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Calanoid copepod diversity and distribution with reference to abiotic factors in coastal Bay of Bengal

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Original Article

Abstract

Understanding the mechanisms that maintain the diversity of plankton communities in marine waters remains a major challenge in modern oceanography. Calanoid copepods are dominant members of marine zooplankton communities. Hence, the present study focuses on the relationship between calanoid copepods and various environmental parameters on the Southeast Coast of India. Zooplankton samples were collected from January to December 2021 from three stations on the Chennai coast. Water abiotic factors, such as temperature, salinity, dissolved oxygen (DO), pH, phosphate, nitrite, nitrate, ammonia, calcium, and magnesium, were studied throughout the study period. A total of 35 calanoid species have been reported from the Coramondal coastline, which is part of the Bay of Bengal. Among these, 26 species were found in the central part of the study area (Marina), 25 species in the southern part of the study area (Kovalam), and 16 species in the northern part of the study area (Ennore). A high Shannon's diversity index was observed during February at the Marina (2.386) and Kovalam (2.543) stations. A significant negative regression coefficient was observed between the calanoid copepods and temperature, calcium, nitrite, nitrate, and ammonia. However, dissolved oxygen was observed with a significant positive regression coefficient at all stations. This study provides a detailed overview of the relationships between various calanoid species and various abiotic parameters along the tropical coast.

Keywords: Bay of Bengal, coastal systems, environmental gradients, calanoida, copepod ecology

Introduction

Zooplankton are primary consumers of the aquatic food chain. They are vital sources of nutrients and energy that are transferred to higher trophic levels (Al *et al.*, 2018). The

dominant and ecologically important members of the marine zooplankton are copepods, especially calanoid copepods, which dominate much of the tropical and subtropical marine environment (Rajthilak *et al.*, 2016). Due to their abundance and their role in the transfer of energy, the processing of nutrients, and the stability of the food web, they are also excellent indicators of ecosystem health. This article aims to study the diversity and distribution of calanoid copepods in the aquatic ecosystems of the Chennai coast while investigating the effects of key physico-chemical factors. The present study investigates the impact of temperature, salinity, pH, and light intensity on the populations of these calanoid copepods to gain better insight into their ecological role and distribution patterns in this region (Li *et al.*, 2008; Deepika *et al.*, 2019). Copepods are useful bio-indicators, as well as playing an important trophic role; thus, understanding these interactions is important in assessing ecosystem health and predicting responses to environmental perturbations (Park and Lee, 2021)

The seasonal variability highlights the dynamic changes in both copepod communities along with environmental variables that can provide a holistic understanding of their dependability (Hussain *et al.*, 2020; De Oliveira Dias *et al.*, 2009). This provides in-depth insights into how physicochemical parameters previously identified to influence aquatic biota, drive copepod community structure and dynamics specifically in tropical estuarine systems (Riyas *et al.*, 2021; Rahman, 2021). Specifically, this study proposes that different physical-chemical gradients resemble different copepod assemblages, and that the abundance and diversity are the highest when temperature and salinity are optimal (Koçum and Sutcu, 2014; Von Weissenberg *et al.*, 2022). This work assumes nutrient availability, nitrates, phosphates, and silicates are directly linked to the abundance of copepods,

primarily linked to phytoplankton growth, used as a food source (Augustine *et al.*, 2014). The predominant copepod species within ecosystems and their relative abundance along sampling sites to achieve a relatively local distribution (Zhang *et al.*, 2019). This style of study goes beyond descriptive surveys and establishes mechanistic connections between the environment and calanoid copepod community structure, greatly addressing a knowledge gap observed in tropical aquatic ecology.

The important ecological role of copepods as primary consumers and a key link to marine food webs to higher trophic levels (Wichard *et al.*, 2008; Sarker *et al.*, 2020), as well as their abundance and the overall copepod community structure, is also a direct measure of ecosystem health and productivity (Nandakumar and Perumal, 2018). It is important to understand the workings of these dynamics to forecast resilience and vulnerability of these aquatic ecosystems under climate change and anthropogenic disturbance (Mukhopadhyay *et al.*, 2007). Changes in parameters, such as temperature, salinity, and pH, can drastically affect copepod reproductive effort and developmental rates, and can also affect the colonisation of copepods by epibionts, affecting their population dynamics and community structure (Von Weissenberg *et al.*, 2022; Kumar *et al.*, 2022).

Furthermore, understanding these sensitivities is critical to assess the cumulative effects of pollution and habitat loss on coastal marine biodiversity. We consider this particularly important as the effects of port activities on plankton community dynamics in terms of abundance, composition, size structure, and nutrient cycling are well known, and calanoid copepods are sensitive to a variety of environmental factors including some that are stressors that can arise from industrial discharges (Milione and Zeng, 2008; Poloczanska *et al.*, 2013; Tibúrcio *et al.*, 2015; Shaikh *et al.*, 2021; Park and Lee, 2021). The environmental changes can result in alterations in planktonic food web-structure and ecosystem metabolism, while influencing dynamics between herbivory and nutrient cycling (Franzé *et al.*, 2022).

The studies on copepods in the southeast coast of India have primarily been descriptive in nature despite their relevance to the ecosystem. Some studies have documented species richness along the Tuticorin coast (Kavitha *et al.*, 2018), the Adayar estuary and Coovum (Shanthi and Ramanibai, 2011), and in Tamil Nadu (Krishnaswamy, 1951; Madhupratap, 1999; Gopikrishna, 2004; Dilshad Begum, 2006; Muthupriya, 2007; Santhanam *et al.*, 2012; Rajthilak *et al.*, 2016; Sivakumar *et al.*, 2021), but there has been no systematic evaluation of how other physicochemical parameters influence copepod diversity and distribution in these systems. Similarly, the study aims to find out whether changes in circulation of the ocean, which are largely influenced by thermal gradients, can affect copepod

distributions and the higher biota, including commercially exploited species (Qiu, 2001). Therefore, this study will present a very useful baseline for monitoring the health of coastal ecosystems as environmental change continues, and also for future ecotoxicological studies using copepods as bio-indicators (Nguyễn *et al.*, 2020; Park and Lee, 2021). This research will therefore shed light on copepod stress response (resilience and adaptation) to multi-stressors, which is becoming increasingly relevant at a global scale, while the results will also assist predictions of future climate scenarios on marine productivity and fisheries, with specific emphasis on copepods' role in the stability of ecosystems.

Material and methods

Study area

Zooplankton samples were collected from three coastal stations in the Bay of Bengal, representing varying levels of anthropogenic impact: (Fig. 1) (Mantha *et al.*, 2012): Ennore (13°12' 23.49" N, 80° 19' 38.01z E) – Impacted by industrial effluents, fly ash, thermal discharges, dredging, and fishing activities, Marina (13° 03' 00" N, 80° 16' 56.64" E) – Affected by domestic sewage and tourism, Kovalam (12° 47' 13.2" N, 80° 15' 1.44" E) – Comparatively pristine, with minimal industrial influence.

