

**Seasonal variation of phytoplankton growth and microzooplankton grazing in a tropical coastal water - off Kochi, Southwest coast of India**

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**Abstract**

Phytoplankton growth and microzooplankton grazing in the coastal waters of Kochi, Southwest coast of India, were assessed during three seasons (Pre-Monsoon; Southwest Monsoon and Northeast Monsoon) using the dilution technique. Nutrients concentration in the study area was low during the Pre-Monsoon (PRM) compared to the Southwest Monsoon (SWM) and Northeast Monsoon (NEM) periods. Phytoplankton biomass (Chl.*a*) and growth rate were the highest during the SWM followed by the NEM. They were influenced mainly by the coastal upwelling and estuarine influx. Microzooplankton grazing rate varied from 0.11 - 0.27 day<sup>-1</sup> and their grazing pressure on phytoplankton production varied from 26 - 80 % day<sup>-1</sup>. The highest grazing pressure of microzooplankton on phytoplankton was found during the PRM, when nutrient concentration was low. It was found that ~80% of the daily phytoplankton production and 31% of their biomass were grazed by microzooplankton during the PRM. On the other hand, microzooplankton grazing on phytoplankton biomass and production were low (11% and 26%, respectively) during the nutrient-repleted SWM. Grazing experiments using size-fractionated phytoplankton showed that microzooplankton prefers nano size fraction of the phytoplankton community. This study presented a baseline information on microzooplankton grazing in the nearshore waters along the southwest coast of India during different seasonal hydrographical setting.

**Key words:** Microzooplankton, Arabian Sea; aloricates, grazing, dilution method, phytoplankton

## 1. Introduction

Microzooplankton (20-200  $\mu\text{m}$  in size) are heterotrophic plankton, which form an important structural and functional component of pelagic ecosystems by acting as a top predator in the microbial food web (Sherr and Sherr, 2002; Landry and Calbet, 2004). Being the major grazers of phytoplankton (~ 60-75% of primary production), microzooplankton plays a major role in the plankton food web (Caron et al., 1999; Landry and Calbet, 2004; Schmoker et al., 2013). Varieties of feeding modes are observed among microzooplankton; ranging from simple phagotrophy to engulfing of large chain forming diatoms (Johnson, 1986; Hansen et al., 1994; Jacobson, 1999). Tintinnid (loricate) ciliates are filter feeders, which sieve the surrounding water to find and capture their prey and usually have an optimal prey size roughly one tenth of their lorica diameter (Heinbokel, 1978; Johnson, 1986; Hansen et al., 1994). On the other hand, heterotrophic dinoflagellates have a vivid spectrum of feeding modes such as phagotrophy and mixotrophy (Jeong et al., 2010).

Research on the ecology of microzooplankton in marine systems has extensive efforts worldwide (Turner and Tester, 1992; Dolan et al., 2002; Landry and Calbet, 2004; Calbet, 2008). In India, many studies are available on the ecology of microzooplankton in estuaries and marine environments (Madhupratap et al., 1996; Gauns et al., 1996; Jyothibabu et al., 2006 and 2008; Ashadevi et al., 2010; Anjusha et al., 2013; Elangovan et al., 2017). However, the grazing rates of microzooplankton, especially on different size fractions of phytoplankton community, is a least studied aspect not only from Indian waters (Jyothibabu et al., 2006; Gauns et al., 2015), but from the rest of the world as well (Landry and Hasset, 1982, Landry, 1994, Calbert and Landry, 2004; Calbert, 2008; Schmoker et al., 2013).

Studies showed that microzooplankton community grazing can differ with their species composition and seasonality of the preferred food resources in an environment. Jyothibabu et al., (2008) pointed out that the hydrography of the nearshore waters of the southeastern Arabian Sea is mainly governed by the estuarine flux and nearshore ocean processes. Also noted earlier that the phytoplankton productivity in the nearshore waters of Kochi has a seasonality associated with monsoons (Madhu et al., 2007; Jyothibabu et al., 2008). Hence, it is worthwhile to measure the seasonal grazing impact of microzooplankton in the coastal waters of Kochi. Among various methods that are employed for quantifying microzooplankton grazing, the dilution method of Landry and Hasset (1982) has been utilized in this study.

World over, most of the studies on microzooplankton grazing have focused on tintinnid (loricate) ciliates (Caprilluo and Carpenter., 1980; Burkill, 1982; Verity, 1985). The very recent study of Anjusha et al., (2018) in the coastal waters Kochi showed that aloricate ciliates numerically dominates the microzooplankton community in the present study area. Considering all the above, we expect a measurable seasonal variations in the grazing rate of microzooplankton in the coastal waters of Kochi. The major objectives of the this study were set as (a) to generate a baseline on the seasonal variations in microzooplankton grazing in the near-shore waters along the southwest coast of India (off Kochi) and (b) to study the size-selective grazing of microzooplankton on phytoplankton in the study region.

## **2. Materials and Methods**

### **2.1. Sampling and analysis**

Altogether 5 dilution experiments were carried out in the present study to understand the seasonal variations of phytoplankton growth and microzooplankton grazing in the near shore waters off Kochi (Fig.1). Water samples were collected during the Pre-Monsoon (March-April), the Southwest Monsoon (July) and the Northeast Monsoon (December - January) of 2014. Vertical profiles of temperature and salinity were collected using a Conductivity Temperature Depth (CTD SBE 911 Plus, USA) profiler. Niskin samplers were used to collect water samples from surface and subsurface layers for measuring dissolved oxygen (DO) and macronutrients (nitrate, phosphate and silicate). DO was estimated following the Winkler's method (Grasshoff et al., 1983) and nutrients were analyzed following standard colorimetric methods (Grasshoff et al., 1983).

### **2.2. Phytoplankton biomass (chlorophyll *a*)**

The total chlorophyll *a* was measured by filtering 500 ml of water on Millipore cellulose nitrate filter paper (0.22  $\mu\text{m}$ ) and subsequent extraction using 10 ml of 90% acetone overnight in cool condition in a refrigerator. The extracted chlorophyll *a* was measured using a Trilogy Turner fluorometer following standard procedures (UNESCO, 1994). Fractionated phytoplankton biomass (micro, nano and pico fraction) was measured following serial filtration of water samples using different filters (Iriarte and Purdie, 1994; Jyothibabu et al., 2013, 2014). One liter of water samples were filtered in a step wise manner through 20  $\mu\text{m}$  sieve and subsequently through 2 and 0.2  $\mu\text{m}$  (47 mm diameter, glass fiber) filter papers (Jyothibabu et al., 2014). The fractionated chlorophyll *a* was estimated using the same procedure adopted for the total chlorophyll *a*. Standard conversion factor of Peterson and Festa, (1984) was used to convert chlorophyll *a* to carbon biomass.

### **2.3. Microzooplankton density and biomass**

Water samples (500 ml) were collected and preserved in 3-8% of acid Lugol's iodine for the grazer density estimation. Initially, samples were concentrated into 40 ml by adopting gravity settling and siphoning procedure. Prior to the microscopic analysis, the initial 40 ml sample was allowed to settle for 2 days and concentrated to 10 ml final concentration. Sub-sample of 1ml each was taken after shaking the samples and was analyzed in Sedgwick Rafter counting chamber under an inverted epifluorescence microscope (Olympus IX 51) equipped with image analyzer. Images of each organisms in the samples were taken and identified into groups/ species following available literature (Kofoid and Campell, 1939; Steidinger and Williams, 1970; Subrahmanyam, 1971; Maeda, 1986; Krishnamurthy et al., 1995). Their images were captured for the later biovolume estimation using the image analyses. Microzooplankton biomass was estimated by considering the cell dimensions of each individual by the image analyzer of the microscope. Based on the morphology, biovolume of ciliates and heterotrophic dinoflagellates, their biovolume was calculated after attributing them suitable geometric shape. Later, biovolume of these individuals was converted into carbon units by adopting standard conversion factors (UNESCO, 1994). The organic carbon content of copepod nauplii was estimated using standard conversion factor available in the literature (UNESCO, 1994).

