal waters of the KG basin (Block PKGM-1) in the western Bay of Bengal (BoB). This region was recognized as a potential site for active oil and natural gas explorations by various organizations of public and private sectors since 2-3 decades back. The BoB is a unique and dynamic tropical ocean basin, where the biological production is largely modulated by the enormous supply of the inorganic nutrients to the photic layer brought in by the perennial rivers and also by many physical processes such as eddy, cyclones, etc (Sarma et al., 2013). The study region also receives large volumes of river discharges containing surplus terrigenous materials of both organic and inorganic forms, especially from the Godavari river during both monsoon seasons (southwest and northeast) (Unger et al., 2003), which subsequently affect the overall hydrological properties of the whole KG basin and its nearby offshore region (Maneesha et al., 2011). During spring intermonsoon (March-May), the BoB waters, in general, are warm in the upper euphotic layers due to the prevalence of thermal stratification, which eventually leads to oligotrophic conditions in terms of inorganic nutrients and phytoplankton (Madhu et al., 2006).

2.2 Sampling strategy

An extensive oceanographic survey was conducted by the CSIR-National Institute of Oceanography (NIO), Regional Centre, Kochi in the coastal waters of Ravva during the waning phase of the winter monsoon (from 21st February to 1st March 2012), as part of the sponsored project “Environmental monitoring around the offshore installations of Cairn Energy Pty Ltd (Ravva field) in BoB” in the marine vessel *MFV Srinivasa*. The hydrographic observations were made from 36 pre-determined stations surrounding 8 offshore oil platforms (Fig.1).

Among these, 9 stations were exclusively located in the marine outfall region (extending to ~1km towards the sea) both running parallel and perpendicular to the coast (Stations-1-9, hereafter coastal stations; CS, 5.8 to 7.8m depth), and 2 stations were selected as the coastal reference stations (RC 1 & RC 2, hereafter RCs, 9 m depth) within 5 km from the outfall location. The remaining 25 stations were fixed in the offshore waters (10-25 m depth) in a grid pattern covering the entire Ravva block. Of these, 16 stations were positioned adjacent to the oil wells at a distance of 1 to 1.5 km (Stations-10 to 24, & 29; oil well platform sites, hereafter OFW, 8.4 to 14.6 m depth), 6 stations were located 2 to 2.5 km away from the wells (Stations- 25 to 28 & 30-31, offshore stations, hereafter OF,

9.6 to 20.2 m depth) and 3 stations were fixed as reference stations (RF 1, RF 2, & RF 3; hereafter RFs, 22.2 to 24.2 m depth), 3 to 4 km away in the offshore waters.

Water samples were collected from the near bottom of each station using a 5 L Niskin sampler (Hydrobios- Kiel) for analyzing the major physico-chemical and biological parameters. A Van-Veen grab (0.05 m²) was operated at all the stations for collecting sediments in duplicates for analyzing the benthic fauna and the sediment characteristics separately.

2.3 Laboratory analysis

The temperature was measured using a conductivity temperature depth profiler (CTD) (with an accuracy of $\pm 0.001^\circ\text{C}$). Salinity was measured using the conductivity probe of CTD (accuracy ± 0.001 psu) after calibration. The suspended particulate matter (SPM) was estimated gravimetrically following the standard procedure (APHA, 2005). A portable pH meter (Systronics, accuracy of ± 0.1) was used for measuring the pH. The estimation of dissolved inorganic nutrients (nitrate, phosphate, and silicate) was carried out using a UV-visible spectrophotometer (Shimadzu 1650PC), following Grasshoff et al. (1983). For chlorophyll-*a* (Chl-*a*) analysis, the bottom water sample (1 L) was filtered through GF/F filter (Whatman, nominal pore size 0.7 μm) and extracted with 10 ml of 90% acetone. The fluorescence of the sample was measured using a Fluorometer (Model 7200, Turner Designs) before and after acidification (Parsons et al., 1984).

Sediment texture was estimated by pipette analysis using the method of Krumbein and Pettijohn (1938). Total carbon and total nitrogen (CHNS Analyser) were analyzed using standard methods. For the estimation of trace metals, cadmium (Cd) and lead (Pb), a known aliquot of oven-dried sediment was digested with hydrofluoric acid to volatilize silica as silicon tetra fluoride. This was followed by treatment with nitric acid and perchloric acid to destroy the organic matter. The residue left after the evaporation of the acids was dissolved in dilute HCl and the cadmium and lead concentrations were determined by Atomic Absorption Spectrophotometer (AAS, Perkin Elmer 3110). The standards and blanks were also digested in the same manner. For the analysis of metals, zinc (Zn) and chromium (Cr), the finely ground, oven-dried, and weighed aliquot of sediment samples were digested in an open PTFE vessel using AR-Grade HF, HClO₄, and HNO₃. The mixture was heated on a sand-bath until incipient dryness. The heating was carried out to ensure complete digestion until clear solutions were obtained. The hot digest was dissolved in 10 ml of 6 N HCl. The dissolved digest was diluted to 50 ml with DI-water. The solutions were analyzed on a Perkin-Elmer Optima-2000 Dual View ICP-OES after calibrating with matrix matched compatible mixed element standards and reagent

blank. Three replicates for each solution yielded precision results with CV typically < 2%. A reference standard USGS-MAG1 was also analyzed to obtain the accuracy of the measurements.

The enrichment factor (EF) has been used to estimate the anthropogenic influences on sediments. Generally, a normalization element (either Al or Fe) is used to moderate the variations produced by the heterogeneous sediments (Landsberger et al., 1982; Loring, 1991). The reference element should be present in such a large quantity in the study area or should otherwise have the least variability in its occurrence that neither small variations nor other synergistic or antagonistic effects should alter the significance of the investigated elements. When compared to the natural sources of Fe, the anthropogenic sources are small, so Fe is often used as a normalizing element (Blomqvist et al., 1992; Rule, 1986; Sharma et al., 1999). Since Fe is found to be abundant in the study area (southeast coast of India), it has been used as normalizing element. The EF is calculated following the equation:

$$EF = (C_a \times Fe_b) / (C_b \times Fe_a)$$

where C_a and C_b are the examined metal content in the sample and the background reference respectively; Fe_a and Fe_b are the Fe content in the sample and the background reference respectively. The categorization of EF was as follows, $EF < 2$ Deficient to Minimal enrichment, $EF = 2-5$ Moderate enrichment, $EF = 5-20$ Significant enrichment, $EF = 20-40$ Very high enrichment, $EF > 40$ Extremely high enrichment. $EF < 1$ indicates crustal origin while $EF > 1$ is considered to be non-crustal (Nolting et al., 1999).

For the collection of the macrobenthic fauna, the sediment samples were passed through a 0.5 mm sieve (Birkett and McIntyre, 1971) and the organisms retained in the sieve were preserved in 4% buffered formalin stained with rose bengal. Biomass of the macrobenthic fauna was determined on an electronic balance and was expressed in $g.m^{-2}$ as wet weight (shell on). The detailed identification of the macrobenthic fauna to the lowest possible taxonomic levels was carried out using standard identification manuals (Day, 1967; Fauchald, 1977; Fauvel, 1953; Gosner, 1971; Nayar, 1959) and the numerical density was recorded as $ind\ m^{-2}$.

