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Assessment of Biogrowth at Two Different Environments of Nuclear Power Plant Cooling Water System Located at Southern Coast of India

S. Ganesh[1], A. Malar Retna[1], S. Godwin Wesley[2], P. Sriyutha Murthy[3,4,*] and T. Subba Rao[3,4]

[1]Department of Chemistry, Scott Christian College (Affiliated to Manonmaniam Sundaranar University,Tirunelveli), Nagercoil-629003, India
[2]Department of Zoology, Scott Christian College, Nagercoil-629003, India
[3]Water & Steam Chemistry Division, Bhabha Atomic Research Centre Facilities, Kalpakkam-603102, India
[4]Homi Bhabha National Institute, Anushaktinagar, Mumbai-400094, India

*Corresponding author: Tel: +91 4637 258818; E-mail: cnpsganesh71@gmail.com

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A systematic assessment of biogrowth development on titanium coupons exposed to ambient seawater (intake) and chlorinated seawater (pump house) environments of a coastal nuclear power plant was carried out. Titanium coupons were exposed for a period of 2 years and periodically removed at monthly intervals for biogrowth assessment. Biofouling biomass at the seawater intake station ranged from 0.8-12.5 kg m^{-2} during the 2 years of study. Continuous chlorination of 0.2 ± 0.1 mg L^{-1} and shock dose chlorination for 1 h/day at residuals of 0.4 ± 0.1 mg L^{-1} was very effective in reducing the biofouling load in the cooling water system. A reduction in fouling biomass of 95% was observed on titanium coupons between the intake and the pump house stations. Biofoulants recruitment was found to occur throughout the year at varying intensities. Diversity of organisms on the coupon was influenced by seasonality and distinct successional patterns were observed at the seawater intake. Barnacles were the dominant fouling organisms followed by mat forming ascidians, bryozoans, oysters, hydroids and seaweeds at the intake station. Sluggish biofouling development was observed on coupons at the intake due to the sub-tidal intake system (-5 m), which had a lesser load of meroplanktonic organisms. The study also showed that low dose continuous chlorination was an effective strategy for biofouling control in the cooling water system of the tropical power station which uses titanium heat exchangers for steam condensation.

Keywords: Power station, Biofouling, Titanium, Barnacles, Chlorination, Control.

INTRODUCTION

Marine biogrowth (biofouling) has been a restraining factor for maritime industry and is a serious problem in most seawater cooling systems of power plants and chemical industries [1]. Although, many possible solutions to control this problem have been suggested, none of them were cooperatively pertinent. While this biogrowth affects the performance of an industrial unit by clogging and reducing the diameter of the seawater conduits. It also has strong hydrodynamic effect on large ships such as tankers, where it increases payload and surface roughness of the hull [2]. Biofouling leads to speed reduction and increases additional fuel consumption in ships, but in the long run it also causes localized corrosion of the structural metal [2].

Biofouling in the cooling system of power plants is a universal problem. It is of considerable interest as it imposes penalty on power production, impairs the integrity of cooling system equipment and in some cases jeopardized safety of nuclear power plants cooling systems [3,4]. In general, most of the invertebrate biota in sea craves for a substratum to metamorphose to an adult, so it is difficult to decorrelate this process from the natural evolution in an ecosystem [5]. Since the biofouling phenomenon varies from site to site, the control methods must take into cognizance the influence of local factors and this warrants regular monitoring for an effective biogrowth control. Different aspects of biofouling intensity in the cooling conduits of coastal power plant from tropical as well as temperate regions have been studied by several researchers [6-12].

A typical cooling water system of a power plant involves a pre-condenser system and the heat exchangers which includes main condenser and process water heat exchangers [13]. The pre-condenser system involves the intake structures and the cooling water system from intake to the pump house. The intake system is either an open canal or pipeline or a tunnel. It has been observed that macro-fouling generally takes place in the pre-condenser system whereas, micro-fouling is observed in the condenser section particularly in the heat exchanger tubes. These variations in fouling process were due to the differences in the flow-rate and temperature. In spite of various physical measures such as trash rack, intake screens, travelling water screens, to control the entry of marine invertebrates, the tiny larval forms of various marine organisms enter the system, settle and colonize and grow. This finally affects the smooth operation of an industrial cooling system [12,13].

Biofouling has been a serious problem in the cooling water system (CWS) of Madras Atomic Power Station, Kalpakkam and Kudankulam nuclear power station, Kudankulam, India. It had affected the cooling system performance of the plant [7,10,14]. Marine biofouling community development in power plants is site specific, diverse and dynamic ecosystems. Species settlement and replacements occur, parallel at temporal scales [15]. Several environmental and biotic factors are known to influence settlement of invertebrate larval forms such as light [16], temperature [17], salinity [18], nutrients [19], waves and tides [20], depth [21], hydrodynamics [22], substratum colour [23], texture, chemical cues from encrusting biofilms [24] and seasonal variation in availability of larval forms [25], Success-ful recruitment of settled organisms is again dependent on pre and post settlement events [26], like influence of settled adult species, grazing, species coexistence, competition for space and food [27]. Initial settlement patterns [28,29] and timing of panel immersion [14,30] are known to influence the structure and type of biofouling community.

Chlorine is the biocide of choice due to its well-known chemistry in seawater, ease of handling and cost [31,32]. Chlorine possesses broad spectrum antifouling activity against different levels of fouling organisms from bacteria, diatoms and invertebrate larval forms [33,34]. Low dose continuous chlorination in the range of 0.2 ppm and periodic shock dose chlorination (0.4 ppm) is generally practiced at the power stations for prevention of biofouling [7,13]. Spite of standardized procedures for biofouling control in seawater cooling systems there is still a need to evaluate the efficiency of the chlorination regime adopted and to monitor the settlement of organisms, their growth and succession. This is because the environmental conditions and location specific species differs from site to site [35].