Sampling design and zooplankton collection

Sampling was conducted monthly from January to December 2021 during early morning hours. At each station, horizontal and 20 m vertical tows in triplicate were conducted 5 nautical miles offshore using a plankton net with a 150 µm mesh. The net (mouth diameter: 0.5 m) was towed at a constant speed of approximately 2 knots for 15 minutes using a dinghy boat. In the absence of a flowmeter, theoretical volume ($V = \pi r^2 L$) was calculated, where length (L) was derived from GPS-recorded towing speed and time. The samples were filtered through a 150 µm sieve and preserved in 5% buffered formalin. Minimal disturbance during retrieval ensured sample integrity.

Taxonomic identification and enumeration

In the laboratory, zooplankton samples were examined under a stereomicroscope (Labovision KS f2000). Only adult calanoid copepods were dissected and identified using standard taxonomic keys (Kasturirangan, 1963; Boxshall and Halsey, 2004; Razouls *et al.*, 2022). Dissected appendages were mounted on slides and examined using a trinocular microscope (Olympus CH21(I)) with camera lucida support. To enhance ecological resolution, copepodite stages were

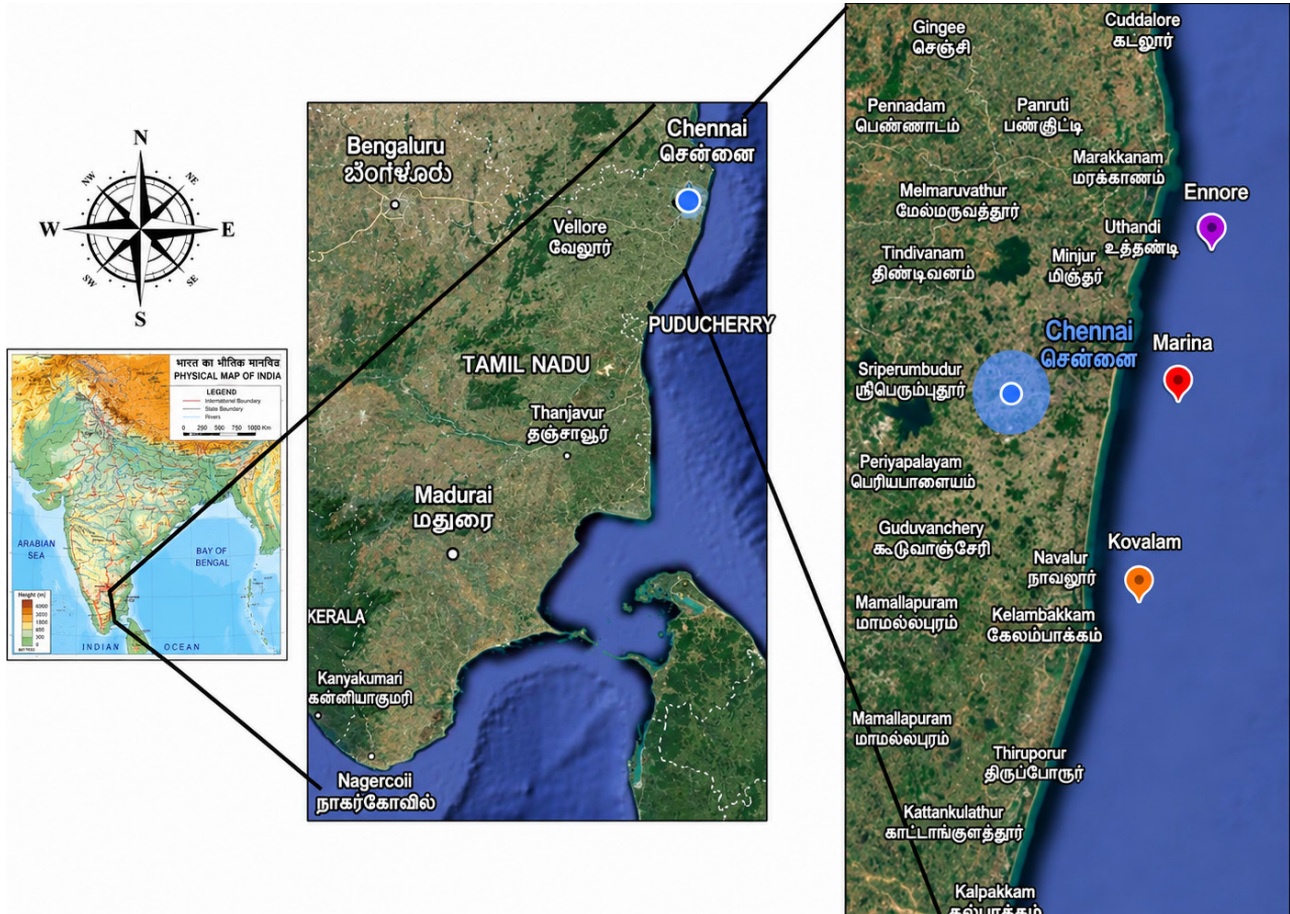


Fig. 1. Sampling stations

also counted. This allowed better assessment of recruitment and temporal dynamics.

Density estimation

Quantification was conducted using a Sedgwick-Rafter counting chamber, with triplicate subsamples per tow. The average count was used for calculating densities per cubic meter (Perry, 2003):

Number of calanoid copepods per cubic meter
 = Average numbers in the drops x Total drops in entire sample/Volume

where Volume = $\pi r^2 L$ and Length (L) is derived from the equation = Speed \times Time.

The average number of animals per drop was calculated as follows:

Average numbers in the drops
 = Numbers of animals observed/Number of drops analysed

Physico-chemical measurements

Water samples were collected simultaneously using a Niskin water sampler (2.5 L). Water samples were collected at the same depth as the zooplankton samples, and the physico-chemical parameters were analysed to ensure homogeneity between the environmental and biological data. In situ parameters included temperature (mercury thermometer), salinity (ERMA RHS 10 ATC), pH (LUTRON PH-210), and DO (LUTRON DO 5510). Calcium and magnesium levels in seawater were determined using a standard method and titrated to the photometric endpoint using EDTA (Malmstadt and Hadjiioannou, 1959). Phosphate, nitrite, nitrate, and ammonia levels were measured according to the standard manual (Strickland and Parsons, 1972). The concentration of nitrite (NO_2) was determined by the formation of a bright azo dye, colourimetrically measured at 540 nm (Wood *et al.*, 1967). Nitrate (NO_3) was measured using the ammonium chloride method following a standard procedure (Strickland and Parsons, 1972). Inorganic phosphate (PO_4) in seawater was analysed using a colourimetric method that produces a brightly colored phosphomolybdate compound (Murphy and Riley, 1962). Ammonia was determined by treating

seawater with sodium hypochlorite and phenol in the presence of sodium nitroprusside in alkaline citrate medium (Solórzano, 1969).