2.4 Statistical analyses

The significance of spatial variation in the biotic and abiotic parameters was tested using a nonparametric Kruskal-Wallis test that compares three or more unpaired groups (the Graph Pad Prism version 5.01). Univariate indices such as Shannon-Wiener index (H' ; \log_2), for species diversity, and Margalef's richness (d) for species richness were carried out using PRIMER software (version 6.1.16) (Clarke and Warwick, 2001). In order to identify the spatial differences in macrobenthic assemblages, multivariate analyses based on Bray-Curtis similarity index and group average linkage were carried

out on the fourth root transformed macrobenthic density data (PRIMER-version 6.1.16). Thereafter hierarchical cluster and non-metric multidimensional scaling (NMDS) were carried out. A Similarity Percentage (SIMPER) analysis (PRIMER-6) was used to identify the species contributing to the observed dissimilarity among the clusters obtained in the NMDS. The significance of spatial variation in the macrobenthic density between the oil well platforms and other sampling sites was tested using Analysis of Similarity (ANOSIM in PRIMER 6) (Clarke and Gorley, 2006). Karl Pearson's correlation was used for investigating the relationship between the abiotic and biotic parameters. Canonical Correspondence Analysis, (CCA) (CANOCO 4.5) was carried out to evaluate the relationship of macrobenthic fauna (major macrobenthic groups and the discriminating species responsible for the spatial distinctions identified through SIMPER analysis) with environmental variables.

Shannon-Wiener diversity index H' was used to assess the habitat quality of the coastal waters as per the Norwegian Classification tool for the soft-bottom macrofauna proposed by Molvaer et al. (1997). The categorization was accordingly, Class I- 'undisturbed' if $H' > 4$, class II- 'slightly disturbed' if $H' 3-4$; class III- 'moderately disturbed' if $H' 2-3$; class IV- 'heavily disturbed' if $H' 1-2$, and class V 'extremely disturbed' if $H' < 1$ (Vincent et al. 2002). The AMBI (Borja et al., 2000, 2007) and M-AMBI (Muxika et al., 2007) indices were evaluated in the study to assess the quality of the environment based on the ecological groups according to AZTI Laboratory (<http://www.azti.es>). The macrobenthic species were classified into five ecological groups based on their sensitivity to an increasing gradient of stress i.e. from the most sensitive species (ecological group 1- EG 1) to the most opportunistic species (ecological group V – EG V). The M-AMBI (Muxika et al., 2007), a combination of Shannon diversity, species richness, and AMBI, was also derived using AMBI software. To assess the reference conditions of the benthic communities in the study region, stations were classified according to the prevailing environmental parameters into two major groups, one consisting of the coastal stations, and two consisting of all other stations (based on the CCA plot). In the absence of pristine environmental conditions, the reference values were taken by increasing the highest diversity and richness values of all replicates at 15% level (Borja and Tunberg 2011) and decreasing AMBI to half of the lowest value. Similarly, for the bad status, reference was taken as same as azoic condition (diversity and richness = 0 and AMBI = 6). Therefore, the reference conditions for M-AMBI in the Raava waters were established as follows: (a) St.1 to 9 (Coastal stations, CS) with a diversity of 3.968 and richness 19.55; and (b) St.10 to 36, RCs and RFs with a diversity of 4.85 and richness 25.3. At 'high' status, the reference condition may be regarded as an optimum where the MAMBI approaches 1. At 'bad' status, the M-AMBI approaches 0. The threshold values for the M-AMBI classification are based upon the

European intercalibration (Borja et al., 2007, 2009): ‘High’ quality, >0.77; ‘Good’, 0.53-0.77; ‘Moderate’, 0.38-0.53; ‘Poor’, 0.20-0.38; and ‘Bad’, <0.20.

Results

3.1 Environmental parameters

The bottom water temperature varied between 27.4 and 27.9 °C in the study area, wherein slightly higher temperature was observed in the oil well platforms (OFW, av. 27.7 ± 0.1 °C) and lower at offshore reference stations (RFs, av. 27.2 ± 0.4 °C) (Table 1). A slight increase in the bottom water salinity was observed with its progression from the coastal stations to the offshore with a statistically significant spatial variation (CS, av. 32.3 ± 0.03 ; RCs, av. 32.4 ± 0.18 ; OFW, av. 32.5 ± 0.14 ; OF, av. 32.7 ± 0.14 ; RFs, av. 33.1 ± 0.07). The concentration of SPM in the bottom waters ranged between 7 and 33 mg/l in the study area, with the highest concentration at RFs (av. 19.67 ± 8.5 mg/l) and lowest at coastal reference stations (RCs, av. 10.5 ± 4.95 mg/l). The bottom water was slightly alkaline and the pH varied from 7.93 to 8.08, with insignificant spatial variation (Table 2). The nitrate concentration varied between 0.01 and 1.78 μM in the study region with a maximum at RFs (av. 0.68 ± 0.46 μM) and minimum at CS (av. 0.14 ± 0.11 μM). On the other hand, the phosphate concentration (0.01 to 0.53 μM) was higher at CS (av. 0.26 ± 0.10 μM) and lower at OF (av. 0.07 ± 0.81 μM). Similar to phosphate, the sulphate concentration was also higher at the CS (av. 3.6 ± 0.4 μM) and lower at the RFs (av. 1.6 ± 1.14 μM). The Chl-*a* concentration also had a similar pattern with higher concentration at the CS (av. 0.63 ± 0.2 mg m⁻³) and lower concentration at the RFs (av. 0.22 ± 0.13 mg m⁻³). The nutrients and Chl-*a* exhibited a significant spatial variation during the study ($p < 0.05$).

3.2 Sediment characteristics; Texture, Composition and Trace metals

The sediment texture analysis revealed the predominance of clayey silt in the CS region (Silt, av. $46.6 \pm 02\%$; Clay, av. $41.9 \pm 19.5\%$), while the substratum was sandy silt in RCs (Sand, av. $30.6 \pm 27.5\%$; Silt, av. $44.5 \pm 34.6\%$). The substratum at the OFW, RFs and OF was dominated by silt fractions (OFW, av. $58.2 \pm 23.6\%$; RFs, av. $62.9 \pm 19.5\%$; OF, av. $45.1 \pm 20.4\%$) (Table 1). The total carbon and nitrogen content in the sediments were found to be higher in the offshore regions, compared to the coastal regions, and exhibited a significant spatial variation ($p < 0.05$) (Table 2).

Regarding the distribution of sediment trace metals, Cu (5 to 90.9 $\mu\text{g/g}$), Cd (0 to 3.2 $\mu\text{g/g}$) and Ni (4.7 to 103.8 $\mu\text{g/g}$) showed an increasing trend from the coastal stations towards the offshore region while Cr (2.7 to 68.9 $\mu\text{g/g}$), Pb (10.4 to 17.2 $\mu\text{g/g}$) and Fe (1015 to 4721 $\mu\text{g/g}$) exhibited an opposite trend (Supplementary Table S1). The concentration of Cu was high at the OFW (54.3 $\mu\text{g/g}$) and surrounding OF (55.3 $\mu\text{g/g}$) regions, whereas high concentration of Zn was observed at the RCs and

the OFW. The concentration of Ni was observed to be high at the RCs and low at the CS, whereas the concentration of Mn was found to be high at the RFs and lower at the CS.