### **2.4. Microzooplankton grazing experiment**

Microzooplankton grazing measurements were carried out using 'dilution technique' of Landry and Hassett (1982). The dilution series was prepared by combining natural (unfiltered) sea water with particle free (filtered) sea water. All experimental containers, bottles and tubing were washed with 10 % HCL and distilled water before the beginning of each experiment. To conduct the grazing experiment, 100 liters of sea water was collected from the sea surface in five 20 liter black carboys and transported to the laboratory. To prepare the diluent, 40 liter of seawater was filtered serially in a stepwise manner through 200 $\mu$ m sieve, 2  $\mu$ m filters and finally through 0.2  $\mu$ m filters. For conducting the microzooplankton grazing experiments, larger grazers (<200  $\mu$ m) were removed from the natural unfiltered samples by screening through a 200  $\mu$ m nylon mesh.

Five dilution series (20, 40, 60, 80 and 100%) were prepared except during the SWM when only four dilutions (25, 50, 75 and 100%) were used by the mixing of filtered sea water and natural assemblage. To protect the delicate protists during the experiments, adequate care was taken during the entire experimental handling. 2L Borosil bottles were used as the incubation container. In each dilution, 6 bottles were used, in which 3 bottles were used as initial and the remaining 3 bottles were incubated for 24 hrs in larger fiber reinforced plastic tanks (FRP) tanks at 0.5 m depth from the

surface under natural light conditions. Continuous water flow was maintained in the FRP tanks to avoid the settling of particles and reduce the temperature in the surface waters. Phytoplankton biomass (Total and size fractionated Chl. *a*), microzooplankton density and biomass estimations were measured in the beginning and end of the experiments using the standard procedures. In each dilution, subsamples of 500 ml each were filtered for measuring total and size-fractionated chlorophyll *a* and for the quantification of the microzooplankton abundances. Nutrients were not added in the present study, as they were already optimum in the study domain (Table 1).

## 2.5. Calculation and expression of results

In all experiments, a linear regression equation was used to obtain the grazing mortality rate, relating the fraction of the undiluted water and the net phytoplankton growth rates estimated from the changes in the chlorophyll concentration during the incubation. As per the dilution method (Landry and Hassett, 1982), changes in biomass between the beginnings ( $C_0$ ) and the end ( $C_t$ ) of the incubation time ( $t_{24}$  hours) were used to calculate the net growth rates ( $k$ , per day) of the total phytoplankton community.

$$P_t = P_0 e^{(k-g)t}$$

$$k = 1/t. \ln (C_t/ C_0)$$

Grazing rate ( $g$ , day<sup>-1</sup>) and apparent growth rates ( $k$ , day<sup>-1</sup>) are the slope and the intercept of the linear regressions between the net growth rates ( $k$ ) and the dilution factor ( $X$ ) (Landry and Hassett, 1982)

$$k = k - gX$$

The daily impact of microzooplankton on the standing stock (% SS, day<sup>-1</sup>) and production (% Pp, day<sup>-1</sup>) was calculated as

$$\% \text{ SS} = (1 - e^{-k}) * 100$$

$$\% \text{ Pp} = g/k * 100$$

The quantity of carbon consumed ( $G$ , mg m<sup>-3</sup>d<sup>-1</sup>) and produced ( $P$ , mg m<sup>-3</sup>d<sup>-1</sup>) were calculated as:

$$G = m * C_m,$$

$$P = g * C_m,$$

Where  $C_m$  (mg m<sup>-3</sup>) is the average chlorophyll *a* or carbon biomass during incubation time and is calculated as:

$$C_m = C_0 [e^{(k-g)t} - 1]$$

$$(k - g)t$$

## 2.6. Statistical analysis

ANOVA was performed to compare the seasonal differences of the phytoplankton growth and microzooplankton grazing. Prior to ANOVA analysis, the homogeneity and distribution of data were analyzed which showed a normal distribution pattern. Initially, the data sets were normalized with mean and standard deviation (Z score transformation) to avoid the unit invariance. Detrended Correspondence Analysis (DCA) was performed for the selection of the appropriate ordination method for the present data sets. The results of DCA represents an axis gradient length of <2, which indicated the use of Linear multivariate RDA for the present data sets. Redundancy Analysis (RDA) was performed using this data to find the relationships between different hydrographical (salinity, temperature, nitrate, phosphate and silicate) and biological (phytoplankton biomass, phytoplankton growth rate and microzooplankton grazing) parameters. The ordination significances were tested with Monte Carlo permutation test (with 499 permutations). ANOVA and the distribution pattern analysis of the datasets were performed using XL-Stat Pro software package and the multivariate RDA was performed in CANOCA 4.5 (Leps and Smilauer, 2003).

## 3. Results

### 3.1. Hydrography

Seasonal variations of salinity, temperature and nutrients were prominent during the study period (Table1). The PRM was characterized by warm, high saline and less nutrient condition, whereas, the water column was cool, nutrient rich and low saline during the SWM (Table1). NEM showed an intermediate levels of environmental conditions between the PRM and SWM. The two main processes which controlled the hydrographical parameters of the study location were estuarine flux and upwelling. During the PRM period, rainfall associated flux was less. However during the SWM period, estuarine flux was high in associated with the seasonal rainfall. During the SWM, vertical distribution of salinity showed large variations with very low surface salinity (8.4) whereas in the subsurface it was ~6 units greater than that of the surface (14.9). During the PRM, dissolved oxygen concentration was high ( $6 \text{ ml/L}^{-1}$ ) and turbidity was low (1.8). Cool and hypoxic subsurface waters was present in the study area during the SWM (Table 1), which indicated the prevalence of upwelling process. During the NEM, environmental parameters were intermediate between the PRM and the SWM. High silicate concentration was obtained during the period (Table 1), whereas nitrate

concentration was comparatively less in the surface waters (1.3  $\mu\text{M}$ ) as compared to the subsurface (5.8  $\mu\text{M}$ ).

### 3.2. Phytoplankton standing stock and carbon biomass

Chlorophyll *a* showed noticeable seasonal variation (Fig. 2). It was less during the PRM and increased significantly (more than two folds) during the SWM (Table1). The surface chl. *a* concentration was generally high during July (9.8  $\mu\text{g L}^{-1}$ ). During the entire study period, nanoplankton was found to be the major phytoplankton (64 - 82%) followed by microplankton (10-33~ %). Larger phytoplankton (micro fraction) biomass was higher during the SWM as compared to the PRM and NEM. Picoplankton contribution to the total chlorophyll were consistently low (3-8%) throughout the study. Standing stock of phytoplankton was the highest during the SWM (492  $\mu\text{g L}^{-1}$ ) followed by the NEM (375  $\mu\text{g L}^{-1}$ ) and the PRM (192  $\mu\text{g L}^{-1}$ ).

### 3.3. Microzooplankton composition, density and biomass

Microzooplankton grazers were composed of both protozoans and metazoans (Supplementary material 1). Ciliates were the major protozoan (~78%) component (Fig. 3), followed by heterotrophic dinoflagellates (HDS). Based on morphology, ciliates present in the sample can be considered in to loricate (tintinnid) and aloricate ciliates. Aloricate ciliates were the major group (~70%) in the present study region followed by loricates (30%). A total of 31 species of microzooplankton were recorded during the present study, which consisted of 14 aloricates, 12 loricates and 5 HDS (Supplementary material 2). HDS was composed mainly of *Protoperidinium* sp and *Gyrodinium* sp.

During the PRM, aloricate ciliates were composed mainly of *Laboea strobila*, *Lohmaniella spiralis* and *Strombidium minimum*, whereas, *Codonellopsis ostenfeldii*, *Tintinnidium primitivum* and *Tintinnopsis beroidea* were the major loricates (Supplementary material 2). During the SWM, larger aloricates *Strombidium conicum*, *Lohmaniella spiralis*, *Strombidium wulffi* and smaller mixotrophic ciliate *Myrionecta rubra* dominated the environment. Also *Myrionecta rubra* and *Euplotes* sp. were found only during the SWM. Aloricate ciliate *Strombidinopsis acuminatum* was found dominant during both PRM and NEM. Three species of *Protoperidinium* were found common, which include *Protoperidinium divergens*, *P. oceanicum* and *P. depressum* (Supplementary material 2).