Statistical analysis

Data were expressed as mean \pm SD, and statistical analyses were performed using SPSS v26.0 and PAST v4.09. One-way ANOVA followed by Tukey's post hoc test ($p < 0.05$) was used to assess significant differences among stations and species. Repeated measures of ANOVA were performed between Stations vs Month and Stations vs Seasons. Pearson correlation analysis was conducted to examine relationships among environmental parameters. Before constrained ordination, Detrended Correspondence Analysis (DCA) was performed. The original axis gradient length was less than 3 standard deviation units, indicating a linear species-environment relationship. According to the recommended criteria, when the gradient length is less than 3, linear methods such as Redundancy Analysis (RDA) are appropriate. Redundancy analysis (RDA) and cluster analysis were carried out using Bray-Curtis similarity indices to evaluate species-environment relationships. Assumptions of normality and homogeneity of variance were tested using the Shapiro-Wilk and Levene's tests, respectively.

Results and discussion

Physicochemical parameters

Fig. 2 and 3 show a comparison between the different stations' water physicochemical parameters. The water temperature varied between 25.3 and 33.9 °C from all stations throughout the study period. High mean temperature was observed during May (33.9 ± 0.9 °C), and low temperature was observed during January (26.2 ± 0.5 °C) (Fig. 2a). Low salinity, dissolved oxygen, and pH were observed from May to July at all stations (Fig. 2 b-d). Ennore station was observed with low dissolved oxygen levels (4.5 ± 0.68 mgL⁻¹) compared to Marina (5.11 ± 0.55 mgL⁻¹) and Kovalam (5.17 ± 0.86 mgL⁻¹), Nitrite and phosphate content were high at Ennore station (2.9 ± 0.71 mgL⁻¹ and 1.3 ± 0.57 mgL⁻¹ respectively) compared to Marina (2.4 ± 0.62 mgL⁻¹ and 1.1 ± 0.45 mgL⁻¹) and Kovalam (2.3 ± 0.52 mgL⁻¹ and 1.1 ± 0.51 mgL⁻¹) (Fig. 3a and 3b). Ammonia levels were also higher at the Ennore station (0.04 ± 0.006 mgL⁻¹) compared to Marina (0.035 ± 0.003 mgL⁻¹) and Kovalam (0.033 ± 0.008 mgL⁻¹) (Fig. 3d). Monthly high nutrient content in water was reported from October to December from all stations. Calcium and magnesium levels varied between (350 - 430 mgL⁻¹ and

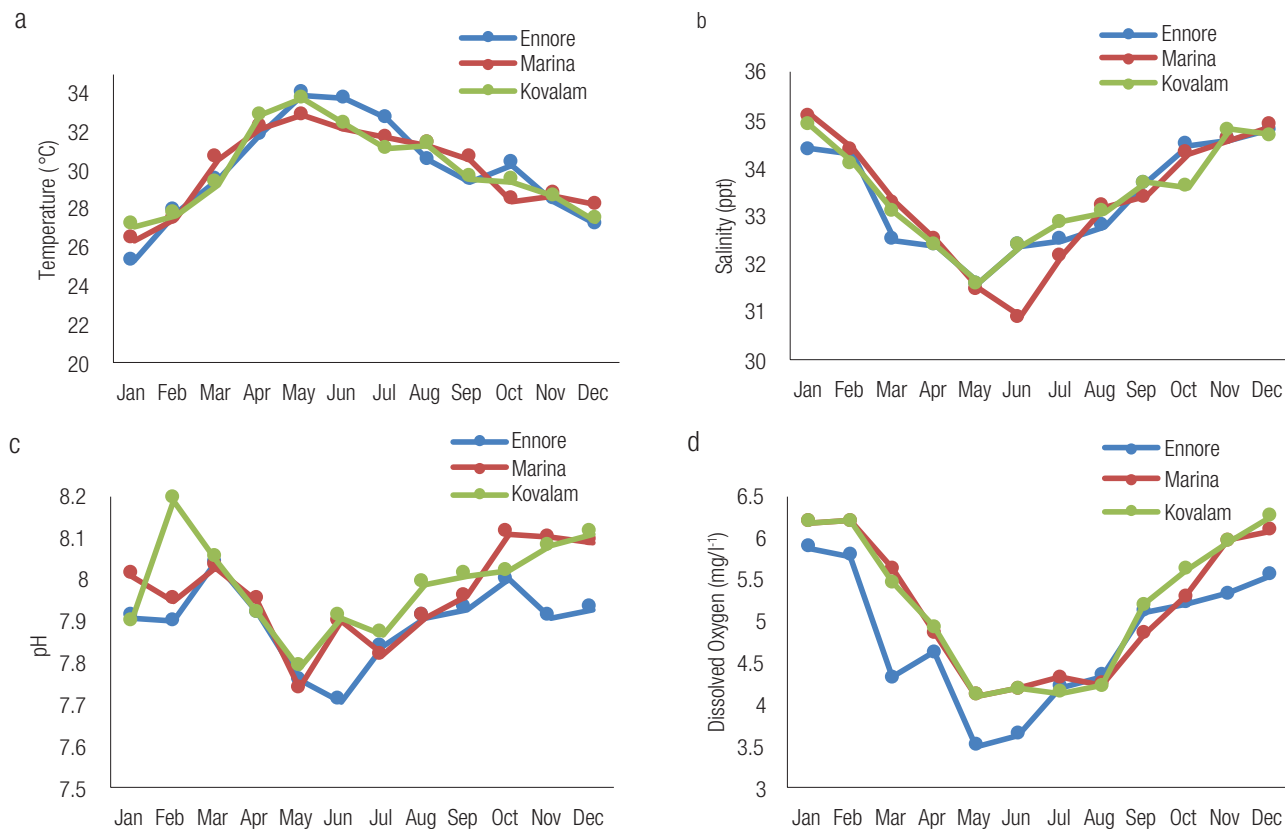


Fig. 2. a) Temperature, b) Salinity, c) pH and d) Dissolved Oxygen in Ennore, Marina and Kovalam stations