Thus, it is imperative to have qualitative and quantitative assessment of biofouling development in cooling water system, such as biomass loading on surfaces, species composition and their temporal variations. This will aid in fine tuning the biocidal regime and evaluating its efficacy. Such an investigation warrants a long term study to understand the factors that influence the species composition in a cooling water system. The present study was designed to assess the long term biofouling community development on titanium surface (titanium was chosen, since it was the condenser tube material) and the coupons were exposed for two year period at two different stations of the power plant *viz.* (i) seawater intake system and (ii) pump house or forebay, which receives treated (chlorinated) seawater. In this study, the seasonal patterns of settlement of organisms, species composition, succession of biofouling organisms were examined and in addition to this the efficacy of chlorination regime practiced for biofouling control was also investigated.

EXPERIMENTAL

Study area: The investigations were carried out for a period of 2 years from 2016 and 2017 at two different stations (intake point in the offshore dyke region and in the pump house/forebay) in the cooling water system of Kudankulam nuclear power station, Southern coast of India (8º9′ N and 77º39′ E). This region on the Southern Coast of India is influenced by the South West monsoon (June-Sep) and the North East monsoon (Oct-Feb) with a pre-monsoon period (March-May) [36]. However, the region receives its active rainfall during the North East Monsoon (NEM).

Cooling water system of Kudankulam Nuclear Power Plant (KKNPP): Kudankulam Nuclear Power Plant (KKNPP) comprises of 2 units of pressurized water reactors of the type VVER-V412 each with an installed capacity of 1000 MWe. The cooling water demand for one unit of KKNPP is ~ 98.8 m^3/s per unit [37]. The seawater intake structure of KKNPP draws water from the confluence of Bay of Bengal and Indian ocean region, through a caisson like structure connected to the breakwater dyke and the intake structure (Fig. 1). The caisson structure has 5 windows and the water is taken from a depth of 5 m from the mean sea level (MSL). The bottom most elevation of the caisson structure is at minus 10.5 m. The inlet of each of the bay structure is protected by a coarse screen mesh of 120 mm size to prevent entry of large organisms and debris. This type of intake represents a sub-tidal intake system designed primarily to avoid entry of pelagic biomass. A fish protection structure with an airlift system was installed at the shore end of the dyke to lift the pelagic biota above the corbel structure and initiate it back to the water. The cooling water from the offshore fish protection device was connected to the forebay (pump house) by three sub seabed reinforced concrete channels of 4 m width. The inlet seawater was chlorinated after the point of fish protection device and at another point in the pump house region. Sodium hypochlorite solution was generated by an electro-chlorination plant and operates on a mode of low dose continuous chlorination with residuals of 0.2 ± 0.1 ppm and shock dose chlorination for 20 min once in 8 h of 0.4 ± 0.1 ppm. Six condenser cooling pumps draw water for condenser cooling purposes with an intermediate cleaning device (travelling screens with fine mesh of ~4 mm). The cooling water from the pump house is supplied to the main condensers. The cooling water system has been designed such that temperature difference (ΔT) does not exceed 7 °C between the intake and the outfall (discharged water).

Hydrographic conditions and measurements: Collection of surface water samples were carried out at weekly intervals from the dyke. Surface seawater temperature was recorded by a thermometer of 0.1 °C accuracy. Salinity was estimated by the silver nitrate method [38]. Dissolved oxygen was measured by the Winkler's method [38]. Samples for dissolved oxygen

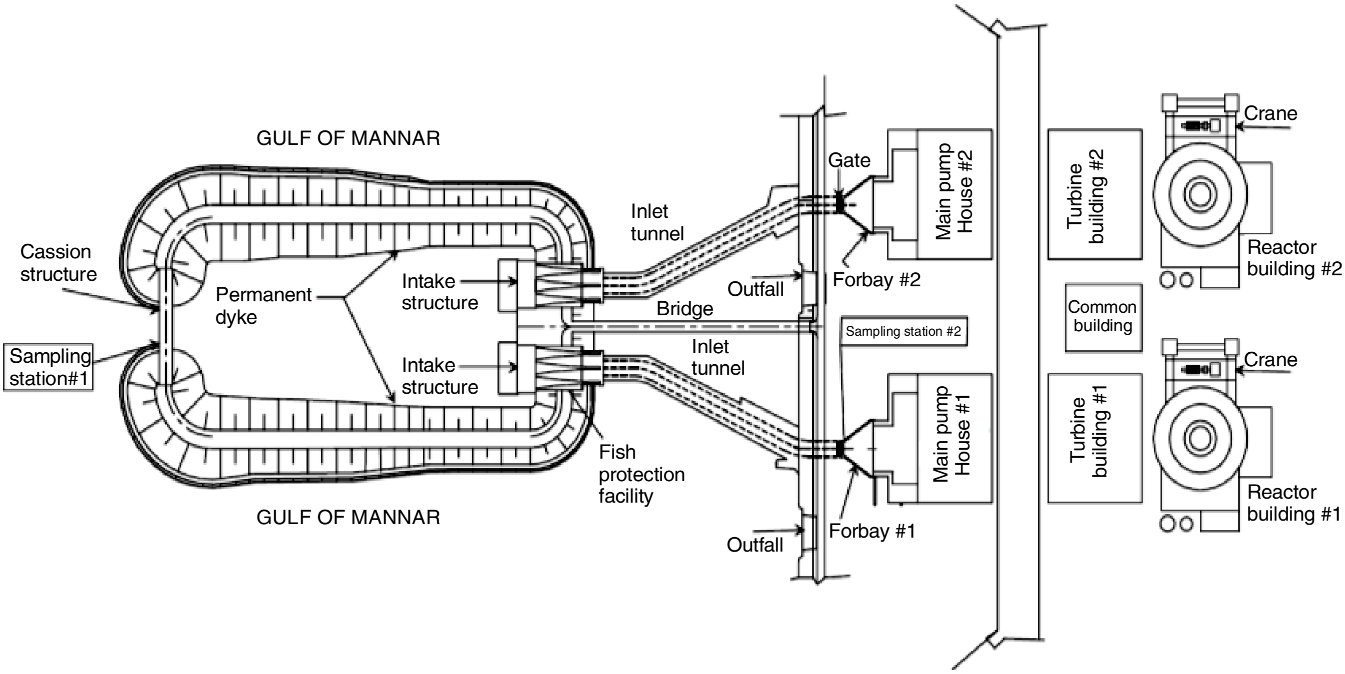

Fig. 1. Schematic diagram of cooling water system of KKNPP and geographical location of test site for coupon deployment