In the present study, maximum density of microzooplankton was obtained during the SWM (3800 No.  $\text{L}^{-1}$ ) followed by the NEM (2200 No.  $\text{L}^{-1}$ ) and the PRM (2100 No.  $\text{L}^{-1}$ ) (Fig.3a). Very high density of aloricates (2700 No.  $\text{L}^{-1}$ ) was obtained during the SWM (Fig. 3b) compared to the other seasons. Aloricate ciliates also dominated in the environment during the NEM. During the PRM and

the NEM, loricate ciliates formed the second major group, whereas during the SWM, H. dinoflagellates formed the second dominant group (18%).

Microzooplankton biomass distribution was similar to their density (Fig. 3a) with the highest in July ( $25.51 \text{ mgC m}^{-3}$ ) and the lowest in December ( $13.39 \text{ mgC m}^{-3}$ ). The aloricate ciliates contributed the highest to the total biomass during the SWM, whereas, during the PRM and the NEM, the contribution of loricate ciliates was the highest (Fig.3b). HDS contributed higher to the MZP community biomass compared the loricate ciliates. Aloricate ciliates dominated the biomass during the NEM period also with comparatively higher loricate contribution than during the SWM.

### **3.4. Microzooplankton grazing on total phytoplankton**

Seasonal variation in phytoplankton growth and microzooplankton grazing rates are presented in Fig.4. It showed a clear seasonal variation in the phytoplankton growth and microzooplankton grazing rates in the study region ( $P < 0.05$ ). The phytoplankton growth rate was the highest during the SWM ( $0.51 \text{ day}^{-1}$ ), followed by the NEM ( $0.41 \text{ day}^{-1}$ ) and the PRM ( $0.36 \text{ day}^{-1}$ ). On the other hand, microzooplankton grazing rate was the highest during the PRM ( $0.24$  and  $0.27 \text{ day}^{-1}$ ), followed by the NEM ( $0.14$  and  $0.19 \text{ day}^{-1}$ ) and the SWM ( $0.11 \text{ day}^{-1}$ ). A representative photomicrograph of microzooplankton grazing on phytoplankton is presented in Fig.5.

Microzooplankton grazing pressure on phytoplankton is presented in terms of daily removal of phytoplankton standing stock (SS -  $\% \text{ day}^{-1}$ ) and production (PP -  $\% \text{ day}^{-1}$ ). During the PRM, microzooplankton grazing accounted for 31% of the standing stock and 80% of the production of phytoplankton (Fig.6a-b). During the SWM, microzooplankton grazing was 11% of the standing stock and 26% of the production (Fig.6a-b). During the NEM, the microzooplankton grazing was 17% of the standing stock and 64% of the phytoplankton production. Daily impact of microzooplankton on phytoplankton in terms of carbon is depicted in Fig.7. It is clear that irrespective of the seasons, carbon produced per day by phytoplankton (P) ( $\text{mgC m}^{-3} \text{ day}^{-1}$ ) was higher than that of the carbon consumed by microzooplankton per day (G) ( $\text{mg C m}^{-3} \text{ day}^{-1}$ ). The remaining part of the carbon produced by the phytoplankton could be either consumed by other grazers or sink down to the bottom (Fig.7).

### **3.5. Microzooplankton grazing on size-fractionated phytoplankton**

Size-fractionated phytoplankton biomass in grazing experiments showed that microzooplankton grazing on nano-phytoplankton was the highest compared to the pico- and micro-phytoplankton. Seasonal variations in nano-phytoplankton growth and grazing rate showed a trend similar to that of the total phytoplankton (Fig. 6c-d), indicating the dominant contribution of the nano-fraction to the



total autotrophic community biomass (Fig. 2b). Microzooplankton grazing rate on nano-phytoplankton was higher during the PRM ( $0.31\text{day}^{-1}$ ), followed by the NEM and the least during the SWM ( $0.18\text{ day}^{-1}$ ) (Fig.8). The microzooplankton community grazing on nano-phytoplankton biomass and production during different seasons showed noticeable variations. During the PRM, microzooplankton grazing was 26% of the standing stock and 87% of the production of nano-phytoplankton. During the SWM, it was 17% of the standing stock and 50% of the production of the nano-phytoplankton (Fig.8). During the NEM period, it was 18 % of the standing stock and 55 % of the production of nano-phytoplankton.

### **3.6. Multivariate Redundancy Analysis**

Multivariate RDA ordinations for the present data sets have been presented in Triplots (Fig.9). Axis 1 (90.7%) and axis 2 (5%) together explain 95.7% of the relationships between the environmental and biological parameters. The Monte Carlo permutation test also showed that these RDA ordinations are significant. RDA Triplot visualized the relationships between hydrographical and biological parameters. The phytoplankton biomass and nutrients axes were aligning closely in the same direction indicating their positive relationships whereas their orientation in the opposite direction of salinity and temperature axes indicate their negative relationship. The axis of phytoplankton growth in the Triplot was oriented to the right side of the plot corresponding to its higher values during the SWM. Phytoplankton growth rate and microzooplankton grazing axes were oriented in the opposite direction indicating their negative relationships.

## **4. Discussion**

Nearshore waters of the SEAS undergoes large seasonal changes in hydrographical settings (Banse, 1968; Jyothibabu et al., 2008). During the PRM, warm, high saline, oxygenated and nitrogen depleted water column predominate the environment. On the other hand during the SWM, well oxygenated, low saline estuarine water occupy the surface while, cool, high saline, hypoxic and nutrient rich upwelled water occupy in the subsurface (Jyothibabu et al., 2008). Compared to the SWM, the water column is warmer and well oxygenated during the Northeast Monsoon. During the PRM, the water column gets thermally stratified and nutrient depleted with low phytoplankton biomass (Madhu et al., 2010; Jyothibabu et al., 2008). The high estuarine influx enriched with nutrients during the SWM causes high phytoplankton biomass and production in the study domain (Madhupratap et al., 2001; Jyothibabu et al., 2006, 2008; Madhu et al., 2007). This low saline estuarine/riverine plume in the surface also inhibit the vertical advection of nutrients in the study area during the SWM (Jyothibabu et al., 2006, 2008). Phytoplankton biomass and composition in the

study region changes seasonally and nanoplankton predominates irrespective of seasons (Madhu et al., 2010). The micro size fraction of the phytoplankton contribute significantly to the total chlorophyll *a* only during the SWM, when nutrient enrichment occurs through estuarine influx and coastal upwelling (Jyothibabu et al., 2008; Madhu et al., 2007; Karnan et al., 2017; Jagadeesan et al., 2017).

#### **4.1. Seasonal variations in microzooplankton**

Noticeably high density of microzooplankton was found during the SWM and during this time aloricate ciliates was dominated in the community. Loricata and aloricate ciliates showed different responses to the estuarine plume water. Positive reciprocation of aloricate ciliates to the freshwater influx was very clear in the present study as recorded earlier elsewhere (Yu et al., 2015). Past studies have also recorded a general increase in ciliate abundance during high fresh water discharge (Chiang et al., 2003; Christaki et al., 2009 and Tsai et al., 2011). The high abundance of ciliates during the SWM (upwelling period) can be linked with the plastidic flagellates usually abundant during nutrient enriched conditions (Verity et al., 1986; Chang, 1990; Jyothibabu et al., 2008; Yu et al., 2015). Conversely, low saline estuarine water during the SWM might cause low abundance of tintinnids due to their low mobility as compared to the aloricates and high predator pressure from carnivorous/omnivorous copepods abundant during the period. Low abundance of hyaline tintinnids in this study could be the result of the coastal/ near shore nature of the study area. The high abundance of *Myrionecta rubra*, a mixotrophic estuarine/ neritic ciliate during the SWM indicate high nutrient availability, high abundance of cryptophyte, low solar radiation and high turbid conditions during the period (Chang, 1990; Johnson et al., 2013).

Low abundance of HDS in the present study area as compared to the ciliates indicated the coastal nature of the study area (Cushing 1989; Jyothibabu et al., 2008; Anjusha et al., 2013). The seasonal highest abundance of HDS found during the SWM was indicative of larger phytoplankton prey available in the environment. Calbet (2008) showed that, heterotrophic dinoflagellates forms the major part of the microzooplankton community in nutrient enriched systems when larger algae dominate in such situation. Three different types of feeding mechanisms occur among the mixo and HDS: direct engulfment, pallium and tube feeding (Gaines and Elbrachter 1987; Hansen and Calado 1999). Therefore, HDS can act as major grazers of bloom-forming diatoms in highly productive hydrographical settings (Sherr and Sherr, 2007).