The mean enrichment of trace elements in the study area were 23.3 for Cu, 192.2 for Cd, 15.04 for Ni, 6.19 for Cr, 28.66 for Pb, 15.6 for Zn and 3.53 for Mn, respectively (Table 3). The sediments of the OFW and RCs were enriched by Ni (significant enrichment and very high enrichment respectively), Zn (very high enrichment), Cr (significant enrichment), and Mn (moderate enrichment). The sediments of the entire study area exhibited very high enrichment for the metal Pb, and extremely high enrichment for Cd. The sediments of the OFW, OF, and RFs also showed very high enrichment for Cu. As the EF values greater than 10 indicate non-crustal source, the trace metals Ni, Zn, Pb, Cd, and Cu were considered to be originated from anthropogenic sources. For all the metals the EF values were higher in the OFW compared to the other sampling locations (except Ni, and Zn).

3.3 Macrobenthic community structure

The macrobenthic faunal density varied from 160 to 1580 ind/m² in the study area. The macrobenthic density was higher at the RFs (av. 1183 ± 320 ind/m²), while lower density was observed at the OFW (av. 770±348 ind/m²) (Fig. 2). The macrobenthic biomass varied between 1.08 and 13.3 g/m² with high biomass at the RFs (av. 7.58 ± 4.99 g/m²) and the low biomass was at RCs (av. 2.64 ± 0.06 g/m²). The species diversity varied from 2.3 to 4.6 with slightly higher diversity at the RFs (av. 4.28 ± 0.04) and lower at the CS (av. 3.74 ± 0.36). The species diversity and species richness were slightly higher in the offshore locations compared to the coastal stations (Fig. 2).

A total of 80 macrobenthic taxa were recorded in the study area during the sampling period. Polychaetes were the dominant group in density except at the CS in the study area (Fig. 3). In the CS, macrobenthic fauna was dominated by cumaceans (30%), followed by amphipods (23%), polychaetes (18%), and foraminiferans (14%). In the RCs, polychaetes (36%) were followed by foraminiferans (27%), bivalves (12%), and amphipods (11%). While in the OFW, polychaetes (63%) formed the predominant group followed by amphipods (11%), foraminiferans (8%), and bivalves (7%). In the OF also, polychaetes dominated (50%), along with amphipods (31%), and isopods (4.5%), and bivalves (5%). In the RFs, the macrobenthic fauna consisted of polychaetes (44%), amphipods (27%), bivalves (8%) and isopods (8%).

In the CS, the major polychaete species observed were *Prionospio* sp. (av. 31 ind/m²), *Glycera longipinnis* (av. 24 ind/m²), and *Goniada* sp (av. 16 ind/m²). In the RCs, the observed major species were *Prionospio* sp (av. 70 ind/m²), *Lumbrineris latreilli* (av. 40 ind/m²), *Sigambra parva* (av. 30 ind/m²), *Amphicteis gunneri* (av. 30 ind/m²), and *Aglaophamus* sp (av. 30 ind/m²). While in the OFW,

Lumbrineris latreilli (av. 134 ind/m²), *Prionospio* sp (av. 73 ind/m²), *Amphicteis gunneri* (av. 45 ind/m²), *Aricidea* sp (av. 30 ind/m²), *Magelona* sp (av. 23 ind/m²), and *Sigambra parva* (av. 18 ind/m²) were the major species. The polychaete species such as *Amphicteis gunneri* (av. 63 ind/m²), *Prionospio* sp (av. 60 ind/m²), *Magelona* sp (av. 50 ind/m²), *Lumbrineris latreilli* (av. 47 ind/m²), and *Aricidea* sp (av. 33 ind/m²) were dominant at the OF. Whereas the polychaetes *Laonice cirrata* (av. 60 ind/m²), *Amphicteis gunneri* (av. 27 ind/m²), *Aricidea* sp (av. 27 ind/m²), and *Aglaophamus* sp (av. 27 ind/m²) were observed at the RFs. It was thus observed that *Prionospio* sp dominated in the CS and RCs whereas *Lumbrineris latreilli* was the major species at OFW, *Amphicteis gunneri* dominated at the OF while *Laonice cirrata* was the major polychaete at the RFs (Supplementary Table S2).

The hierarchical clustering of sampling locations based on the fourth root transformed macrobenthic density data exhibited the formation of distinct groups at 45% similarity level. The results of the NMDS plot (Fig. 4a) and the discriminating species identified through SIMPER analysis (Average group dissimilarity CS & OFW, = 69.32; CS & OF = 70.08; OFW & OF = 59.80; CS & RCs = 57.66; OFW & RCs = 56.73; OF & RCs = 54.09; CS & RFs = 67.49; OFW & RFs = 65.40; OF & RFs = 57.88; RCs & RFs = 59.98) (Supplementary Table S3) have affirmed the spatial distinctness in the study area. Significant difference in the macrobenthic density between the CS, OFW, and OF sites was evident from the results of ANOSIM analysis (Global R=0.332, p < 0.01).

The CCA analysis of macrobenthic community (major groups) with environmental variables revealed a clear spatial distinction of the locations (Fig. 4b), in which Axes 1 and 2 were able to explain 94% of the variation in community data of which the depth, Ni EF, sand, temperature, silt, and Cu EF formed the major influencing factors. Macrobenthic biomass was mainly associated with sand and total nitrogen; density and diversity was influenced by silt and metal concentration; polychaeta was influenced by metal concentration (Cu) and total nitrogen, amphipoda was influenced by SPM and cumacea positively related with chlorophyll a (Fig. 5a). The CCA analysis carried out using the discriminating species revealed the species-specific relationship with environmental variables, *L. latreille* and *Prionospio* sp was positively correlated with lead EF and temperature; *A. gunneri* had affinity towards Cu EF; *Ampelisca* sp with temperature and silt; *Aricidea* sp with Zn EF, *Magelona* sp with Cu EF, TN and sand; *S. parva* with TN, and *L. cirrata* with salinity (Fig. 5b).

According to the Norwegian system for classification of environmental status with regard to fauna (using Shannon-Wiener H index), the study region was categorized as follows, CS >OFW >RCs >OF >RF, in which CS, OFW, and RCs were under slightly disturbed conditions while OF, and RF were under undisturbed conditions. Using the AMBI analysis, among the 81 taxa, 76 were fit into five ecological groups based on the AZTI classification and the remaining 4 taxa were not included in

the species list for analysis. The list of identified species along with the assigned ecological groups is given in the Supplementary Table S4 according to the species list of AMBI (December 2020). The percentage of unassigned taxa after updating the species assignment had a mean value of 1.86.