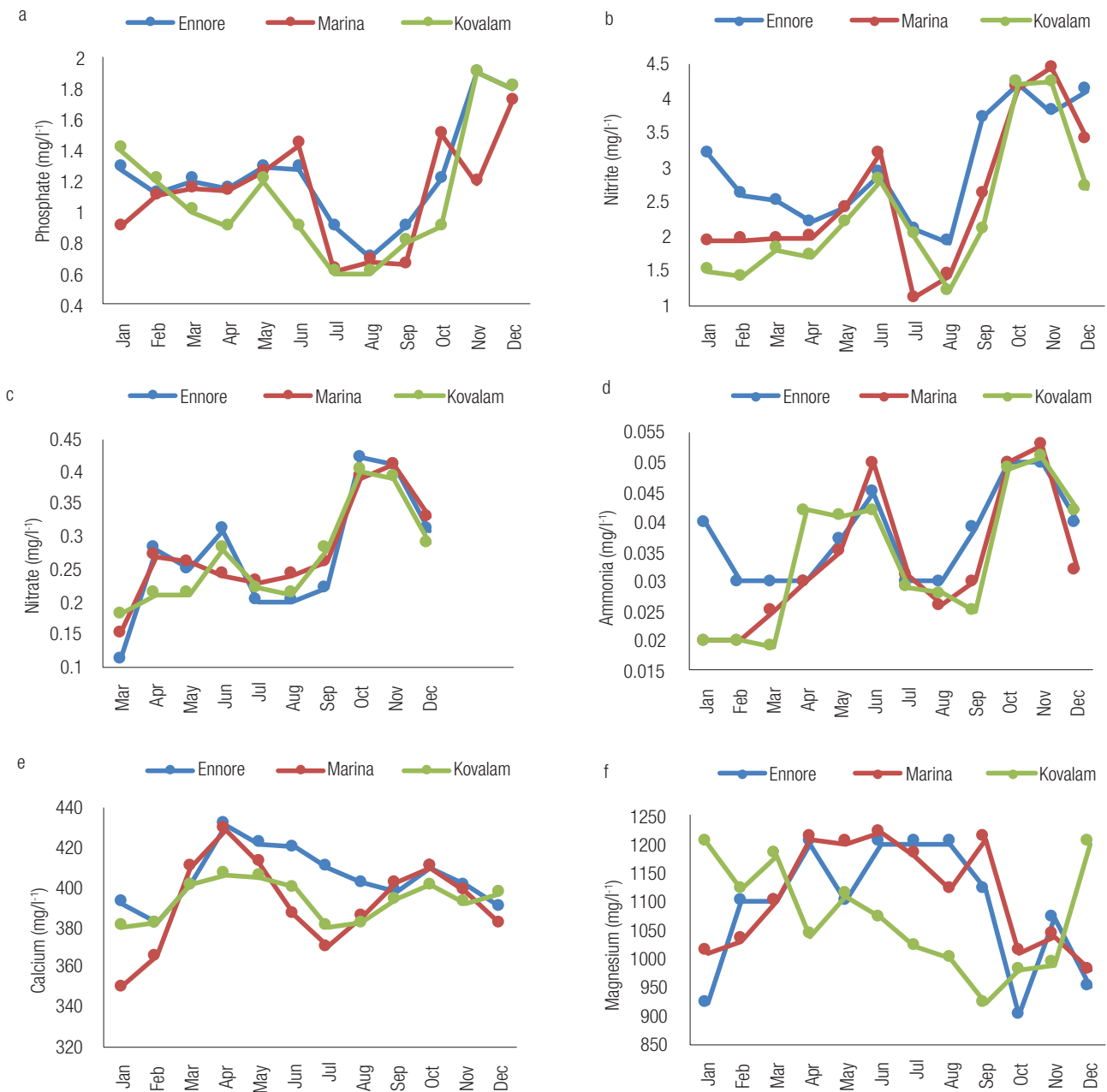


Fig. 3.a) Phosphate, b) Nitrite, c) Nitrate, d) Ammonia, e) Calcium and f) Magnesium levels in Ennore, Marina and Kovalam stations

900 - 1210 mg/l⁻¹, respectively) (Fig 3e and f) throughout the study period. Fig. 4 shows correlation coefficients between various physicochemical parameters from all three stations. A high negative correlation coefficient was observed between temperature and dissolved oxygen, salinity, and pH at all stations. Dissolved oxygen content is known to be affected by water temperature, as oxygen is more soluble in colder water than in warmer water (Harvey *et al.*, 2011).

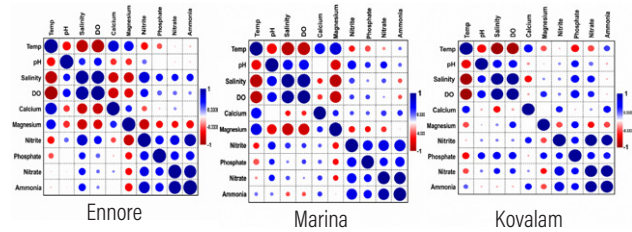


Fig. 4. Correlation coefficients between physicochemical parameters

Spatial and temporal variations in calanoid copepods

In the present study, 35 species of calanoid copepods were reported from all 3 stations, with the highest number of 26

Table 1. Mean density ($\times 10^3$ ind. \cdot m $^{-3}$) of calanoid copepods of Ennore Marina and Kovalam stations

Family	Species	Ennore	Marina	Kovalam
Acartiidae	<i>Acartia tonsa</i> (Dana, 1849)	-	36.6 \pm 4 ^{abc}	-
	<i>Acartia erythraea</i> (Giesbrecht, 1889)	118 \pm 15.7 ^a	83 \pm 12.1 ^{abcd}	97.3 \pm 8.9 ^a
	<i>Acartia spinicauda</i> (Giesbrecht, 1889)	118 \pm 15.7 ^a	35.6 \pm 7.2 ^{abc}	86.3 \pm 9.4 ^a
Paracalanidae	<i>Acrocalanus gibber</i> (Giesbrecht, 1888)	289.6 \pm 5.8 ^b	276.3 \pm 9.07 ^{abc}	175 \pm 6.5 ^a
	<i>Acrocalanus gracilis</i> (Giesbrecht, 1888)	626.6 \pm 98.4 ^c	766.6 \pm 21.2 ^e	698.6 \pm 13.5 ^b
	<i>Paracalanus parvus</i> (Claus, 1863)	83 \pm 8.7 ^a	32.3 \pm 5.6 ^{abc}	-
	<i>Paracalanus aculeatus</i> (Giesbrecht, 1888)	19.6 \pm 6.5 ^a	-	-
Calanidae	<i>Canthocalanus pauper</i> (Giesbrecht, 1888)	133.6 \pm 25.6 ^a	233.3 \pm 4.9 ^d	259.6 \pm 24.1 ^a
	<i>Mesocalanus tenuicornis</i> (Dana, 1849)	5 \pm 3.4 ^a	-	-
Centropagidae	<i>Centropages furcatus</i> (Dana, 1849)	-	36.3 \pm 3.5 ^{abc}	67 \pm 8.8 ^a
	<i>Centropages tenurinis</i> (Thompson I.C and Scott A, 1903)	61.6 \pm 8.08 ^a	136.3 \pm 11.6 ^{abcd}	54.6 \pm 7.3 ^a
	<i>Centropages dorsispinatus</i> (Thompson and Scott, 1903)	-	13.6 \pm 6.02 ^a	-
	<i>Centropages orsini</i> (Giesbrecht, 1889)	-	-	62.6 \pm 7.5 ^a
Eucalanidae	<i>Subeucalanus monachus</i> (Giesbrecht, 1888)	20.3 \pm 0.5 ^a	58.3 \pm 2.8 ^{abcd}	30.3 \pm 5.03 ^a
	<i>Subeucalanus subcrassus</i> (Giesbrecht, 1888)	107.3 \pm 10.06 ^a	99.6 \pm 12.5 ^{abcd}	128.6 \pm 7.5 ^a
Candaciidae	<i>Candacia discaudata</i> (Scott A, 1909)	-	27 \pm 1 ^{abc}	34.3 \pm 2.5 ^a
Euchaetidae	<i>Euchaeta marina</i> (Prestandrea, 1833)	-	176 \pm 3.5 ^{ab}	-
Lucicutiidae	<i>Lucicutida flavicornis</i> (Claus, 1863)	-	20 \pm 2 ^{ab}	-
Pontellidae	<i>Labidocera pavo</i> (Giesbrecht, 1889)	-	-	39 \pm 4 ^a
	<i>Labidocera acuta</i> (Dana, 1849)	6.6 \pm 3.05 ^a	28 \pm 2.6 ^{abc}	46 \pm 6.9 ^a
	<i>Labidocera minuta</i> (Giesbrecht, 1889)	35.6 \pm 3.2 ^a	5.3 \pm 3 ^a	4.6 \pm 2.5 ^a
	<i>Labidocera bengalensis</i> (Krishnaswamy, 1952)	-	46 \pm 2.1 ^{abc}	103 \pm 15.8 ^a
	<i>Calanopia minor</i> (Scott A., 1902)	-	-	26.3 \pm 2.3 ^a
	<i>Calanopia aurivillii</i> (Cleve, 1901)	-	-	27 \pm 5 ^a
Pontellopsidae	<i>Calanopia elliptica</i> (Dana, 1849)	-	22.6 \pm 5.03 ^{ab}	40.6 \pm 7.3 ^a
	<i>Pontella danae</i> (Giesbrecht, 1889)	-	-	2 \pm 1 ^a
	<i>Pontellopsis scotti</i> (Sewell, 1932)	-	-	2.6 \pm 2 ^a
	<i>Pontellopsis herdmani</i> (Thompson I.C. and Scott A., 1903)	-	-	6.6 \pm 3.5 ^a