## 4.2. Phytoplankton growth and microzooplankton grazing

Earlier studies showed that food quantity, quality, temperature, taste, digestibility, catchability and toxicity can play significant roles in microzooplankton feeding (DeMott, 1986; Montagnes and Frankil, 2001; Mitra et al., 2007). RDA Triplot clearly visualized that microzooplankton grazing on the standing stock and the phytoplankton production was relatively high during the PRM period compared to the SWM. This was due to the high abundance of medium sized aloricate ciliates, loricate ciliates (tintinnids) and nano-phytoplankton in the environment. The optimum food size has a major role in deciding the microzooplankton grazing rate (Burkill et al., 1987; Calbet et al., 2008; Huang et al., 2011). The major phytoplankton type during the PRM was nanoplankton, which is the optimal prey size for most of the microzooplankton. As mentioned earlier, the low growth and biomass of phytoplankton observed in the study area during the PRM were related to the stratified and low nutrient water column.

The highest phytoplankton growth rate in this study was obtained during the nutrient-enriched SWM period. This observation corroborates the past observations that significantly high phytoplankton standing stock occurs along the southwest coast of India during the SWM (Madhupratap et al., 2001; Jyothibabu et al., 2008; Habeebrehman et al., 2008). Conversely, the microzooplankton grazing rate was the lowest during the SWM when remarkably high phytoplankton standing stock was present in the environment. The reasons for this situation was (a) inefficiency of the majority of microzooplankton components to feed efficiently on larger phytoplankton and (b) the surplus amount of phytoplankton biomass available during high nutrient conditions. The ranges of phytoplankton growth and microzooplankton grazing rates recorded in the present study was well within the observed ranges elsewhere (Table 2). In spite of the high growth rate of nanoplankton, their mortality rate was found to be higher in the present study. High microzooplankton community grazing on nano-phytoplankton can be attributed to the high occurrence of the prey (nanoplankton) and grazer (microzooplankton dominated by ciliates). Medium-sized ciliates prefer to graze on nano-sized phytoplankton which were abundant in the present study area (Ayo et al., 2001; Struder-Kypke and Lynn, 2003).

This study also measured the microzooplankton grazing on size-fractionated phytoplankton stock, which is the first attempt along the southwest coast of India. Microzooplankton grazing rates vary among different groups of microzooplankton and also the quality of food particles. Usually, ingestion rates increase in proportion to the increase in prey abundance as represented here in the fraction of unfiltered seawater. Microzooplankton grazing rate might reach a maximum at a certain level of food concentration and thereafter it remains constant in spite of further increases in the prey

abundance (Heinbokel, 1978; Teixeira et al., 2014). In this study, the microzooplankton grazing rate on phytoplankton standing stock and production was the highest during the PRM when nano-phytoplankton was abundant in the environment (Jyothibabu et al., 2006; 2008; Madhu et al., 2007). In essence, this study showed that phytoplankton growth rate in the study area is the highest during the SWM, while the highest microzooplankton grazing occurs during the PRM.

## **5. Summary and conclusion**

The seasonal variation in phytoplankton growth and microzooplankton grazing rates in the coastal waters of Kochi, along the southwest coast of India, has been addressed in this paper. Phytoplankton growth and microzooplankton grazing rates were noticeably influenced by the nutrient variations associated with seasonal changes in hydrographical settings, which was evident in multivariate RDA Triplots. The highest microzooplankton grazing on phytoplankton was found during the PRM and during that time 80 % of the total phytoplankton production was grazed by microzooplankton. On the other hand, microzooplankton grazing on phytoplankton production was the lowest (26%) during the SWM. Size-fractionated herbivory experiments showed that microzooplankton prefer nano-phytoplankton as their preferred food. The study evidenced the dominant role of microzooplankton as the grazer of phytoplankton community in the study area especially during the PRM.