In the CS, 40-95% of the species were grouped under EG I, 5.3-44% in EG II, 0-21 % in EG III, 0-3.5 % in EG IV. In the RCs 34.3-45.5 %, 18.2-31.4 %, and 34.3-36.4 % of the species were grouped into EG I, EG II, and EG III respectively. In the OFW, 12.2-66.7 %, 7.1-66.7 %, 0-63.6%, 0-8.3%, and 0-4.3% of the species belonged to EG I, EG II, EG III, EG IV and EG V respectively. In the OF 27.7-63%, 9.2-27.7%, 21.7-38%, 0-4.3%, and 0-8.5 % of the species were belonged to EG I, EG II, EG III, EG IV and EG V respectively. In the RFs 48.3-57.6 %, 22.4-39.4 %, 0-25.9 %, and 2.9-3.4 % species belonged to EG I, EG II, EG III, and EG IV respectively (Fig. 6a). The AMBI values revealed a slightly disturbed condition at OFW (av. 1.64) and RCs (av. 1.43) while undisturbed condition prevailed at CS (av. 0.608) and RFs (av. 0.988, except RF 2) (Fig. 6b). The mean M-AMBI value was 0.76 ± 0.079 in the CS, 0.654 ± 0.0748 in the RCs, 0.652 ± 0.0959 in the OFW, 0.732 ± 0.0531 in the OF, and 0.775 ± 0.0135 in the RFs, with the lowest value observed at OFW and highest at RFs. Hence the M-AMBI values exhibited a status of good-high at CS, good at RCs, moderate-good-high at OFW, good-high at OF, and good-high status at RFs (Fig. 6c, d).

The Pearson correlation analysis carried out to understand the relationship between the macrobenthic community and the environmental and sediment characteristics, showed a significant positive correlation of the macrobenthic biomass with SPM ($p < 0.01$, $r = 0.43$) and salinity ($p < 0.01$, $r = 0.45$) whereas the diversity exhibited a positive correlation with total nitrogen ($p < 0.05$, $r = 0.37$) and salinity ($p < 0.05$, $r = 0.38$). Polychaetes exhibited significant positive relation with Cu concentration ($p < 0.05$, $r = 0.39$) and total nitrogen ($p < 0.01$, $r = 0.48$), cumacea showed a positive relation with Chl-*a* ($p < 0.01$, $r = 0.43$), Pb ($p < 0.01$, $r = 0.43$) and clay. The AMBI index was negatively correlated with Chl-*a*, and positively correlated with total nitrogen, Cu, Cd and Ni concentration (Supplementary Table S5).

Discussion

The present study conducted a comprehensive evaluation of the environmental alterations and sediment trace metal distribution generated by the oil and gas exploration activities and its impacts on the distribution and community structure of macrobenthic fauna in the KG basin near Ravva coast, western Bay of Bengal. The study evidenced lower macrobenthic density at stations nearer to the oil well platforms and an increase in locations farther from it. Similar to the density, the macrobenthic biomass and diversity were also low at the oil wells compared to the other offshore sites indicating the

influence of oil and gas exploration activities on the distribution of benthic fauna. Similar observations of decreased density/biomass and diversity from the Campeche shelf, southern Gulf of Mexico by Hernández-Arana et al. (2005) and substantial reduction in the diversity with increased dominance of opportunistic species within 500 to 1000 m of the oil installations at the Ekofisk and Eldfisk oilfields, the North Sea by Gray et al. (1990) adds support to the view.

The distribution of different macrobenthic faunal groups showed a clear variation among the stations; with more or less even distribution of the groups at the coastal stations (CS) located away from the oil wells (Fig. 3). Similarly, a difference in the macrobenthic assemblage in the adjacent areas of oil platforms has been reported at the Campeche shelf, southern Gulf of Mexico (Hernández-Arana et al. 2005; Machain-Castillo et al., 2019). Here, a remarkable dominance of cumaceans observed in the coastal stations compared to other locations, can be linked to the increased availability of food, as evidenced by their significant positive correlation with the bottom water Chl-*a*. The study evidenced a noticeable increase in dissolved inorganic nutrients and Chl-*a* in the coastal stations compared to the other sites. Usually, the increased nutrient levels favor the proliferation of large-sized phytoplankton such as diatoms and dinoflagellates in the tropical coastal waters (Agawin et al., 2000; Madhu et al., 2006). Observations of Blazewicz-Paszkowycz and Ligowski (2002) on cumaceans primarily relying on detritus and epilithic diatoms for their food requirement further substantiates our finding. The reduced density of cumaceans observed in the oil well platforms and surroundings suggests their less preference to regions impacted by oil pollution. Conlan et al. (2004) have suggested cumaceans as negative bioindicators that exhibit a reduction/elimination of the population in contaminant laden regions.

Polychaetes formed the predominant macrobenthic taxa in all the oil wells platform sites (OFW-63%), with a noticeable decrease in their density with an increase in distance from the oil wells (RCs-36%, OF-49%, RFs-44%). Polychaetes, characterized by varied feeding strategies (Fauchald, 1977), display high stability and adaptability to different habitats (Simboura et al., 2000; Simboura et al., 1995) and are often found to dominate in polluted environments compared to other macrobenthic taxa. As this taxon includes both tolerant and opportunistic species, they can easily dominate regions where other taxa fail to proliferate. Similar results observed in an estuary at the New Bayou, Texas, (Nance, 1991) substantiates the observation. Other macrobenthic groups like amphipods, foraminiferans, bivalves, gastropods, and brittle stars exhibited lower density in oil well sites. The decrease in the density of amphipods at the oil well sites and their increase at locations away from the oil wells (Fig. 3) indicate their higher sensitivity to ecosystem disturbances. Earlier studies have also documented high mortality of amphipods subsequent to oil spills (Dauvin, 1987; Sanders et al., 2017). The

noticeable dominance of EG 1 (sensitive species) in stations away from the oil well sites (av. CS-71%, RCs-40%, OFW-31%, OF-48%, RFs-54%) with low AMBI values also supports the above finding.

Previous studies have shown that macrobenthic faunal distribution in the Bay of Bengal is influenced by multiple environmental variables such as depth, water temperature, salinity, dissolved oxygen, sediment texture and organic matter concentrations (Harkantra et al. 1982; Ganesh and Raman 2007; Raman et al. 2015; Gopal et al. 2020). The present study also evidenced the influence of depth, sediment texture, temperature, and metal concentration on the distribution of the macrobenthic community structure. Prior studies on the effect of oil pollution on the macrobenthic community have reported that variation in the hydrocarbon concentration and organic carbon as the most prominent factors responsible for creating community shifts (Nance, 1991; Sukumaran et al., 2014). The present study has evidenced higher concentrations of total carbon and nitrogen near the offshore oil platforms similar to the observation of Yang et al. (2020). The oil pollutants can limit the entry of water and oxygen into the soils, and thus act as a barrier for microbial degradation (Adam and Duncan, 2002; Yang et al., 2018). In addition, the positive correlation of AMBI index with total nitrogen indicates the decrease in ecological quality with increased total nitrogen concentration. Similar results were observed by Feebarani et al., 2016 from the southwest coast of India.

Though the present study provides many substantial evidences on the effects the petroleum hydrocarbons have on the distribution of the benthic fauna, the lack of data on the petroleum hydrocarbon distribution of the study area limits in providing the direct influences associated with oil pollution. However, data on the sediment trace metal concentrations in the oil well platforms can be used as an effective alternative in understanding the impact of oil and gas related activities in aquatic systems as observed by Rasheed et al. (2012) that an increase in the concentrations of trace metals near oil/gas producing wells in the petroliferous areas of Krishna Godavari Basin were due to the influence of hydrocarbon microseepage suggesting the successful application of trace metal anomalies for finding hydrocarbon microseepage in the petroliferous regions.