Family	Species	Ennore	Marina	Kovalam
Pseudodiaptomidae	<i>Pseudodiaptomus serricaudatus</i> (Scott T, 1984)	99 \pm 4 ^a	209.7 \pm 4.1 ^{bcd}	225.6 \pm 12.8 ^a
	<i>Pseudodiaptomus annandelei</i> (Sewell, 1919)	15.3 \pm 3.05 ^a	46 \pm 3 ^{abc}	-
	<i>Pseudodiaptomus aurivillii</i> (Cleve, 1901)	71 \pm 8.7 ^a	41 \pm 4.3 ^{abc}	-
Temoridae	<i>Temora turbinata</i> (Dana, 1849)	274.6 \pm 25.7 ^b	215.6 \pm 10.6 ^{cd}	246.6 \pm 16.2 ^a
	<i>Temora discaudata</i> (Giesbrecht, 1889)	-	79.6 \pm 1.5 ^{abcd}	95.3 \pm 11.1 ^a
	<i>Temora stylifera</i> (Dana, 1849)	47 \pm 4.5 ^a	40.3 \pm 3.2 ^{abc}	54.6 \pm 6.3 ^a
Tortanidae	<i>Tortanus forcipatus</i> (Giesbrecht, 1889)	-	21 \pm 8.5 ^{ab}	-
Copepodid		309777 \pm 342.67 ^d	3520.65 \pm 444.62 ^f	3594.09 \pm 73.712 ^c
	Nauplius	3554.40 \pm 348.24 ^e	3834.42 \pm 375.19 ^g	3931.92 \pm 566.45 ^d
F value		270.916	230.105	93.598
P value		0.000	0.000	0.000

Species with the same alphabet superscripts in a column denote they were grouped in ANOVA followed by DMRT's test ($p < 0.05$).
- denotes absence of the species

species observed in Marina, followed by 25 species in Kovalam, and 18 in Ennore (Table 1). *Acrocalanus gracilis* was observed to be the dominant species with an abundance of $626.6 \pm 98.4 \times 10^3$ ind. \cdot m $^{-3}$, $766.6 \pm 21.2 \times 10^3$ ind. \cdot m $^{-3}$, $698.6 \pm 13.5 \times 10^3$ ind. \cdot m $^{-3}$ from Ennore, Marina, and Kovalam, respectively. *Mesocalanus tenuicornis* ($5 \pm 3.4 \times 10^3$ ind. \cdot m $^{-3}$) in Ennore, *Labidocera minuta* ($5.3 \pm 3 \times 10^3$ ind. \cdot m $^{-3}$) in Marina and *Pontella danae* ($2 \pm 1 \times 10^3$ ind. \cdot m $^{-3}$) in Kovalam showed low density throughout the study period. Kavitha *et al.* (2018) also reported *A. gracilis* as a dominant calanoid species from the coast of Tuticorin, south India. Paracalanidae copepods are generally predominant in tropical and subtropical regions (Cornils and Blanco-Bercial, 2013). High mean density was observed during February from all three stations: Ennore ($239.6 \pm 9.01 \times 10^3$ m $^{-3}$), Marina ($281 \pm 14.7 \times 10^3$ ind. \cdot m $^{-3}$) and Kovalam ($294.3 \pm 14.2 \times 10^3$ ind. \cdot m $^{-3}$) (Table 2). However, low density was observed during July in Ennore ($113.3 \pm 16.6 \times 10^3$ ind. \cdot m $^{-3}$), October in Marina ($175.6 \pm 17.8 \times 10^3$ ind. \cdot m $^{-3}$) and June in Kovalam ($185 \pm 2.6 \times 10^3$ ind. \cdot m $^{-3}$). Overall, high density is observed in Marina ($219.02 \pm 17.4 \times 10^3$ ind. \cdot m $^{-3}$) and low density is observed in Ennore ($170.3 \pm 10.3 \times 10^3$ ind. \cdot m $^{-3}$). The current study showed substantial variation in calanoid copepod density between Marina and Ennore stations ($p < 0.05$), but not between Marina and Kovalam stations, as revealed by Tukey's post hoc test. The notable difference in the density of calanoids at Ennore and Marina can be explained based on physicochemical factors, such as availability of nutrients, load of pollutants, and hydrodynamic regime, which have been found to contribute significantly to the spatial distribution of plankton communities (Govindasamy *et al.*, 2000; Santhanam and Perumal, 2003).