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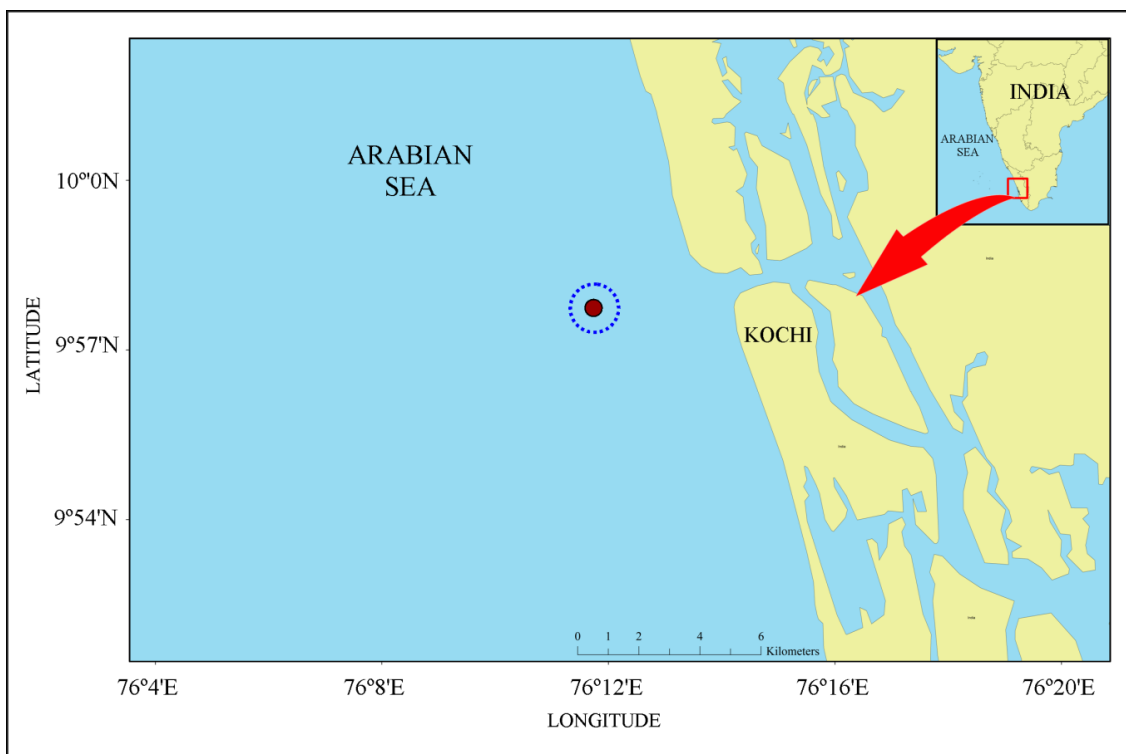
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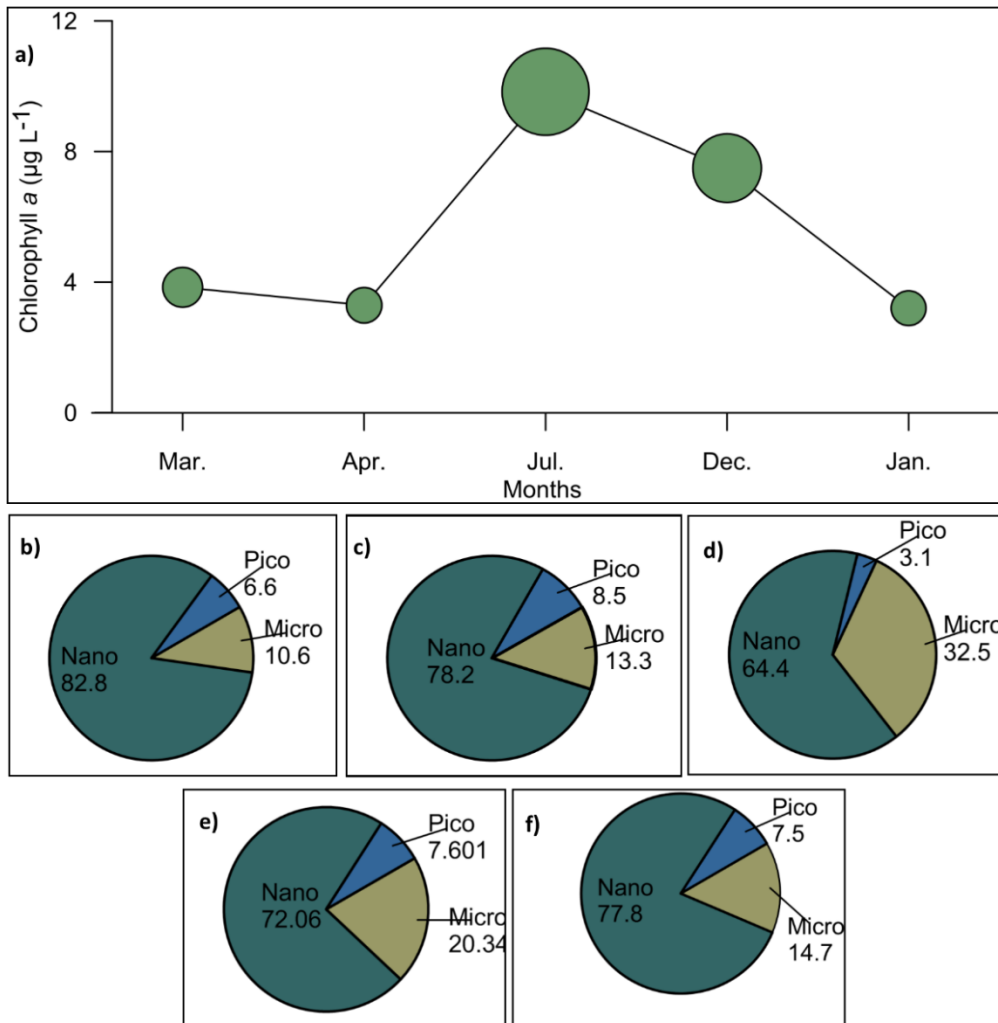
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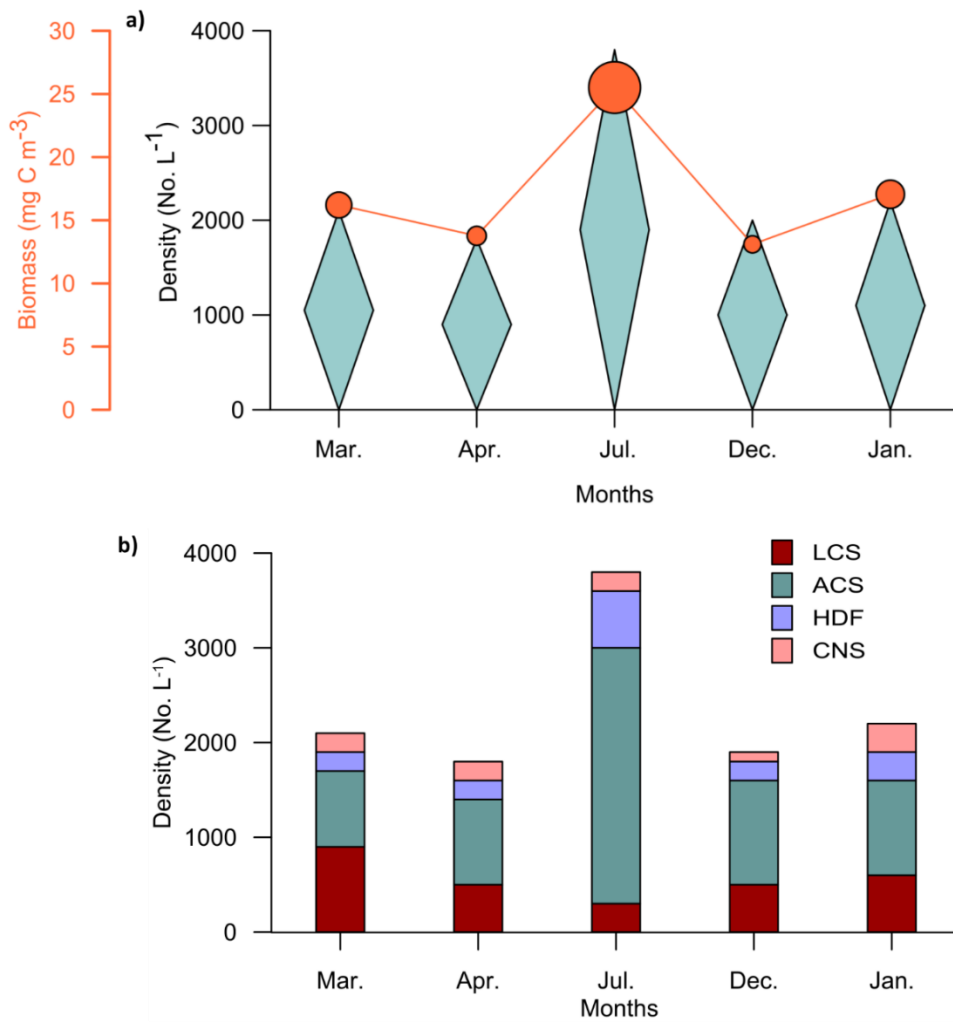
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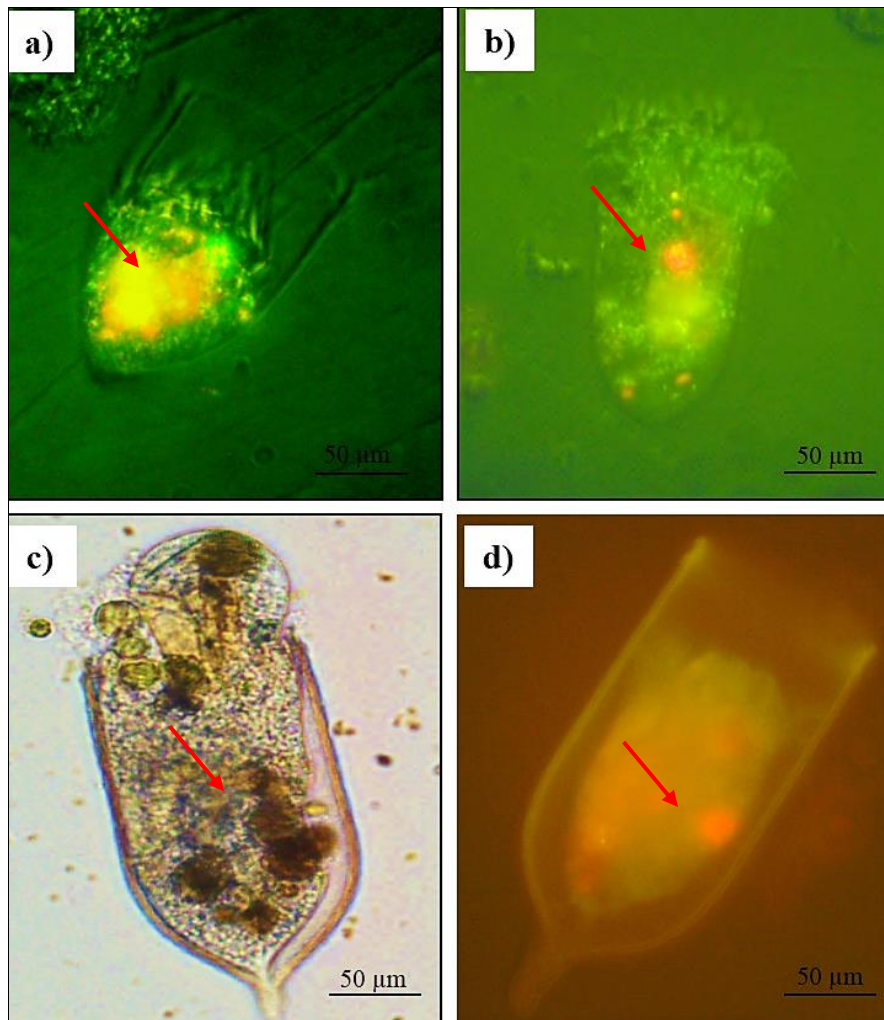
**Fig. 1** - The sampling location in the coastal waters off Kochi (blue dotted circle)