were fixed in the field immediately upon collection and taken to the laboratory for analysis. Turbidity and pH were measured by a turbidity and pH meter respectively. Dissolved inorganic nutrients (nitrite, nitrate, phosphate, silicate and ammonia) were measured according to the reported procedures [38]. Residual chlorine was measured as total residual oxidant (TRO) at the intake station and at the pump house using the HACH pocket colorimeter II(R) 5870000 with DPD tablet No. 4 (Lovibond, USA). The instrument had a measurement range of 0.1-1.0 ppm with a resolution of 0.01 ppm. TRO measurements were carried on a daily basis and the values averaged for the different months.

Coupon exposure and assessment of biofouling loading, species diversity and density: Titanium (condenser tube material of KKNPP) coupons were chosen for the study. Two environmentally different locations *viz.* (i) intake station, an offshore dyke located 1145 m from the shore and (ii) pump house station receiving chlorinated seawater with a flowrate of 3 m s^{-1} were chosen for deployment of the coupons for the longterm study. Identical test coupons measuring 10 × 10 cm and uniform thickness of 2 mm were used. The titanium metal coupons were polished from 80 to 480 grit with silicon papers to get a uniform surface finish, pre-weighed with a digital balance (0-2 kg with 0.1 g) up to the second decimal point. Triplicate samples of each coupon were prepared, weighed, tagged and suspended. The metal coupons were attached to an metal frame by the use of steel bolts and nuts and then suspended in the dyke region of the intake at a water depth of 1 m (Fig. 1). In pump house, the coupons could not be suspended *in situ* as the velocity of water in the region is high, which results in the swinging and banging of coupons against the walls. Hence, the test coupons were deployed in a 2000 L polypropylene tank which was fed continuously with seawater from a condenser pump. The flow through system was maintained continuously for a period of 2 years. The coupons were suspended at both locations simultaneously and retrieved periodically every month for a period of 2 years.

Periodically at the end of every month, test coupons in triplicate were retrieved based on the tags from both the locations and their wet weight was determined in the field. The coupons were then fixed in 5% formalin, then transferred to the laboratory and then photographed. Biofouling biomass in terms of loading, species composition and abundance of biofouling organisms, from both the sides of the coupons were analyzed separately and the mean values were calculated. Assessments of species diversity and density on coupons were carried out by the method as outlined by Nandakumar [39]. The abundance of biofouling organisms were counted manually by counting the number of individuals after separating them into different groups and species. The percentage area cover of the coupons was estimated using the freeware Image J software.

Statistical analysis: All exposures studies were conducted with triplicate coupons and the results expressed as mean and standard deviation. Triplicate seawater samples were collected for hydro-biological measurements and the results were expressed as mean with standard deviation. Statistical analysis was done using the software Graphpad Instat. Pearson's correlation was carried out for water temperature, salinity on biofouling load and species density. One-way ANOVA was done on biofouling loading between the two tests substrates and between the two different sites of exposure.

RESULTS AND DISCUSSION

Monthly and seasonal variations in the physico-chemical parameters are shown in Fig. 2a-c. The surface seawater temperature varied between 25.5 and 31.5 ºC during the entire two year study period with the annual seasonal variation being

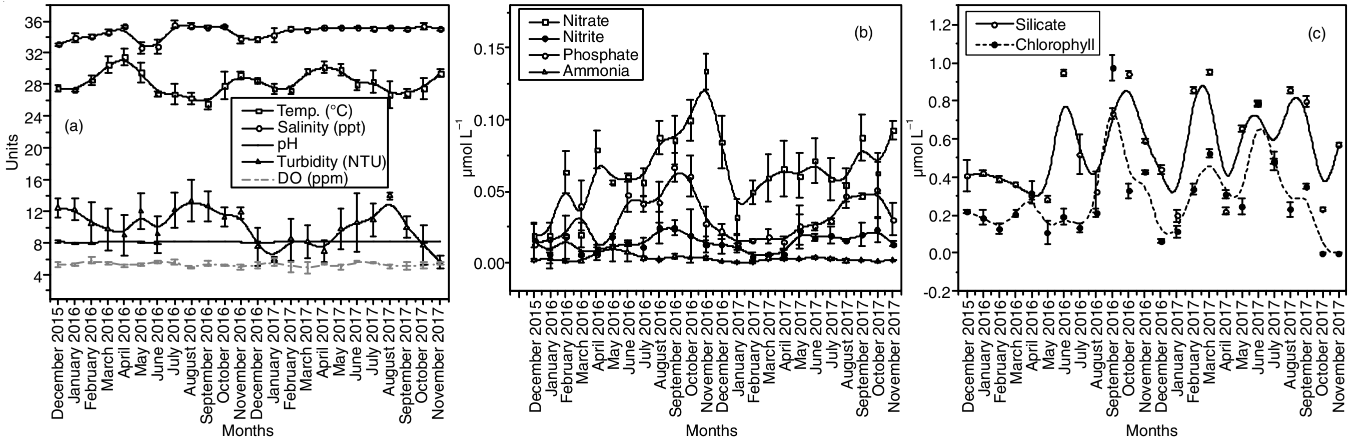

Fig. 2. Seasonal variation in water quality parameters at the power plant intake (a) temperature, salinity, pH, turbidity, dissolved oxygen, (b) nitrate, nitrite, phosphate, ammonia, (c) silicate and chlorophyll