Table 2. Density ($\times 10^3$ ind.m⁻³) of calanoid copepods at different months

Months	Ennore ($\times 10^3$ ind.m ⁻³) (mean \pm SD)	Marina ($\times 10^3$ ind.m ⁻³) (mean \pm SD)	Kovalam ($\times 10^3$ ind.m ⁻³) (mean \pm SD)
Jan-2021	171.6 \pm 27.3	231 \pm 10.5	248.6 \pm 12.09
Feb-2021	239.6 \pm 9.01	281 \pm 14.7	294.3 \pm 14.2
Mar-2021	162.6 \pm 7	219.6 \pm 12.3	233.3 \pm 7.5
Apr-2021	164 \pm 17.8	201.3 \pm 20.7	214.6 \pm 12.6
May-2021	179.6 \pm 21.1	186.3 \pm 20.5	191 \pm 9.8
Jun-2021	169.3 \pm 42.1	204.6 \pm 23.4	185 \pm 2.6
Jul-2021	113.3 \pm 16.6	239 \pm 17.6	201.3 \pm 6.3
Aug-2021	203.3 \pm 15.6	265 \pm 19.4	224.3 \pm 23.6
Sep-2021	157.3 \pm 19.1	229.3 \pm 9.7	229 \pm 7.2
Oct-2021	157 \pm 20.7	175.6 \pm 17.8	204.6 \pm 5.5
Nov-2021	165.3 \pm 14.7	183.3 \pm 22.05	199.6 \pm 15.04
Dec-2021	159.3 \pm 7.5	212 \pm 20.07	189 \pm 8
Mean	170.2 \pm 20.6 ^a	219.02 \pm 17.4 ^b	217.9 \pm 10.3 ^b

Stations with the same alphabet superscripts in the column denote they were grouped in ANOVA followed by Tukey's test ($p < 0.05$).

Ennore, an industrially influenced estuarine area, tends to have greater organic pollution and consequent nutrient enrichment, which favours increased plankton productivity. Marina, a coastal station with high tidal flushing and reduced pollution input, could provide suboptimal conditions for calanoid copepod congregation. The lack of large variation between the Marina and Kovalam stations is consistent with previous research by Sivakumar *et al.* (2021), where coastal water masses with comparable hydrodynamic regimes were found to have a homogeneous plankton distribution.

Additionally, the irregular distribution of calanoid copepods, which is typical of planktonic organisms, supports the non-normal distribution patterns observed in the current study. This finding concurs with Madhupratap's (1999) report that the aggregation of calanoid copepods in marine communities depends on both biological interactions and hydrographical conditions. Seasonal variations observed in the data are probably caused by variations in temperature and salinity, rainfall, nutrient loading, and phytoplankton blooms, as observed in a study in a tropical estuarine system (De Oliveira Dias *et al.*, 2009). The most common copepod species also vary seasonally, as variable species are appropriate for variable situations (De Oliveira Dias *et al.*, 2009). Geographical variations in copepod abundance are caused by upwelling (Giraldo *et al.*, 2009). The present results highlight the necessity for long-term monitoring and spatial mapping of plankton communities to further elucidate the drivers of their distribution in dynamic coastal systems.

Repeated measures of ANOVA indicated main effects of Station ($F(2,4) = 23.46$, $p = 0.006$), Month ($F(11,22) = 227.73$, $p < 0.001$),

and a significant effect for Station \times Month ($F(22,44) = 2.35$, $p = 0.008$), indicating that temporal variation was significantly different between sampling stations. Two-way repeated measures ANOVA indicated significant main effects of Station ($F(2,4) = 21.43$, $p = 0.007$), Season ($F(3,6) = 224.50$, $p < 0.001$), and a significant Station \times Season interaction ($F(6,12) = 3.98$, $p = 0.020$), which confirmed that sample locations dynamically responded to particular seasons across the region (Table 3).

The dominance and diversity indices of the calanoid copepods are listed in Table 4. Increased dominance at Ennore shows decreased species evenness and several dominant species, whereas Kovalam supports an even species distribution. The increased Shannon diversity at Kovalam shows that it has a more stable and diverse community than Ennore, where ecological stress was higher. The Simpson dominance index (D) and Shannon diversity index (H) showed significant spatial differences in the plankton community structure between the Ennore, Marina, and Kovalam stations. The dominance index was maximum at Ennore, indicating that some species dominate the ecosystem, which agrees with earlier findings emphasising industrial pollution and eutrophication-induced

Table 3. Repeated Measures Anova of calanoid copepods between Stations vs Months and Stations vs Seasons

Parameters	Station/ Months	F-value	df	p-value	Interpretation
Stations vs Months	Station	23.46	(2, 4)	0.0062*	Significant
	Month	227.73	(11, 22)	< 0.001*	Highly significant
	Station \times Month	2.35	(22, 44)	0.0079*	Significant
Stations vs Seasons	Station	21.43	(2, 4)	0.0073*	Significant
	Season	224.50	(3, 6)	< 0.001*	Highly significant
	Station \times Season	3.98	(6, 12)	0.0201*	Significant

Table 4. Dominance and Diversity indices of calanoid copepods at different stations

Months	Simpson dominance (D) index			Shannon diversity (H) index		
	Ennore	Marina	Kovalam	Ennore	Marina	Kovalam
January	0.1626	0.1566	0.1058	1.723	2.121	2.421
February	0.154	0.1181	0.0931	2.104	2.386	2.543
March	0.1579	0.1432	0.1265	1.93	2.127	2.247
April	0.2248	0.1730	0.1356	1.668	1.98	2.164
May	0.2058	0.1696	0.1565	1.684	2.002	2.05
June	0.1879	0.1643	0.1523	1.805	2.01	2.056
July	0.1520	0.1160	0.1420	1.909	2.393	2.185
August	0.1382	0.1095	0.1340	2.122	2.44	2.25
September	0.2189	0.1491	0.1313	1.746	2.099	2.205
October	0.1769	0.1978	0.1414	1.849	1.813	2.195
November	0.1941	0.1847	0.1532	1.781	1.88	2.091
December	0.2253	0.1524	0.1524	1.634	2.136	2.136

species changes in estuaries (Govindasamy *et al.*, 2000). The availability of pollutants and organic enrichment frequently encourages the proliferation of pollution-resistant species, and species evenness decreases. Conversely, Kovalam had the lowest dominance index and highest Shannon diversity index, indicating a more stable and diverse plankton community, in agreement with earlier observations in less disturbed coastal waters (Santhanam and Perumal, 2003). The increased diversity at Kovalam may be attributed to improved water quality, increased mixing, and lower anthropogenic disturbances, promoting a more heterogeneous and balanced plankton community.

As reported in previous studies on dynamic hydrographic coastal ecosystems, Marina stations reflect moderate dominance and diversity due to tidal influences and fluctuating environmental conditions (Madhupratap, 1999). The absence of any appreciable differences in diversity between Marina and Kovalam (as revealed by Tukey's test) implies comparable environmental conditions and connectivity among these coastal regions. In general, the results affirm the role of anthropogenic activities and natural hydrodynamic processes in controlling plankton community structure, with a focus on continued monitoring and conservation efforts in ecologically sensitive areas, such as Ennore.

Various fishing activities and waste discharge from the Ennore thermal power plant probably make Ennore the site with the lowest biodiversity compared to other stations. The bioaccumulation of trace metals in various fish species has also been observed in the Ennore Creek (Jayaprakash *et al.*, 2015). Ennore Creek also reported a very low diversity of foraminifera and benthic harpacticoid copepods (Nagendra *et al.*, 2015; Mantha *et al.*, 2012). According to a study conducted by Sivaswamy (1990) on the water bodies of Ennore, the pollution levels of Ennore water and sediments are above the safe limit. However, Sivakumar *et al.* (2021) reported high species diversity of calanoid copepods at the Marina station. Sugumaran *et al.* (2009) conducted a study on the meiofauna of Chennai coast, which showed high diversity of meiofauna in Marina station as compared to Royapuram and Pulicat. Similarly, Mantha *et al.* (2012) reported a high density of harpacticoid copepods and meiobenthic fauna on the Chennai coast during February.