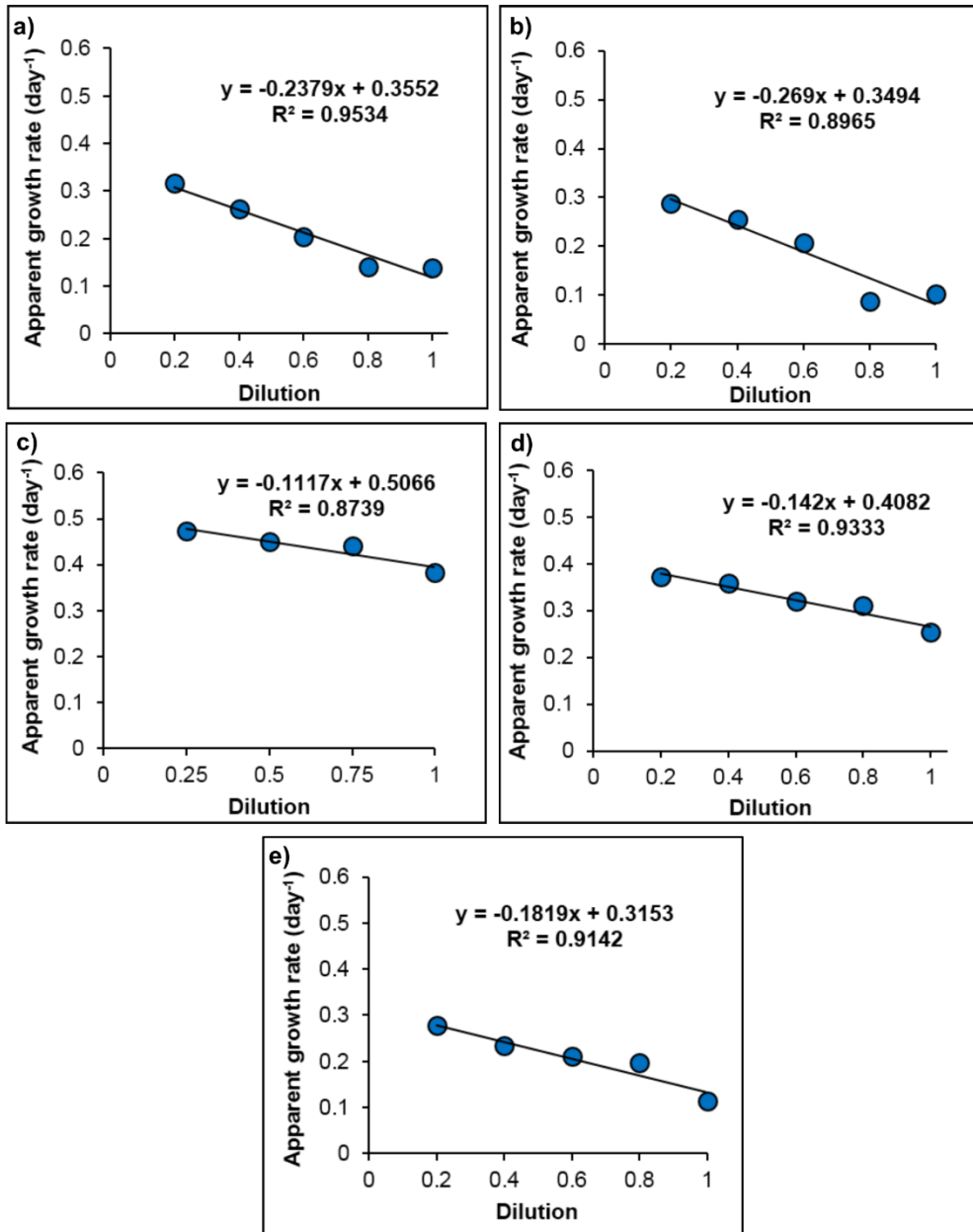
**Fig. 2** - Total phytoplankton biomass (a) and contributions of various size fractions of phytoplankton (percentage) to the total biomass during March (b), April(c), July (d), December (e) & January (f)



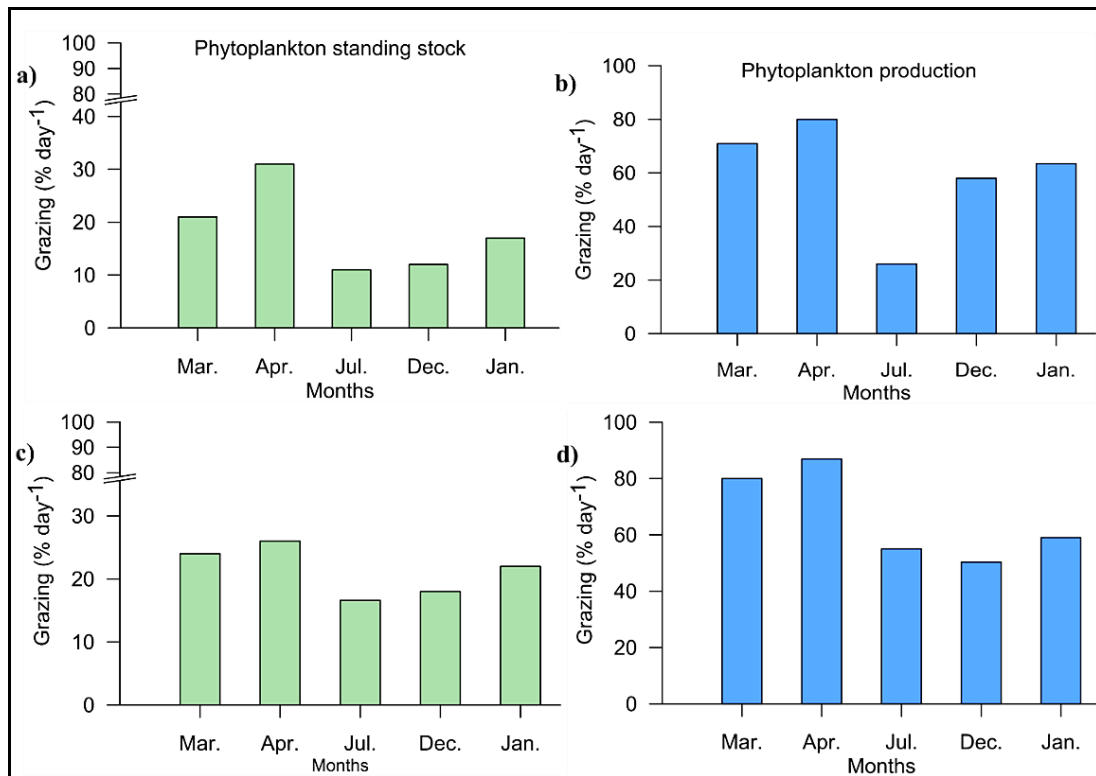
**Fig. 3 - Variations** in microzooplankton density, biomass (a) and group density (b) during the experiment period. **Abbreviations:** LCS- Loricate ciliates, ACS-Aloricate ciliates, HDF-Heterotrophic dinoflagellates, CNS- Crustacean naupliiii