~5.2 ºC. The highest water temperatures were observed during the month of April in 2016 and 2017. Positive correlation was observed with temperature and other measured water quality parameters (Table-1). Similarly, the lowest water temperature was recorded during the month of September during two consecutive years. In present study, a negative correlation was observed between temperature and biofouling loading, on the test surface titanium ($p = 0.3886$). Similarly, the number of recruits also showed a negative correlation with temperature titanium ($p = 0.8977$). Salinity is another important parameter, which influences the biofouling load and recruitment of species. Lowest salinity was observed during May 2016, whereas the maximum salinity in July 2016. Seawater salinity ranged between 32.7 and 35.6 ppt during this study. There was no major source of terrestrial input of freshwater into the coastal region. Likewise, in temperature relationship, there was negative correlation between salinity and biofouling load ($p = 0.0947$). Again, the number of recruits also showed a negative correlation with salinity ($p = 0.5175$).

Seawater pH showed a minimal change during the study period, however, turbidity of seawater varied widely during different seasons of the year, ranging from 5.6 to 21 NTU as the power station is present in the confluence region of Bay of Bengal and Indian ocean, the change in monsoon and oceanic currents result in turbulence. Dissolved oxygen levels did not show marked variations, ranging between 3.8 and 5.0 mL L^{-1}

TABLE-1
SEASONAL VARIATION IN WATER QUALITY PARAMETERS AT THE POWER PLANT INTAKE

Year	Month	Temp. (°C)	Salinity (ppt)	pH	Turbidity (NTU)	DO (mg/L)	Chlorophyll a (mg/m^3)	Nitrite (µmol/L)	Nitrate (µmol/L)	Phosphate (µmol/L)	Silicate (µmol/L)	Ammonia (µmol/L)
2015	Dec	27.5±0.4	33.1±0.2	8.2±0.2	12.4±1.2	4.3±0.3	0.19±0.14	0.01±0.00	0.08±0.02	0.02±0.00	0.44±0.07	0.00±0.00
2016	Jan	27.3±0.2	33.8±0.6	8.0±0.1	12.2±3.4	4.3±0.2	0.13±0.08	0.00±0.00	0.01±0.01	0.01±0.00	0.42±0.09	0.00±0.00
	Feb	28.5±0.7	34.1±0.3	8.1±0.0	10.5±4.7	4.8±0.4	0.21±0.12	0.01±0.01	0.06±0.01	0.01±0.00	0.39±0.04	0.00±0.00
	Mar	30.5±1.0	34.6±0.3	8.1±0.0	9.7±4.7	4.4±0.2	0.32±1.06	0.00±0.00	0.02±0.00	0.04±0.03	0.36±0.00	0.00±0.00
	Apr	31.5±1.0	35.3±0.1	8.1±0.0	8.9±2.6	4.2±0.1	0.11±0.06	0.00±0.00	0.07±0.02	0.00±0.00	0.30±0.22	0.00±0.00
	May	29.6±2.3	32.7±4.7	8.1±0.1	19.1±1.2	4.3±0.2	0.33±0.36	0.01±0.00	0.05±0.00	0.01±0.00	0.28±0.01	0.01±0.01
	Jun	26.8±0.3	32.8±4.9	8.1±0.2	9.1±3.3	4.6±0.1	0.19±0.14	0.01±0.00	0.26±0.05	0.04±0.01	0.94±0.07	0.00±0.00
	July	26.8±1.2	35.6±0.5	8.2±0.0	14.2±6.3	4.6±0.3	0.13±0.08	0.01±0.00	0.21±0.22	0.04±0.00	0.52±0.10	0.00±0.00
	Aug	26.3±0.7	35.4±0.5	8.2±0.0	13.3±7.7	3.8±0.1	0.21±0.12	0.02±0.01	0.08±0.04	0.04±0.02	0.32±0.12	0.00±0.00
	Sep	25.5±0.6	35.2±0.2	8.2±0.0	12.7±1.9	4.4±0.3	0.97±0.07	0.02±0.00	0.35±0.21	0.06±0.01	0.73±0.42	0.00±0.00
	Oct	27.9±1.8	35.4±0.1	8.1±0.0	11.2±1.2	4.2±0.1	0.32±1.06	0.02±0.01	0.30±0.05	0.06±0.01	1.04±0.31	0.00±0.00
	Nov	29.2±0.5	33.7±0.5	8.1±0.0	11.8±0.7	3.9±0.3	0.42±0.21	0.01±0.00	0.13±0.08	0.02±0.01	0.59±0.36	0.00±0.00
	Dec	28.5±0.4	33.7±0.3	8.1±0.1	7.5±2.4	4.2±0.4	0.06±0.00	0.01±0.00	0.08±0.02	0.02±0.00	0.44±0.07	0.00±0.00
2017	Jan	27.4±0.6	34.3±0.9	8.1±0.0	6.0±0.3	4.6±0.5	0.11±0.06	0.01±0.00	0.03±0.01	0.01±0.00	0.19±0.18	0.00±0.00
	Feb	27.3±0.5	35.1±0.5	8.1±0.0	8.5±5.7	5.0±0.6	0.33±0.36	0.00±0.00	0.05±0.00	0.01±0.00	0.85±0.74	0.00±0.00
	Mar	29.7±0.3	34.9±0.2	8.1±0.0	8.1±2.1	3.9±0.7	0.52±0.60	0.00±0.00	0.05±0.01	0.01±0.00	0.75±1.21	0.00±0.00
	Apr	30.3±0.8	35.1±0.1	8.1±0.0	7.0±1.3	4.3±0.1	0.31±0.22	0.00±0.00	0.06±0.06	0.01±0.00	0.22±0.15	0.00±0.00
	May	29.9±0.7	35.2±0.1	8.1±0.0	9.8±5.6	5.0±0.3	0.24±0.09	0.02±0.01	0.23±0.18	0.02±0.01	0.65±0.19	0.00±0.00
	Jun	27.9±0.6	35.2±0.1	8.1±0.0	10.6±3.7	4.6±0.1	0.78±0.43	0.01±0.00	0.27±0.05	0.02±0.00	0.79±0.27	0.00±0.00
	July	28.4±1.4	35.1±0.3	8.1±0.0	10.9±5.1	4.5±0.1	0.48±0.48	0.01±0.00	0.22±0.06	0.02±0.00	0.48±0.19	0.00±0.00
	Aug	26.7±1.7	35.2±0.1	8.1±0.0	21.0±0.5	4.0±0.3	0.23±0.10	0.02±0.00	0.35±0.01	0.04±0.00	1.05±0.11	0.00±0.00
	Sep	26.9±0.6	35.0±0.2	8.1±0.0	10.0±1.4	4.1±0.5	0.35±0.28	0.02±0.00	0.28±0.03	0.04±0.00	0.80±0.04	0.00±0.00
	Oct	27.5±1.4	35.4±0.4	8.1±0.1	7.7±3.5	4.2±0.4	0.00±0.00	0.02±0.00	0.32±0.01	0.05±0.02	0.23±0.11	0.00±0.00
	Nov	29.5±0.5	35.0±0.2	8.1±0.0	5.6±0.8	4.4±0.2	0.00±0.00	0.01±0.00	0.14±0.09	0.11±0.09	0.57±0.01	0.00±0.00