The concentration of sediment trace metals were in this order Cd> Pb> Cu> Zn>Ni>Cr>Mn in the study area. The estimated EF values were higher than 10 for the trace metals Ni, Zn, Pb, Cd, and Cu, which indicated their origin from anthropogenic sources. Also, the sediments of oil well platform sites were enriched with Cd (extremely high enrichment), Pb, Cu, Zn (very high enrichment), and Ni (significant enrichment). Similarly, higher concentration and increased EF values of trace metals like Cu, Zn, and Pb reported recently from the Karoon River Basin, Iran corroborates the substantial influence of the oil and gas activities on the trace metal distribution (Keshavarzi et al., 2015). In concordance with this, the EF values of most of the trace metals in the present study were higher in

the oil well platforms and the surrounding sites, thus substantiating their contribution from oil and gas exploration activities. The lowest EF (except Cr) values observed for all the metals in the outfall region (near CS) compared to the oil well sites might have happened by the sufficient dilution treatments conducted on the effluents at various ambient conditions before its discharges into the sea.

The study showed a prominent influence of metal concentration (especially Ni EF, Cu EF, Mn EF,) on the macrobenthic community distribution (Fig. 5). Also, the CCA analysis and the Pearson correlation have showed a significant relationship between the concentration of trace metals and the density of polychaetes. Polychaetes exhibited a significant positive correlation with Cu concentration ($p < 0.05$) while cumaceans and foraminiferans were positively correlated with Pb whereas the tanaids were negatively correlated. Chen et al. (2010) observed that many species of polychaetes exhibit high tolerance to heavy metal concentrations. Earlier studies have indicated the environmental concerns related to trace metals in marine sediments around the oil and gas production facilities (Kennicutt et al., 1996a; Kennicutt et al., 1996b). In addition, their adverse effects have also been reflected on the macrobenthic community structure and diversity (Chen et al., 2010; Mucha et al., 2003). Based on the resistance to heavy metals toxicity marine organisms were divided into different groups: more sensitive (crustaceans), less sensitive (molluscs), and resistant (polychaetes) (Railkin, 2003). Our study also observed the dominance of opportunistic polychaetes at stations nearer the oil wells and which in turn confirms their ability to occupy disturbed habitats.

Species-specific preference towards salinity, temperature, metal concentration, total carbon, and nitrogen was evident in the CCA analysis plotted using the *discriminating species* density. Considering the species specific variation, the polychaete, *Lumbrinereis latreille* was dominant at the oil well platforms while *Prionospio* sp dominated at other sites except at offshore stations (OF) and offshore reference sites (RFs), where *Amphicteis gunneri* and *Laonice cirrata* formed the dominant species respectively. The dominant polychaete *Lumbrineris latreilli* observed at the oil platform stations was also reported from the oil impacted locations (Kröncke et al., 1992). These organisms are reported to produce halogenated aromatic compounds as a defensive or antipredatory mechanism (Coutinho et al., 2018). Hence, this adaptive strategy might have helped them in colonizing the oil platform sites,. The observation of Daan et al. (2006) on the occurrence of *L. latreille* near the oil well sites at a distance of 35 - 45 m in the Dutch sector, where oil based mud cuttings have been discharged further justifies the view. Another abundant polychaete observed at the oil platform sites was *Prionospio* sp, with lower density at the coastal stations and vice-versa at the oil platforms, and an apparent decline in the density with the increasing distance from the oil platforms sites. The polychaete of the genus *Prionospio* have been observed in organic enriched areas and is considered as an indicator

of organic enrichment (Elías et al., 2005). The opportunistic nature of these organisms, favors them to dominate in disturbed conditions (Giangrande et al., 2005; Rehitha et al., 2017). *Amphicteis gunneri*, regarded as tolerant to disturbances (Borja et al., 2000) was observed in high densities at the oil platforms and the offshore stations and exhibited a decline in their abundance away from these locations. Rygg (1985) observed *Laonice cirrata* as non-tolerant to the trace metal Cu, and are likely to avoid those sites (Hiscock et al., 2004). Hence their dominance at the offshore reference stations situated far away from the oil wells indicates their increased sensitivity to the metal pollutants. *Magelona* sp and *Aricidea* sp, considered as sensitive species to disturbances (Bigot et al., 2008), was observed adjacent to the oil well sites. However, *Aricidea* sp has been reported abundantly from a strip mining effluent area at Cape Rosier, Maine (EPA, 1970). Further, recently, Sivadas et al., 2016 considered *Magelona a* sp as EG III category as it exhibited a sudden increase in abundance after the upwelling and a conspicuous decline thereafter.

Another noticeable observation was the lower density of the amphipod, *Ampelisca* sp. in the oil well platforms compared to the offshore stations and the offshore reference stations. According to Kingston, (2002), these amphipods are very sensitive to oil contamination and are observed to have low density or disappear from the oil contaminated sites. The amphipod genus *Ampelisca* exhibited a high sensitivity to toxins especially sediment PCBs, pesticides, metals, and PAHs (Gesteira and Dauvin, 2000; Bagge, 1969), and can be excellent indicators of oil pollution because of their high sensitivity (Lee et al. 1977) to these pollutants. Hence, their lower density at oil well platforms and relatively higher occurrence at offshore stations and offshore reference stations indicate the impact of oil and gas exploration activities on their distribution. The polychaete *Terebellides stroemi*, exhibited lower density at the oil well platforms, where the sediment Cu concentration was higher compared to the adjacent regions. It has been observed that high sediment concentration of Cu was toxic to this polychaete (Rygg, 1985). The present study revealed the distinct preferences of different organisms inhabiting the oil impacted regions and the locations away from the oil well sites.

While considering the less abundant macrobenthic taxa, though their contribution to the total macrobenthic density was inconspicuous, their mere presence/absence forms crucial in assessing the anthropogenic influences in a region. The occurrence of the species such as *Eteone siphodonta*, *Oxydromus* sp, *Malacoceros indicus*, *Micronephthys oligobranchia*, *Schistomeringos* sp, *Barantolla* sp, *Euclymene* sp, *Praxillella* sp, and *Cirratulidae* exclusively in the oil well platforms indicates their tolerances to the disturbed environment. Polychaete species belonging to *Phyllodocidae*, *Spionidae*, and *Capitellidae* were identified as opportunistic species by several studies (Grassle and Grassle, 1974; Pearson and Rosenberg, 1978), and their presence indicates their strategy of colonization of unstable

habitats. The presence of species like *Amythasides macroglossus*, *Pontogenia* sp, and *Paraonis gracilis* only in the offshore stations, justifies their preferences to inhabit less polluted environment or marginal/transitional areas adjacent to polluted environments. *Amythasides macroglossus* is listed as a sensitive organism to anthropogenic activities (Borja et al., 2000). Prior study by Mair et al. (1987) have shown a marked reduction in the abundance of this species at the North Sea oil platforms. The polychaete, *Paraonis gracilis* was reported as pollution tolerant in an organically enriched sea loch system (Pearson 1971). Previous studies by Davies et al. (1984) illustrating the occurrence of *Exogone* sp in marginally disturbed areas or 'transitional zone' and their complete absence in the building impacted site of a power station by Musco et al. (2004) further adds evidence to their sensitive nature. Since the present study lacks replicate sampling of benthic fauna; we considered it as a limitation of the study, though it covered many stations adjacent to and away from the oil well platforms.