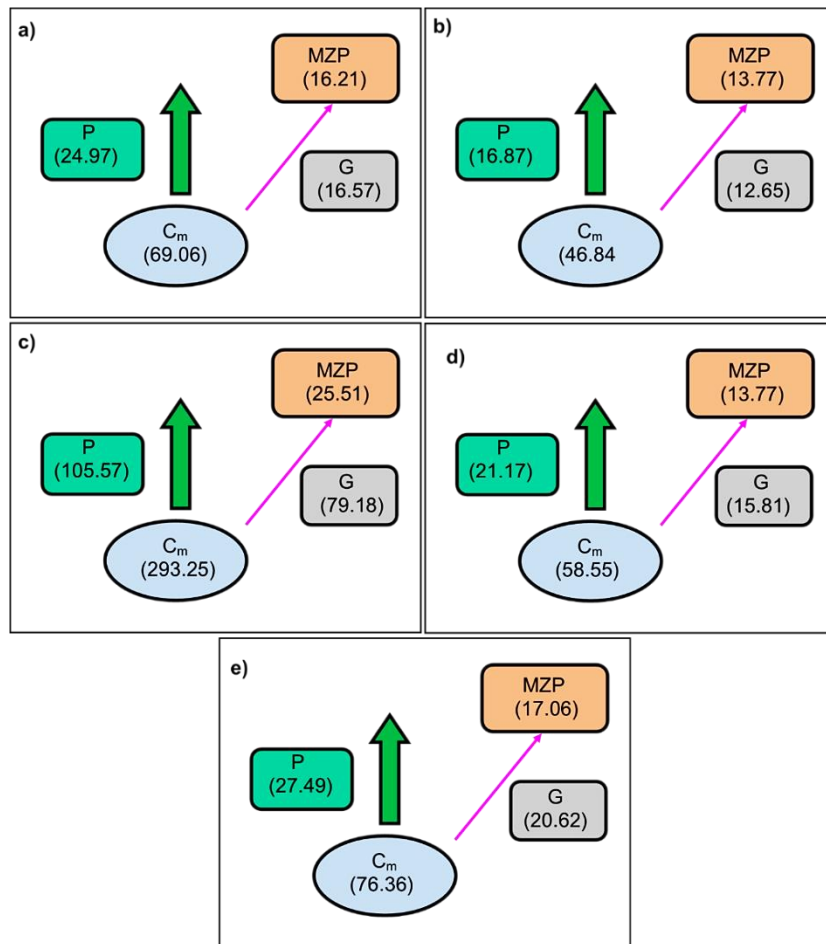
**Fig. 4** - Photomicrographs showing microzooplankton grazing on phytoplankton during the experiments (red arrows).Red chlorophyll autofluorescence indicate ingested phytoplankton materials.



**Fig. 5** - Daily impact of microzooplankton grazing on total phytoplankton biomass (Chl. *a*) in the months of March (a), April (b), July (c), December (d) and January (e) in the study area

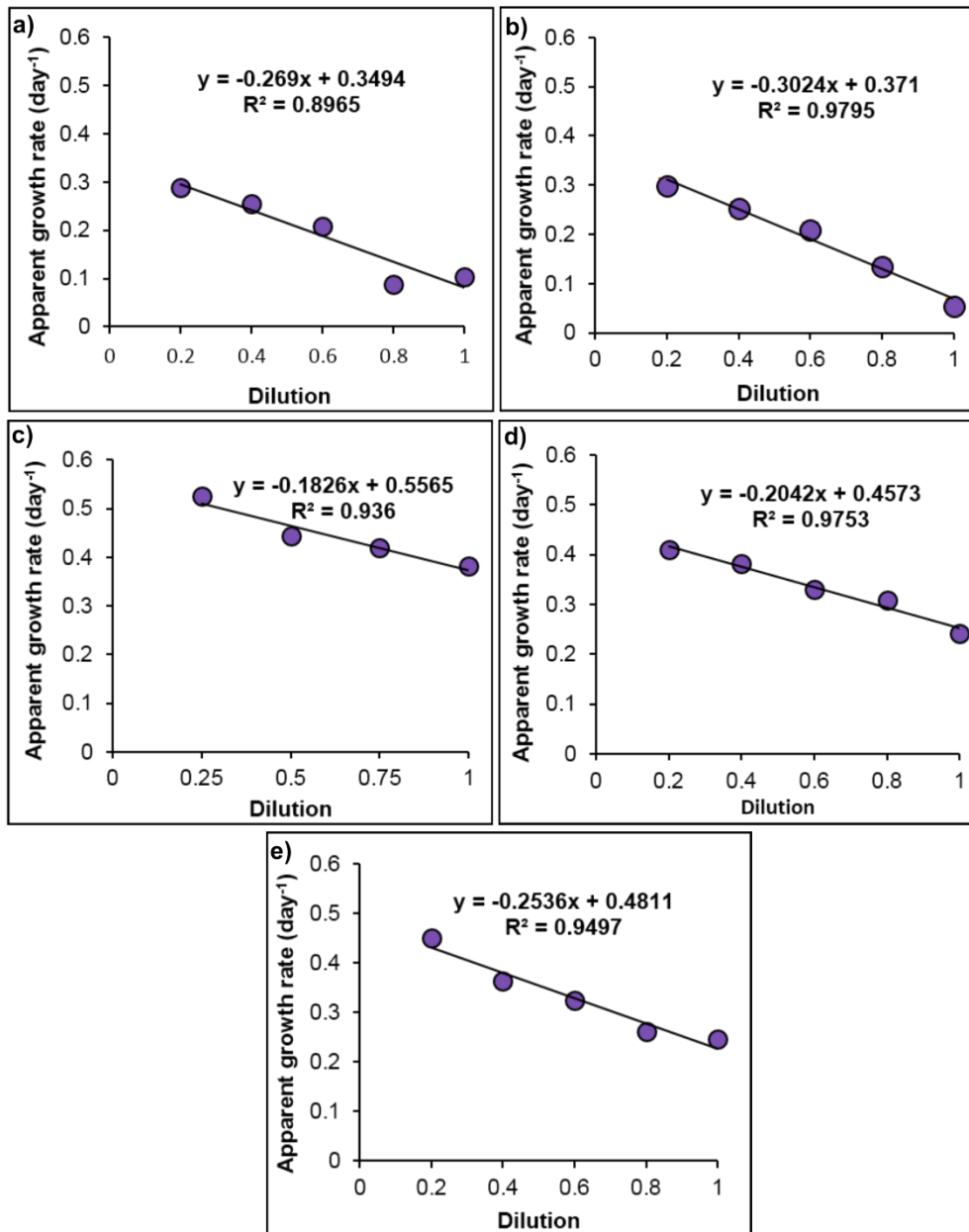


**Fig. 6** - Daily impact of microzooplankton on phytoplankton standing stock, SS (% day<sup>-1</sup>) and potential production, Pp (% day<sup>-1</sup>). The panels (a & b) represent the microzooplankton grazing on total phytoplankton and (c & d) on nano-phytoplankton

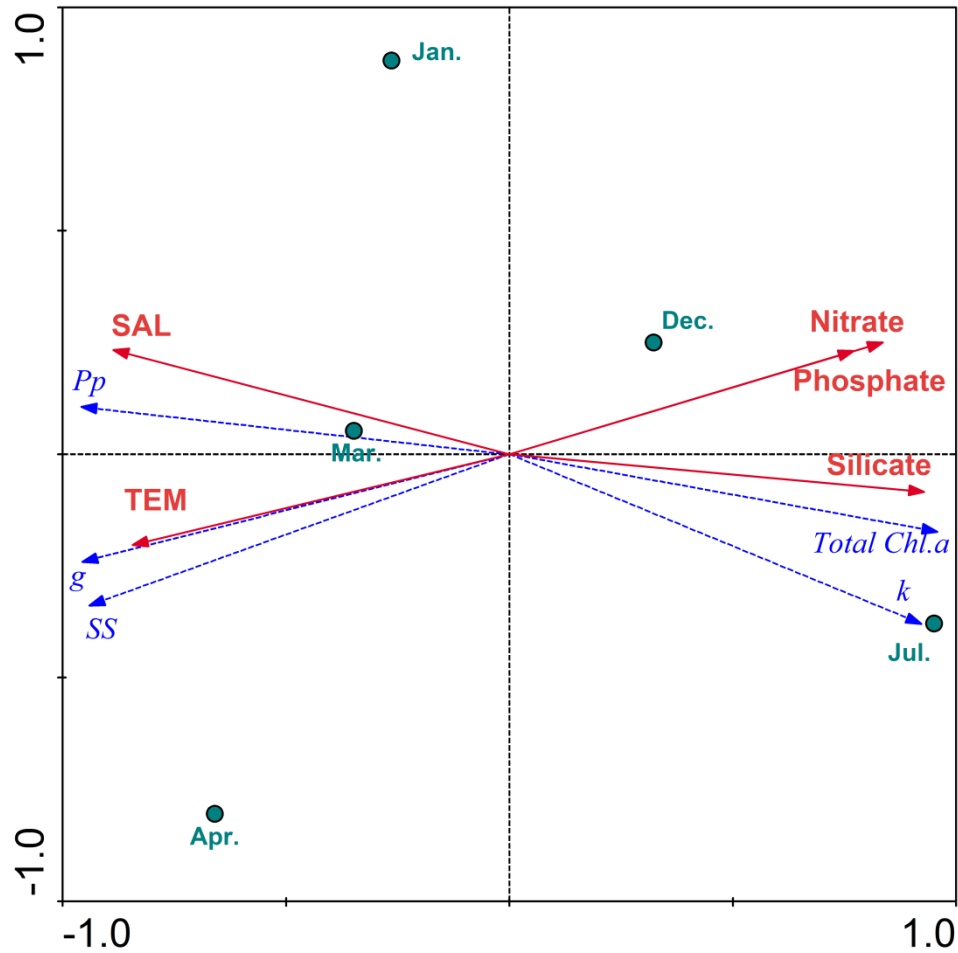


**Fig. 7** - Daily impact of microzooplankton on phytoplankton. Abbreviations MZP- microzooplankton,  $C_m$ - mean phytoplankton carbon biomass during incubation (mg C m<sup>-3</sup>),  $P$ - quantities of carbon produced per day (mg C m<sup>-3</sup> day<sup>-1</sup>) and  $G$ - quantities of carbon consumed per day (mg C m<sup>-3</sup> day<sup>-1</sup>)