during the two year monitoring period. Chlorophyll ‘a’ levels at intake was found to vary seasonally ranging from below detectable limits (BDL) to 0.97 mg m^{-3}. The levels of inorganic nutrients in seawater were normal, they did not show any marked variation during the entire study period. Levels of inorganic nitrite ranged from BDL to 0.02 µmol L^{-1}, nitrate from 0.01 to 0.35 µmol L^{-1}, phosphate from BDL to 0.11 µmol L^{-1}, silicate from BDL to 1.05 µmol L^{-1} and ammonia from BDL to 0.01 µmol L^{-1}. Inorganic nitrate levels showed marginal increase during the south west monsoon during consecutive years. Residual chlorine (Fig. 3) was estimated at two different locations *viz.* (i) at the point of dosing in the intake structure after fish protection device, before entry to the pump house or forebay the concentrations ranged from 0.30 to 0.39 mg L^{-1}. The biannual average being 0.34 ± 0.02 mg L^{-1} at the intake station. (ii) Residual chlorine values at the pump house ranged from 0.20 to 0.40 mg L^{-1}, with the biannual average being 0.30 ± 0.05 mg L^{-1}. Predominantly, sampling for residual chlorine measurements were carried out during the time when the shock dose chlorination regime was *in vogue* at the power station.

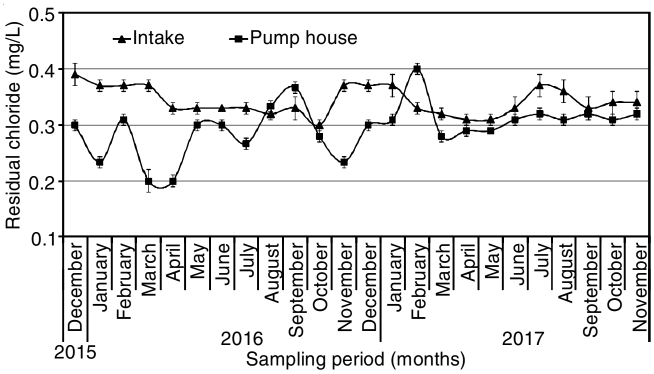

Fig. 3. Residual chlorine levels in the cooling water measured at the doing point at the intake and at the pump house station. The chlorine residuals were measured during booster dosing

Fouling biomass on surfaces in two different environmental conditions: The total biofouling load on the test coupons (Fig. 4) at the offshore intake point in the dyke region varied from 0.23 to 12.5 kg m^{-2} on titanium surface (Fig. 5a). Biomass loading on surfaces increased gradually with period of exposure and maximum loading was observed after 24 months of exposure. A spike in barnacle settlement was observed in the month of June 2017, *i.e.* during the second year of the study, which resulted in a sudden increase in biomass loading on titanium substratum. Comparison of biofouling loading between intake and the pump house was found to be highly significant ($p < 0.0001$), this could be due to the continuous chlorination regime in practice. A marked reduction in the settlement of biofouling organisms was observed between the untreated intake location and the test coupons exposed to chlorinated seawater at the pump house, where significant chlorine residuals are present. The coupons in the pump house accumulated only detritus, microbial biofilm and macroalgae and hydroids species. This resulted in the test coupons showing a minor increase in their biomass loading (Fig. 5b). The coupons exposed in the pump house were devoid of macrofouling organisms such as barnacles, oysters, ascidians and tubeworms. The percent area coverage, data revealed that the panel surface tend to accumulate more fouling organisms at the seawater intake station (Fig. 6) during the entire period of study.