Distribution patterns in calanoid copepods

The Bray-Curtis cluster diagram expressed the relationship between calanoid copepods. Dendrograms visually depict the relationships and similarities between different species (Fig. 5). The vertical axis is similarity, with higher values

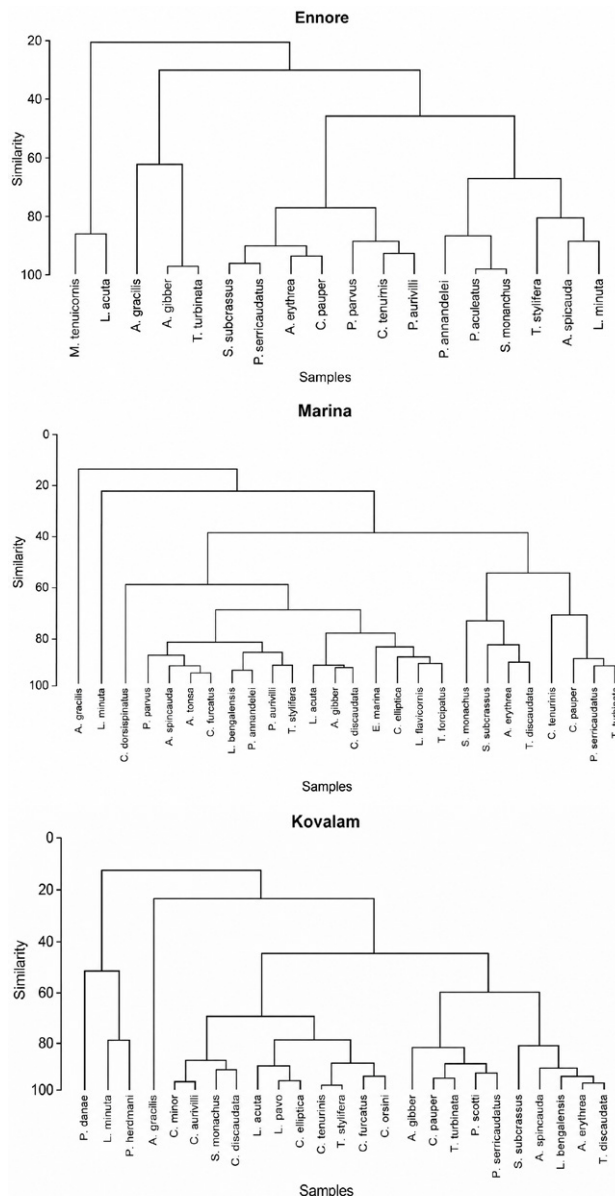


Fig. 5. Cluster dendrogram of calanoid copepods assemblage at different stations

showing greater resemblance. The dendrogram shows clear groupings, suggesting potential ecological or genetic connections between the species. *M. tenuicornis* and *Labidocera acuta* are the outliers, with a greater difference from other clusters in the Ennore stations. Some species, such as *Acrocalanus gracilis* and *Labidocera minuta*, are more diverged from most, and these have their clusters with a higher dissimilarity index in the Marina Station. In the Kovalam station, *Pontella danae*, *L. minuta*, and *Pontellopsis herdmani* were distinct and had their cluster, showing lesser similarity with other species. These species may occupy different ecological niches. The species found at the Kovalam

station are differently ordered compared to those found in Marina and Ennore stations, indicating potential differences in the environment. The *A. gracilis* was present at all three locations, but with variation. The penetration of oceanic water masses into the nearshore areas due to seasonally caused hydrographic variations could have made them shift. Such spatial heterogeneity in the structure of zooplankton communities has been noted in other nearshore systems on the Indian coast (De Los Ríos *et al.*, 2019), with salinity gradients, nutrient availability, and anthropogenic factors likely driving such patterns (Ratnam *et al.*, 2022). The episodic presence of mesopelagic copepods in coastal waters has been reported in the Bay of Bengal and the Arabian Sea through monsoonal changes and eddies (Madhupratap *et al.*, 1999). *Euchaeta marina* and *L. flavicornis* in near-surface collections could also signal passive entrainment or transitory recruitment from deeper water following the disruption of cues for vertical migration by shifts in light penetration or salinity gradient (Yamaguchi *et al.*, 2002).

Interaction between calanoids and physico-chemical parameters

Regression analysis of calanoid copepod abundance with physico-chemical parameters at the Ennore stations indicated that none of the parameters were statistically significant predictors at 5% significance level, nevertheless dissolved

oxygen ($\beta = 0.899$, $p = 0.156$) and calcium ($\beta = 0.606$, $p = 0.098$) showed relatively strong positive associations, which suggests that these parameters may support calanoid copepod populations by supporting the metabolism associated with aerobic respiration and exoskeleton formation, respectively. However, there were also statistically significant negative effects of temperature ($\beta = -0.848$, $p = 0.082$) and nitrite ($\beta = -0.442$, $p = 0.152$) (Table 5).

The regression analysis between calanoid copepod abundance and physico-chemical parameters at the Marina stations showed that none of the variables demonstrated to be statistically significant at the 5 % level. However, calcium ($\beta = 0.653$, $p = 0.258$), magnesium ($\beta = 0.426$, $p = 0.293$), nitrite ($\beta = 0.630$, $p = 0.306$), and nitrate ($\beta = 0.374$, $p = 0.296$) indicated relatively strong, positive associations with the abundance of calanoid copepods and possibly contribute to the growth of calanoid copepods via structural contributions or nutritional aspects. Temperature ($\beta = -0.174$, $p = 0.301$), pH ($\beta = -0.567$, $p = 0.360$), dissolved oxygen ($\beta = -0.001$, $p = 0.999$), phosphate ($\beta = 0.072$, $p = 0.700$), and ammonia ($\beta = -0.759$, $p = 0.188$) (Table 5) indicated weak or negative associations, therefore may contribute to possible stress aspects or limited control over calanoid copepod abundance.

The regression analysis of calanoid copepod abundance and physico-chemical parameters at the Kovalam stations showed that none of the parameters had a significant enough effect at the 5% level; however, dissolved oxygen and calcium exhibited relatively stronger positive relationships ($\beta = 0.529$, $p = 0.199$; $\beta = 0.500$, $p = 0.081$) (Table 5), signifying their potential ecological relevance to calanoid copepods. The results indicate that, despite the relatively weak statistics, environmental factors may have a significant influence on calanoid copepod distribution.