Several studies effectively validated the performances of AMBI and M-AMBI indices regarding their ability to account for the effects of various anthropogenic activities in different geographical areas including Indian waters (Borja et al., 2003; Muxika et al., 2005; Bigot et al., 2008; Sivaraj et al., 2014; Feebarani et al., 2016; Joydas et al., 2017; Naidu et al, 2018; Jayachandran et al., 2020; Santibanez-Aguascalientes et al., 2020). The slightly disturbed conditions revealed by AMBI, and moderate-good-high status according to M-AMBI near the oil well sites indicate that the macrobenthic fauna is under stress. Similarly, slightly disturbed condition with either high or good ecological status was observed after 12 years of oil Spill (1991) in western Arabian Gulf (Joydas et al., 2017). Whereas slightly and highly polluted, condition with moderate to high status was obtained in the Nandgaon coastal waters affected by industrial effluents (Sivaraj et al., 2014). The positive correlation of AMBI index with the metals Cu, Cd, and Ni indicates the decrease in the ecological quality status with the increase of these metal concentrations. The slightly disturbed condition (H' index and AMBI) was observed at a distance of 1-1.5 km away from the oil platforms (OFW) with the dominance of opportunistic species and undisturbed condition was found at the regions 3-4 km away from the platforms indicating the impact of these activities on the environment. The study by Hernández-Arana et al. (2005) have shown the impact of the disturbances at about 1 km from the oil production platforms with more severe effects at regions within 500 m radius with a clear domination of opportunistic macrobenthic species. Muxika et al. (2005) also observed a clear impact of the oil platforms up to 500-1,000 m distance using AMBI in the northern North Sea, in which the same pattern has been detected by Davies et al. (1984), for the same oilfields, using community structure, further affirms the applicability of these biotic indices. According to AMBI 88% of the stations at the oil well sites were under slightly disturbed conditions indicating relatively low deterioration of benthic

communities at the oil well sites. The M-AMBI index exhibited moderate-good–high conditions at the oil well sites, compared to areas farther away from it thus revealing a progressive increase in the habitat quality at regions situated further away from the oil well platforms.

2. Conclusion

The study evidenced a marked reduction in the macrobenthic standing stock and diversity in the oil well platform sites with a conspicuous increase in the abundance of the opportunistic species. The distribution of macrobenthic groups showed clear spatial variability among the oil well sites and other sampling locations, with noticeable domination of polychaetes in the oil well sites. The high enrichment factor (> 10) of the trace metals in the oil well platforms indicated their anthropogenic origin. Along with the environmental factors, such as depth, sediment texture, and composition, metal concentration was found to have a prominent effect on the distribution of macrobenthic fauna. Thus the study depicting slightly disturbed conditions at distance of 1-1.5 km away from the oil well platforms and high quality status farther away from the wells as per the AMBI index based analysis, reveals the impact of these activities on the benthic habitat quality. The results of the present study put forth the necessity for further extensive evaluations aimed at understanding the persistence and degradation period of these pollutants, the role of various physical oceanographic processes on their distribution, and also the toxic effects these pollutants impart on the benthic community.

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Table 1 Major environmental parameters and sediment characteristics (average) in the oil and gas exploration sites of Ravva Coast (CS-Coastal stations, RCs-Coastal Reference stations, OFW- Oil well platforms, OF- Offshore stations, and RFs- Offshore Reference stations).

Parameters	CS	RCs	OFW	OF	RFs
Depth (m)	7.1±0.6	9±0	11.3±2.1	16.7±3.4	23.4±0.9
Temperature (°C)	27.5 ±0.03	27.6±0.03	27.7±0.1	27.5±0.1	27.2±0.4
Salinity	32.3±0.03	32.4±0.2	32.5±0.14	32.7±0.14	33.1±0.07
SPM (mg/l)	16.8±5.1	10.5±4.9	16.7±4.9	16.8±8.5	19.7±8.5
pH	8.03±0.04	8.05±0.03	8.02±0.04	8.01±0.04	7.99±0.01
Nitrate (µM)	0.14±0.12	0.32±0.1	0.33±0.4	0.27±0.1	0.68±0.5
Phosphate (µM)	0.27±0.1	0.2±0.08	0.15±0.12	0.08±0.05	0.17±0.03
Silicate (µM)	3.6±0.4	2.78±0.34	2.69±0.7	3.06±0.9	1.59±1.2
Chlorophyll-a (mg m ⁻³)	0.63 ±0.2	0.37 ±0.01	0.34 ±0.1	0.41 ±0.2	0.22 ±0.1
Sand (%)	11.45±16.8	30.6±27.5	12.8±18.3	19.9±23.7	7.8±3.4
Silt (%)	46.6±22.02	44.5±34.6	58.2±23.6	45.1±20.4	62.9±19.5
Clay (%)	41.9±19.5	25±7.1	30.3±18.5	34.9±12.9	29.2±17.1
TC (%)	0.63±0.7	1.4±0.8	0.82±0.3	1.10±0.3	1.1±0.5
TN (%)	0.02±0.004	0.07±0.02	0.05±0.03	0.06±0.03	0.07±0.03

SPM-Suspended particulate matter; TN-Total nitrogen; TC-Total carbon

Table 2 Results of the non-parametric Kruskal-Wallis test of major biotic and abiotic parameters in the oil and gas exploration sites, Ravva Coast.

Parameters	P value	F value
Temperature (°C)	0.04	15.35
Salinity	< 0.0001	33.09
SPM (mg/l)	0.576	0.73
pH	0.47	0.91
Nitrate (µM)	0.02	11.70
Phosphate (µM)	0.01	13.82
Silicate (µM)	0.002	5.61
Chlorophyll-a (mg m⁻³)	0.001	6.290
Sand (%)	0.665	2.384
Silt (%)	0.553	0.765
Clay (%)	0.552	3.034
TC (%)	0.02	3.502
TN (%)	0.01	14.23
Biomass (g/m²)	0.037	4.36
Density (ind/m²)	0.152	1.81

Table 3 Variation of Enrichment factor (average) for the sediment trace metals in the oil and gas exploration sites, Ravva Coast.

Parameters	CS	RCs	OFW	OF	RFs
Cu	13.87	15.03	30.67	21.45	21.56
Cd	79.35	35.32	268.6	79.2	238.5
Ni	8.86	21.06	19.31	11.03	15.09
Cr	4.38	5.66	8.04	3.43	7.51
Pb	23.58	27.75	33.67	23.93	25.96
Zn	8.08	21.8	20.55	13.65	12.48
Mn	2.61	3.9	4.12	3.79	3.07