Species abundance, succession and community structure on two different surfaces: Seven different groups of biofouling organisms were recorded on the test coupons, during the 2 years of coupon exposure study at the seawater intake dyke station (Fig. 7a-b) of the power plant. The abundance in settlement and succession pattern of individual species varied considerably on a temporal scale as well as the test substratum. It was observed that the test coupons deployed in the pump house were almost completely free of macrofouling organisms for the entire study period with occasional settlement. The domi-

Fig. 4. Coupons deployed at the intake station and pump house station for long-term study

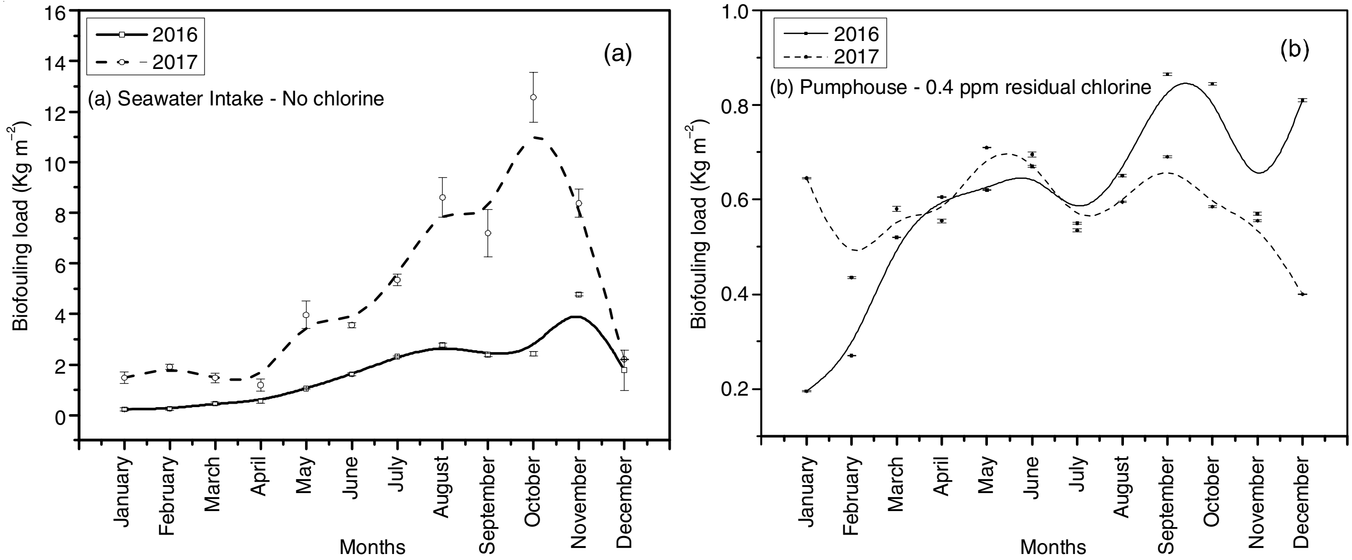

Fig. 5. Biofouling loading on titanium surfaces at (a) intake point and (b) pump house (chlorinated environment)

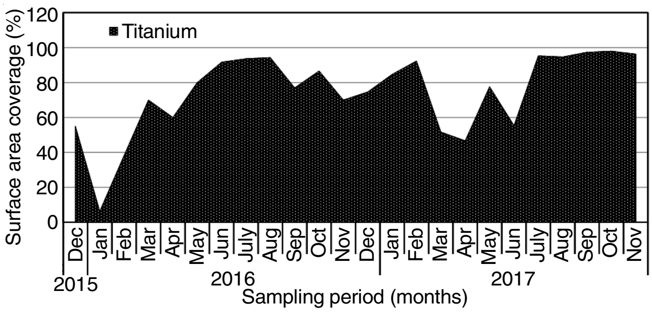

Fig. 6. Seasonal variation in percentage surface area coverage of titanium coupons by biofouling organisms

nant groups of fouling organisms recorded on surfaces included barnacles (*Balanus amphitrite*), oysters (*Crassostrea* sp), tubeworm (*Hydroides norvegicus)*, alga (*Cheateromorpha linum*), Cnidarian hydroids (unidentified), bryozoans (*Membranipora* sp.) and ascidians (unidentified mat-forming species).

Interestingly, green algae (*Chaetomorpha linum*) were found to be the primary colonizers on unused metal coupons for a period of time, which was the only species recorded during the first month (January, 2016) of immersion with a surface coverage of 55% on titanium. Surface coverage decreased to 6.3% and 5.7% during the second month of exposure. Subsequently, during the third and fourth months, the algae was conspicuously absent on the panel surface. Discontinuous recruitment of the green algae was observed during the 24 months of monitoring. A spike in fresh recruitment of the algae was observed during the North East monsoon (October-February).

Barnacle recruitment pattern showed marked difference over 24 months of monitoring. It was interesting to observe that the initial settlement of barnacles occurred on the substratum after a period of 90 days with an initial density of 3.4 numbers cm^{-2} on the titanium surface. High post settlement