**Fig. 8** -Daily impact of microzooplankton on nanophytoplankton biomass (Chl. *a*) in the months of March (a),April (b),July(c),December(d) and January(e) are presented



**Fig. 9** - RDA triplot representing the interrelationships between the hydrographical parameters (SAL – salinity; TEM- Temperature) and the phytoplankton biomass (total Chl.a), apparent phytoplankton growth rate (k), microzooplankton grazing rate (g), standing stock of phytoplankton biomass removed daily (SS) and phytoplankton potential production grazed daily (Pp).The green circles represent the sampling observations and the blue dotted lines represent biological parameters and red solid lines represents the hydrographical parameters.

Parameters	Depths	PRM			SWM	NEM	
		Mar.	Apr.		Jul.	Dec.	Jan.
Temperature ( $^{\circ}\text{C}$ )	S	30.51	31.43		27.07	30.11	29
	SS	30.22	29.75		26.26	29.93	28.9
Salinity	S	32.07	33.46		8.4	30.11	30.8
	SS	34.14	34.35		14.91	32.4	31.82
Turbidity (NTU)	S	1.83	6.5		7.34	4.04	8.05
	SS	9.24	14.69		27.8	23	9.56
DO ( $\text{ml L}^{-1}$ )	S	6.13	4.62		8.92	7.74	7.9
	SS	4.63	4.01		2.98	7.39	7.74
Nitrate ( $\mu\text{M}$ )	S	0.65	0.75		1.94	1.3	1.5
	SS	0.82	0.81		5.82	1.87	1.45
Phosphate ( $\mu\text{M}$ )	S	0.32	0.19		0.62	0.29	0.45
	SS	0.3	1.09		1.75	0.37	0.29
Silicate ( $\mu\text{M}$ )	S	1.85	2.82		15.72	14.43	3.47
	SS	7.15	6.84		21.88	21.49	3.32
Chl. <i>a</i> ( $\mu\text{g L}^{-1}$ )	S	3.84	3.29		9.83	7.49	3.2
	SS	3.25	1.42		8.35	6.61	4.25

**Table 1-** Variations in environmental and biological parameters during the experimental period. Abbreviations S- surface, SS- Subsurface, PRM- Pre- monsoon, SWM-Southwest monsoon, NEM- Northeast monsoon

		PRM		SWM	NEM	
		Mar.	Apr.	Jul.	Dec.	Jan.
Phyto.	<b>k</b>	0.36	0.35	0.51	0.41	0.32
	<b>g</b>	0.24	0.27	0.11	0.14	0.19
	<b>SS</b>	21.1	31	10.5	13	17
	<b>Pp</b>	71	80	26	55	63.5
Nano phyto	<b>k</b>	0.35	0.37	0.57	0.46	0.48
	<b>g</b>	0.27	0.31	0.18	0.2	0.25
	<b>SS</b>	24	26	16.6	18	22
	<b>Pp</b>	80	86.9	50.3	55	59

**Table 2** - Seasonal variations in phytoplankton growth and microzooplankton grazing rate. Symbols: k - apparent phytoplankton growth rate ( $\text{day}^{-1}$ ), g - microzooplankton grazing rate ( $\text{day}^{-1}$ ), SS - Standing stock of phytoplankton biomass removed daily ( $\% \text{ day}^{-1}$ ), Pp - phytoplankton potential production grazed daily ( $\% \text{ day}^{-1}$ ), PRM – Pre-Monsoon, SWM – Southwest Monsoon, NEM – Northeast Monsoon

Area	k ( $\text{day}^{-1}$ )	g ( $\text{day}^{-1}$ )	% PP	Reference
Coastal waters off Western Australia	0.25 - 1.55	0.39 - 1.31	79 - 155	Ayukai and Miller, 1998
Arabian Sea	1.2 - 1.8	0.11 - 0.68	4 - 60	Edwards et al., 1999
Gulf of California	1.58 - 1.82	1.25 - 1.93	89 - 106	Garcia et al., 2001
Coastal waters of Chile	0.19 - 0.25	0.26 - 0.52	> 100	Bottjer and Morales, 2005
Coastal waters of South Brazil Bight	<0.1 - 1.3	0.38 - 2.13	>80	Mc Manus et al., 2007
Eddy pair, Off Western Australia	0.09 - 0.12	0 - 0.23	69 - 205	Paterson et al., 2007
Coastal waters of NW Mediterranean	0.04 - 0.64	0.21 - 0.99	24 - 104	Calbet et al., 2008
East China Sea	0.16 - 1.86	0.25 - 1.54	59 - 150	Zheng et al., 2015
Southwest coast of India (Zuary estuary)	0.69 - 1.24	0.3 - 0.53	58 - 97	Gauns et al., 2015

**Table 3**- Earlier reports on phytoplankton growth (k) and microzooplankton grazing (g). % pp indicates the % of the primary production grazed per day

### Supplementary material



**Supplementary material 1.** Major micrograzers in the study area. *Tintinnopsis beroidea* (a), *Tintinnopsis tocaninensis* (b), *Strombidium* sp (c), *Strombidium conicum* (d) and *Laboea strobila* (e)

Species name	SIM	SWM	NEM
<b>Loricata ciliates</b>			
<i>Eutintinnus lusus undae</i>	+	-	-
<i>Favella azorica</i>	+	-	-
<i>F. philippinensis</i>	+	-	-
<i>Codonellopsis schabii</i>	-	-	+
<i>C. ostenfeldii</i>	+	+	+
<i>Leprotintinnus nordquistii</i>	-	+	+
<i>Tintinnopsis beroidea</i>	+	+	+
<i>T. cylindrica</i>	+	-	+
<i>T. lohmanni</i>	-	-	+
<i>T. mortensenii</i>	-	-	+
<i>T. tocaninensis</i>	+	-	+
<i>T. uruguayensis</i>	+	-	+
<b>Aloricata ciliates</b>			
<i>Labeo strobila</i>	+	-	-
<i>Lohmaniella oviformis</i>	+	+	+
<i>L. spiralis</i>	+	+++	-
<i>Rimostrombidium conicum</i>	+	-	-
<i>Strombidium acuminatum</i>	+	-	++
<i>S. bilobum</i>	+	-	+
<i>S. wulffi</i>	-	++	-
<i>S. conicum</i>	-	+++	+
<i>Strombidium</i> sp.	+	+	-
<i>Strobilidium minimum</i>	+	+	+
<i>Halteria chlorelligera</i>	+	+	+
<i>H. grandinella</i>	-	++	+
<i>Euplotess</i> sp.	-	+	-
<i>Myrionecta rubrum</i>	-	+++	-
<b>H. dinoflagellates</b>			
<i>Protopridinium conicum</i>	+	+	-
<i>P. oceanicum</i>	-	+	+
<i>P. divergens</i>	+	+	+
<i>Protopridinium depressum</i>	-	-	+
<i>Gyrodinium glacialis</i>	+	+	+

**Supplementary material 2.** Microzooplankton species list during the study period. Symbols +, ++ and +++ 0- 200, 200-400, and 400-600 No.L<sup>-1</sup> of organisms. – denotes absence.