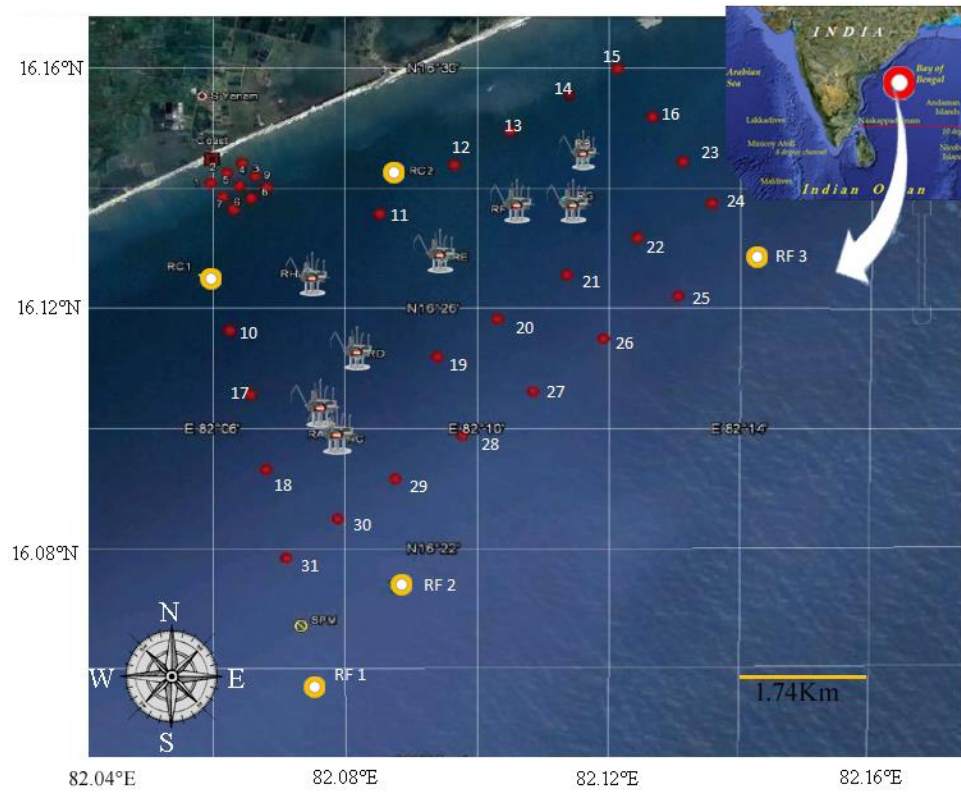


Fig. 1 Map showing the sampling locations in Krishna-Godavari basin (Ravva coast)

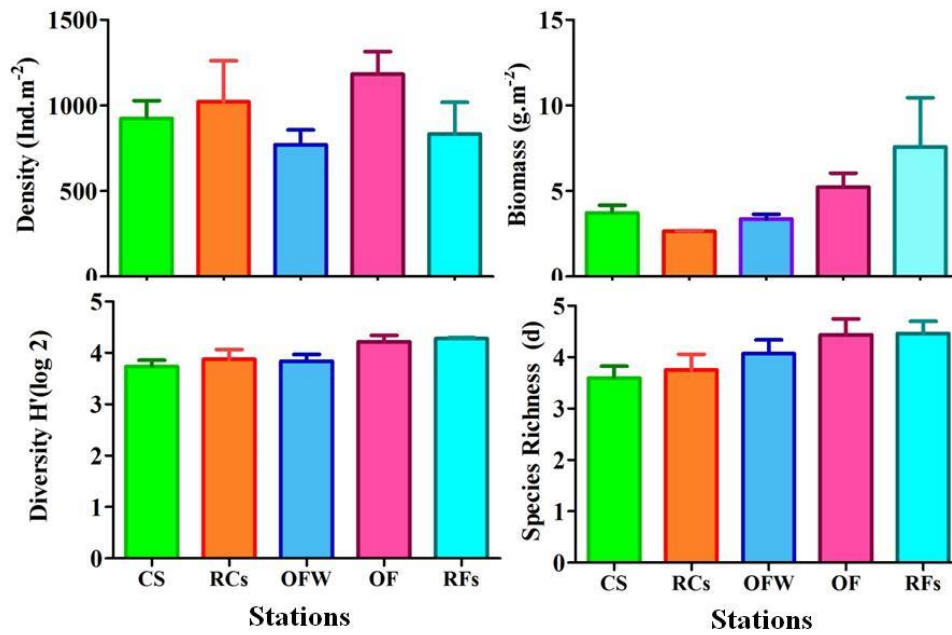


Fig. 2. Distribution of macrobenthic density, biomass, diversity and species richness (mean with SEM) in the sampling locations at the oil and gas exploration sites, Ravva Coast.

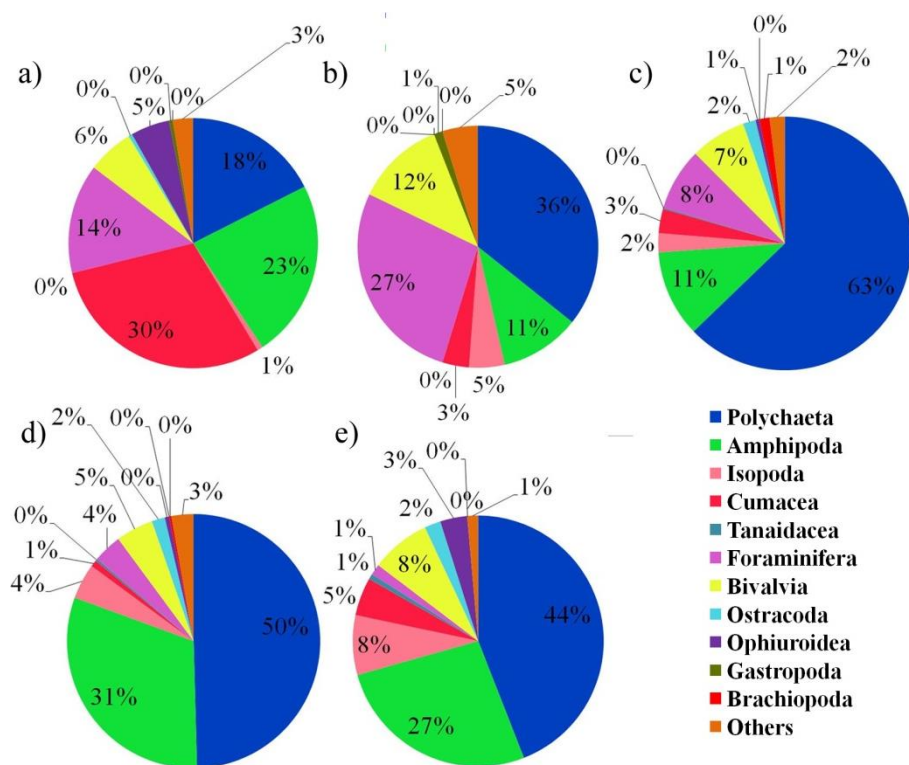


Fig. 3 Pie chart showing the distribution of different macrobenthic groups in the oil and gas exploration sites, Ravva Coast; (a) Coastal stations, (b) Coastal Reference stations, (c) Oil well platforms, (d) Offshore stations, and (e) Offshore Reference stations.