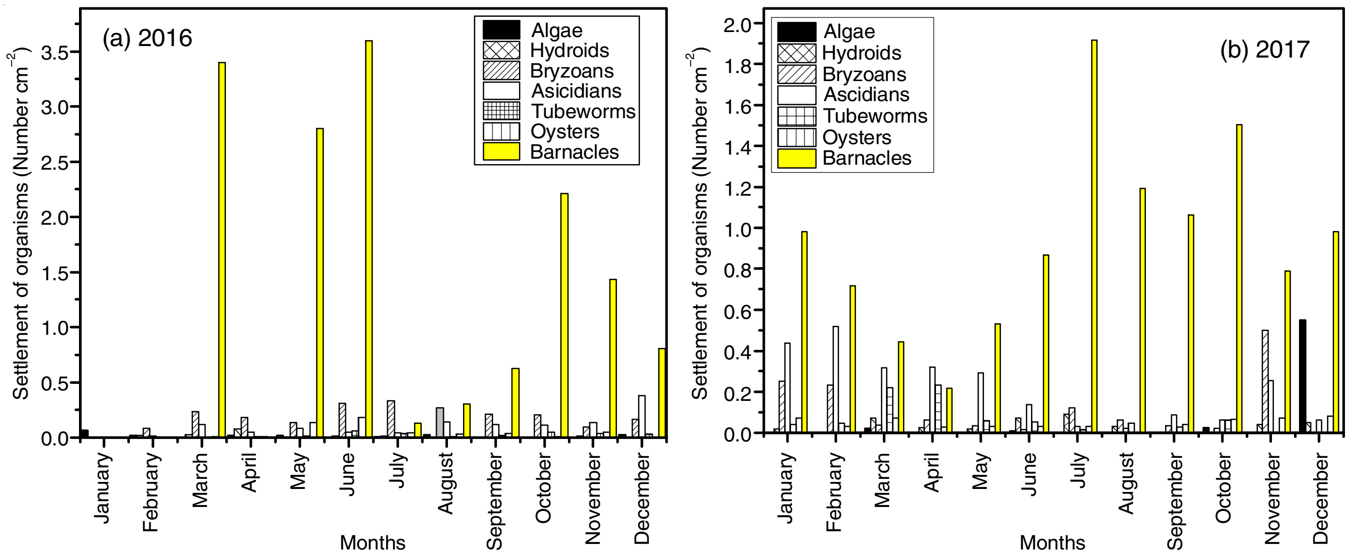

Fig. 7. Seasonal changes in the pattern of settlement and colonization of different biofouling organisms on titanium surfaces (a) 2016 and (b) 2017 at intake dyke region

mortality of barnacles was observed during the sampling in subsequent month (April 2017). Fresh settlement of barnacles occurred during the entire course of the south west and north east monsoon period (0.13 to 1.92 numbers cm^{-2}). The seasonal pattern of barnacle settlement and recruitment was observed during the first year did not corroborate with the settlement pattern during the second year of the study wherein the barnacles were recruited in high numbers during all three seasons. The recruitment of Cnidarian hydroids was observed on test coupons from the second month (60 days) of exposure of coupons. Similar to the green algae settlement, discontinuous recruitment of hydroids was observed on the test coupons during the study period. Maximum settlement was observed in the month of April for two subsequent years on both surfaces however, their densities varied. The percentage coverage of hydroid recruits was found to be low when compared to other fouling species. The recruitment of bryozoans occurred from the third month and fresh settlement was observed on the metal coupons during monthly sampling. Recruitment density of tube worms was found to be different between the 2 years of study. Initial recruitment of tubeworms was observed after five months of exposure on titanium surface. Fresh settlement was observed during all the seasons on the coupons and the density of tubeworms ranged from 0.007 to 0.25 numbers cm^{-2}.

Initial recruitment of ascidian species (mat-forming organism) occurred from the third month of exposure on the test surface and fresh settlement was observed during all the seasons of the study. The maximum percentage coverage 0.633 was observed in the month of February 2017. Colony size of the ascidians increased and covered the areas which were not occupied by barnacles. Settlement of oyster species was also observed after four months of exposure of the coupons, their density ranged from 0.007 to 0.027 numbers cm^{-2}.

In tropical marine environments, hydrological parameters have little effect on the settlement and recruitment of fouling organisms on surfaces except for factors like water temperature and salinity [40], which was found to be negatively correlated to organism settlement density. Biomass loading on the coupons was dependant on substratum type [41], this seems to be influenced by the settlement preference of organisms in the present study with titanium showing higher coverage. Inorganic nutrient levels and hydrodynamics in cooling water system (CWS) of power plants [6] has showed to influence the settlement and succession in biofouling community. In present study, the offshore intake of seawater was from a depth of 5 m from the surface. This intake type has a profound effect on the settlement of organisms on the substratum exposed inside the CWS that showed a slow rate in settlement and reduced diversity. This mode of seawater intake has a direct effect on larval availability along the vertical water column in the study region [42]. The maximum surface water temperatures of 30.3 and 31.5 ºC observed during the month of April and the lowest temperature observed during the month of August-September, which may be attributed to the onset of the SW monsoon and NE monsoon in this region. Reversal in the long-shore currents occurs during the change from SW to NE monsoons affect the circulation pattern in the region. These observations are in accordance to the earlier studies carried out in this region by Satheesh & Wesley [14] and along the East Coast of India [43,44].

Salinity is an important parameter that influences settlement and recruitment of larvae on surfaces [43]. Maximum salinity was observed during July 2016 and lowest was recorded during May 2016. Such salinity variations in this region (30 and 35.2 ppt), were also reported [14]. Similar variations were observed along the East Coast of India at different locations *viz.* (Gulf of Mannar 33.84 to 35.71 ppt) [45]; Kalpakkam (27.43 to 35.56 ppt) [43,44]. Dissolved oxygen levels (3.8 and 5.0 mg L^{-1}) were found to be similar to other regions of Bay of Bengal *viz.* Kalpakkam (3.38 to 6.6 mg L^{-1}) [43,46] with an independent study reporting values of 5.0 to 6.5 mg L^{-1} in the Bay region [47].

It was also observed that nitrate (NO_3) levels were higher than nitrite (NO_2), which corroborates with other studies [14, 47,48]. The observed low concentration of nitrate during the pre-monsoon period might be due to the consumption of nitrate by photosynthetic organisms. Maximum values of NO_2, NO_3, PO_4 and NH_4 were observed during the months of August to September during both the years of study. This could be due to the result of monsoon activity with significant discharge from land runoff.

Biomass loading observed on titanium surfaces (12.5 kg m^{-2}) over the 2 year exposure at the inlet dyke region was found to be low when compared to a similar study carried out at Madras Atomic Power Station southeast coast of India [7,49]. Comparatively biomass loading at the same location was higher (9.17 g dm^{-2}) in coastal waters in a study carried out during the construction phase (pre-operation period) of the KKNPP reactors [36]. Biomass loading on surfaces at Madras Atomic Power Station was 43.0 ± 8.6 kg m^{-2} on titanium surface [13], which is relatively high. One of the plausible reasons for the very low biofouling loads in the intake dyke region may be due to the abstraction of seawater through a sub-tidal inlet at a depth of 5-10 m, which may have less larval density in the water column. It is well-known that most of the larval forms of intertidal fouling organisms are concentrated at the surface of seawaters (1-2 m depth). The low-dose continuous and shock-dose chlorination regimes were found to be effective in preventing the settlement of fouling organisms in the condenser section of the power plant. Larval settlement was completely inhibited on the coupons deployed at the pump house and biomass loading was found to be very less (0.56 ± 0.001 kg m^{-2}). The biomass was mostly comprised of detritus and microbial biofilm, macroalgae and hydroids on the test surfaces. Similarly, the chlorination regime (low and shock dose) practiced at Kalpakkam site also revealed that the biocide was able to reduce the biomass loading from 43.0 kg m^{-2} to 2.7 ± 0.8 kg m^{-2} on the titanium coupons.