The redundancy analysis (RDA) ordination indicates that the first two canonical axes explain most of the joint variation between the measured physico-chemical variables and calanoid copepod density at the three stations (Ennore, Marina, Kovalam). Axis 1 is chiefly related to temperature, salinity, pH, dissolved oxygen, nitrate and ammonia, which positively load and cluster with high-density calanoid copepod samples across all study months, indicating that warmer and more saline, and oxygenated waters with higher nitrogen forms favoured greater calanoid copepod abundance. Axis 2 is understood to be associated with phosphate, magnesium, and calcium, which point away from the majority of the calanoid copepod points, indicating that the relationship of these nutrients with calanoid copepod density was comparatively weaker or possibly even negative. Seasonal clustering is evidence that shows winter months clustered toward the negative side of Axis 1, where

Table 5. Regression coefficient of calanoid copepods with physicochemical parameters at different stations

Parameters	Ennore	Marina	Kovalam
Temperature (°C)	-0.848 (0.082)*	-1.174 (0.301)	-0.648 (0.122)
pH	-0.303 (0.129)	-0.607 (0.360)	-0.288 (0.118)
Salinity (ppt)	0.102 (0.731)	0.232 (0.716)	0.286 (0.348)
Dissolved Oxygen (mg/l ⁻¹)	0.899 (0.156)	-0.001 (0.999)	0.529 (0.199)
Calcium (mg/l ⁻¹)	0.606 (0.098)	0.653 (0.356)	0.500 (0.081)
Magnesium (mg/l ⁻¹)	0.109 (0.404)	0.426 (0.293)	-0.316 (0.120)
Nitrite (mg/l ⁻¹)	0.442 (0.152)	0.630 (0.300)	-0.506 (0.148)
Phosphate (mg/l ⁻¹)	-0.169 (0.217)	0.072 (0.700)	0.171 (0.197)
Nitrate (mg/l ⁻¹)	-0.491 (0.147)	0.374 (0.296)	0.184 (0.459)
Ammonia (mg/l ⁻¹)	0.128 (0.497)	-0.759 (0.188)	-0.104 (0.495)

*within parentheses mentioned p-value

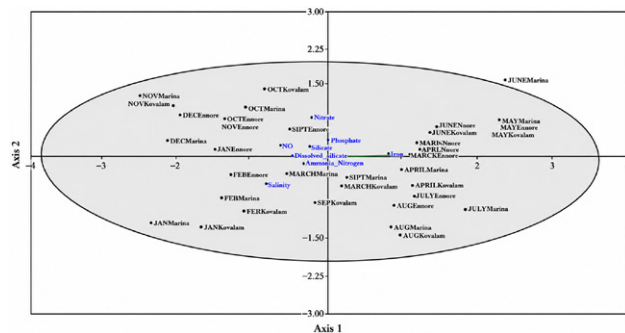


Fig. 6. Redundancy Analysis (RDA) of calanoid copepods and physico-chemical parameters at different stations

the nutrient concentrations were lower, while summer months were clustered toward the positive side, where these physico-chemical characteristics peaked, where temperature and nitrogen compounds were at their highest, and corresponded to increases in calanoid copepod counts. Overall, the RDA suggests that temperature, salinity, pH, dissolved oxygen, and nitrogenous nutrients may be the key drivers of spatial-temporal variations in calanoid copepod density at the three coastal stations, while phosphorus, magnesium, and calcium may exert minor influences (Fig. 6). RDA shows environmental gradients linked to calanoid copepod distribution. The statistical relationship is weak when the variables are tested separately, as seen in regression analysis.

Acartia species are capable of producing three types of eggs: subitaneous eggs (they hatch immediately in most cases unless environmental conditions are unfavourable), diapause eggs (development is stopped for a while), and delayed hatching eggs (they hatch after a longer period of time when conditions are suitable) (Tsunashima *et al.*, 2021). It is known that temperature is an important abiotic component affecting the biological activities of organisms at all levels, and marine invertebrates such as crabs and fish often shift their geographic distribution in response to temperature fluctuations (Milione and Zeng, 2008). It also affects the seasonal and geographic distributions of marine calanoid copepods (Abo-Taleb *et al.*, 2020). However, dissolved oxygen is vital to aquatic organisms, and low dissolved oxygen levels indicate water pollution, which leads to the death of an organism (Bozorg-Haddad *et al.*, 2021). Likewise, high levels of ammonia are toxic to aquatic organisms and reduce the hatching rate of calanoid copepod eggs (Eddy, 2005). Nitrite is a naturally occurring component of the nitrogen cycle in ecosystems and has been shown to cause several physiological disorders in aquatic organisms, even at low concentrations (Carmargo, 2005). Although nitrates are less toxic than nitrites, they are known to convert oxygen-transporting pigments into ineffective forms, resulting in lower oxygen uptake by aquatic organisms. However, the toxicity of nitrates to aquatic invertebrates increases with increasing nitrate concentration

in the water and with increasing exposure time, and decreases with increasing body size (Jensen, 2003). High concentrations of nitrite, nitrate, phosphate, and ammonia also cause the rapid growth of phytoplankton in aquatic ecosystems, which in turn reduces copepod productivity (Umer *et al.*, 2020). High phytoplankton density causes an algal bloom, which leads to the production of various toxins that are dangerous to calanoid copepods. Calcium and magnesium are essential for many biological processes; however, at high quantities, they can be hazardous to aquatic organisms (Van Dam *et al.*, 2010). The present study has revealed that the station Ennore showed a lower value of dissolved oxygen with higher concentrations of ammonia, nitrite, calcium and phosphate compared to other stations. This difference explains the lower abundance and geographic range of calanoid copepods at this site. During February, all the stations had high levels of dissolved oxygen and low temperatures, coinciding with the highest values of calanoid copepods. Salinity also plays an important role in copepod distribution, as very high and low salinity levels reduce copepod hatching success (Peck *et al.*, 2015). Lee *et al.* (2020) observed a low egg production rate in copepods in a low pH environment. The salinity pH of Ennore and Kovalam are found to be the least in June and July in the present study. This provides a probable reason why fewer calanoid are in evidence at this time. But the water has a high nutrient content in October, so the Marina's density is low.

Conclusion

In the present study, the relationship between calanoid copepods density and physico-chemical parameters was studied in the sub-plankton region over three stations of the Chennai coast. While temperature, dissolved oxygen, calcium and selected nutrients had significant relationships with calanoid abundance in regression analyses, most of these could not be considered as drivers $p > 0.05$ but rather indicative trends. Lower calanoid density at Ennore was simultaneous with higher ammonia and nitrite, and lower dissolved oxygen, while higher densities in February were associated with high dissolved oxygen and low temperature. These observations indicate that the seasonal hydrographic state, predominantly linked to DO variability, could modulate calanoid occupancy. Long-term investigations are suggested to provide a more complete characterisation of these interactions.

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Author contributions

Conceptualisation: KSK; Methodology: KSK; Data Collection: MAN, PMP, SVM; Data Analysis: MAN, PMP, SVM; Writing Original Draft: MAN, PMP, SVM; Writing Review and Editing: KSK, Supervision: KSK.

Data availability

The data are available and can be requested from the corresponding author

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of sensitive samples/ protected environments.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

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