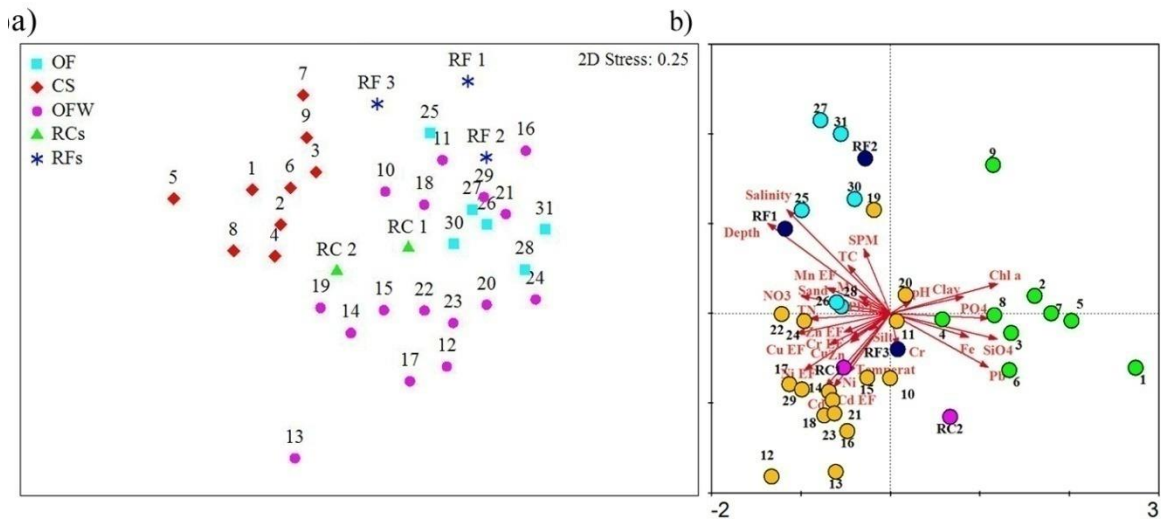


Fig. 4. Bray-curtis similarity based on hierarchical clustering of sampling stations depicted through (a) NMDS (non-metric multidimensional scaling) showing macrobenthic assemblage pattern in the oil and gas exploration sites, Ravva Coast and (b) Canonical Correspondence Analysis (CCA) scatter plot showing ordination of sampling sites with respect to environmental variables and trace metals.

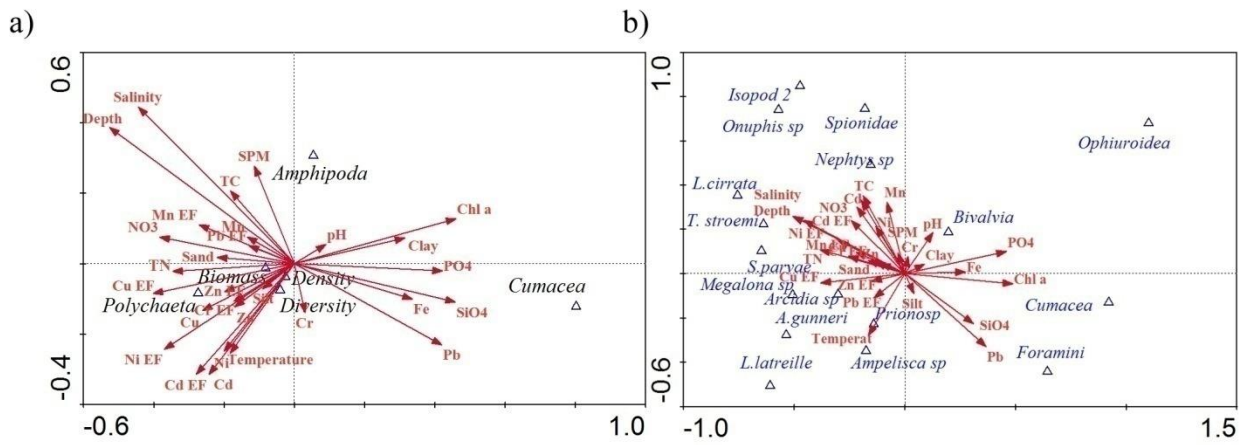


Fig. 5. Canonical Correspondence Analysis (CCA) biplot showing ordination of (a) macrobenthic groups and (b) major discriminating species with respect to environmental variables and trace metals.

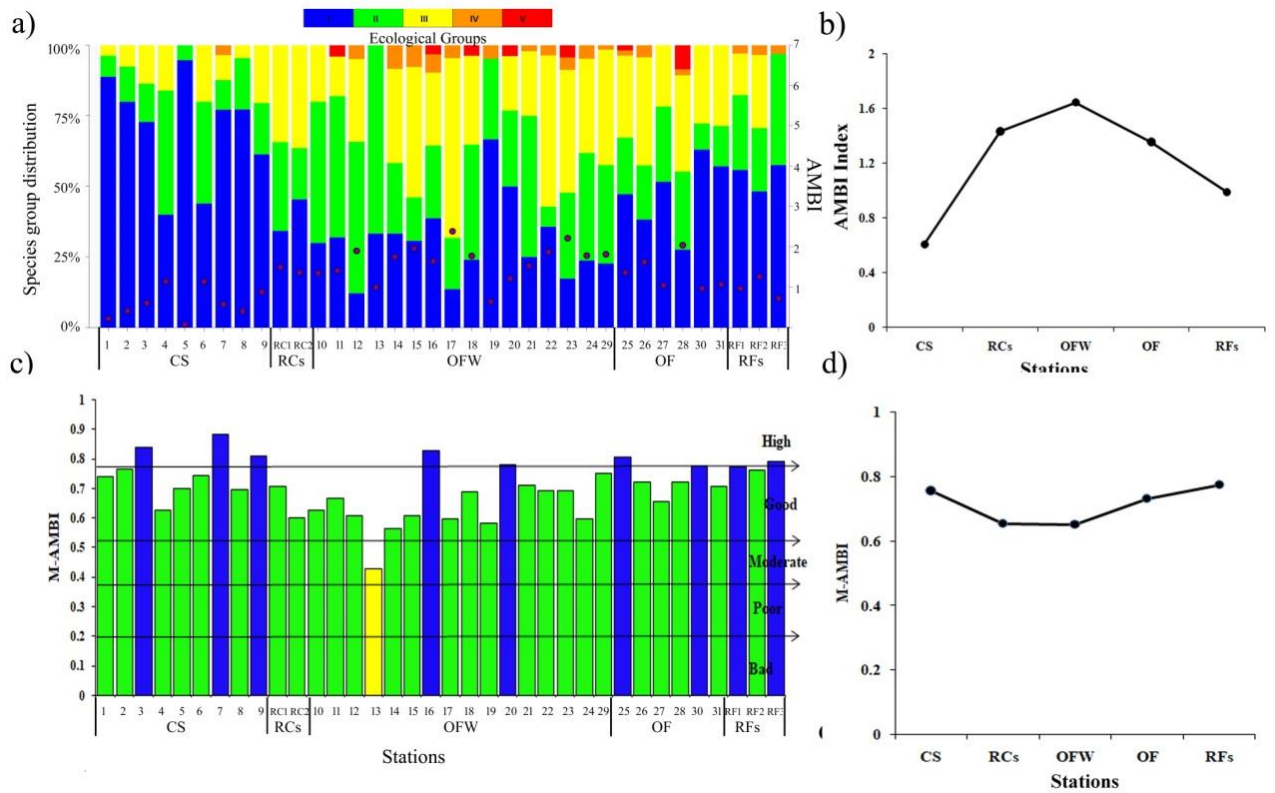


Fig. 6. Variations in the AMBI (a & b) and M-AMBI (c & d) indices in the oil and gas exploration sites, Ravva Coast; (CS) Coastal stations, (OFW) Oil well platforms, (OF) Offshore stations (RCs), Coastal Reference stations, and (RFs) Offshore Reference stations.