In this study, 7 major groups of taxa were recorded on the test surfaces barnacle (*Balanus amphitrite)*, Cnidarian hydroids (unidentified), ascidians (unidentified), tubeworm (*Hydroides* sp.), oysters (*Crassostrea* sp.), bryozoans (*Membranipora* sp.) and green alga (*Enteromorpha* sp.). Marked temporal variation in the settlement of each of these organisms was observed during the study period. Temporal variation in the recruitment of fouling organisms in coastal waters in the tropical region was influenced by the substratum type, hydrodynamic features, larval availability and predation [50-52]. In addition, the spawning periods of biofouling organisms in tropics show high seasonality and are dependant to a great extent on fluctuations of environmental parameters like salinity and temperature which influence larval release and subsequent recruitment [51].

All the 7 groups of organisms showed seasonal variation in their recruitment pattern. Seaweeds constituted an important constituent of fouling community, in present study, wherein the green algae *Chaetomorpha linum* was recruited in high numbers on the coupons and were dominant during the first four months of exposure. Dense recruitment of these algae prevented the settlement of other fouling organisms during the initial stages, which may be attributed to the resistance exhibited by algal communities on new settling species [53]. It was also been observed that seaweeds decrease barnacle recruitment by mechanical interference, which abrades the substratum and dislodges the larvae during settlement [54,55]. This could be the reason for the low recruitment in the barnacles on the exposed coupons.

It is a natural phenomenon that species replacement occurs in fouling communities and are influenced by the species possessing different set of organismic properties [56]. The seaweeds were replaced by barnacles, hydroids and bryozoans on exposed surfaces. Except for a brief absence during the pre-monsoon months of April to June, the intertidal barnacle of the species *Balanus amphitirite* reached its peak settlement in the month of March. However, according to Gaonkar & Anil [57], barnacle recruitment in tropical region along the west coast of India was found to be influenced by monsoon, spatial and temporal scales. Similar observation on biofouling organism recruitment was observed by Murthy *et al*. [13] at Kudankulam. The species that settled in high numbers during the SW and NE monsoon in present study can be attributed to the seasonal fluctuations. Other factors like hydrodynamics influence the retention and dispersal of larvae in adult populations [57]. Interestingly, the seasonal settlement of this species (absence in pre-monsoon months) was observed only during the first year of the study which was also reported by Satheesh & Wesley [36]. The biologically conditioned surfaces during the second year attracted barnacle settlement during all months irrespective of seasons in the immersion study. This may be attributed to the presence of favourable bacterial films and gregarious behaviour of the larvae [58]. In earlier study at the same site by Satheesh & Wesley [36], it was reported that peak ascidian settlement inhibited barnacle recruitment. However, this was not observed in the present study where barnacles and ascidians were recruited in parallel on the same coupons.

The settlement of Cnidarian hydroids was observed from the second month of exposure and it continued to settle up to a period of six months. In general, hydroids preferred to settle during the pre-monsoon months in high numbers. Hydroids in general colonize vacant substrates [59] and form an important role in pelagic and benthic coupling of communities. The discontinuous settlement on coupons observed during the two years study period may be attributed to their settlement behaviour wherein the larvae avoid sediment coated surfaces [60]. It is highly probable that these species were settled on the empty spaces on the coupons, which were devoid of other foulants.

Settlement of tubeworms was significant on the titanium surface during the first year of study but the recruitment was high during the second year with peak settlement during the pre-monsoon period. Such observations have also been reported by Rajagopal *et al*. [61] on east coast of India. Ascidians also showed seasonality in settlement and peak settlement was observed during the pre-monsoon months on the panel surfaces. They settled in small numbers during the SW and NE monsoons. This pattern may be attributed to the breeding activity, larval availability and environmental factors. Similar observations were reported by other researchers too [36,43]. Correspondingly, bryozoans settled in large numbers during the first year of immersion of the coupons, however, their density was reduced during the second year. No seasonal preference was observed in settlement of these foulants. The edible oyster *Crassostrea madrasensis* was found to settle on the test surfaces during the first year of immersion, while their numbers reduced during the second year. Among the factors which influence the settlement and recruitment on surfaces, predation pressure may also be responsible for the changes observed on the exposed coupons and replacement of species [52]. In general, the diversity of biofouling organisms on artificial structures are generally low when compared to natural habitats and this was found to vary between regions and sites [62]. The temporal patterns of settlement of foulants observed in the study may be attributed more to the effects on larval availability in the seawater, rather than to the physico-chemical parameters. Cooling water systems are highly specialized ecosystems which vary in their hydrodynamic regimes and types of surfaces.

Conclusion

The biogrowth development on the titanium coupons was studied after being subjected to the seawater intake (ambient) and chlorinated seawater pump house (chlorinated) environments of a coastal nuclear power plant situated at Kudankulam, India. The investigated results revealed that the fouling community was dominated by barnacles and bryozoans with a temporal variation in settlement of species observed and low biofouling loading on coupons in cooling water system was observed, which could be hypothesized to a low larval availability due to sub-tidal seawater intake system. Moreover, the existing low dose continuous chlorination being very effective in inhibiting settlement of organisms at the pump house or forebay region.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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