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Ecology of soil microbes in a tropical mangrove forest of south east coast of India

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ABSTRACT

Present work enumerated nine groups of microorganisms in the soil samples drawn at 10depths from two mangrove sites for four seasons in two years, along with 23 physicochemical characteristics in a mangrove forest. The microbial density was higher in dense mangrove sediments than that in sparse ones. Among the microorganisms, actinobacteria, total heterotrophic bacteria (THB), thraustochytrids, yeasts and fungi were high in dense mangrove sediments. Microbial counts reduced with increasing soil depth. Physical factors displayed profound effect on microbes than chemical factors did. Among the physical factors, the dense mangrove sediment exhibited many fold higher silt, clay, redox potential, lower sand and higher pore water salinity than sparse mangrove sediment did. Among the chemical factors, total organic carbon (TOC) was 52% and soil nitrogen was 4.5% higher in dense mangrove sediment than that in sparse mangrove sediment. This work reiterated significance of mangrove forest for conserving marine microbiota for maintaining carbon and nutrients in coastal sediment.

1. Introduction

Mangroves are the only tall tree forest on the earth lying at the boundary between land and sea in the tropical regions. The mangrove forests are among the world's most productive ecosystems. (Kathiresan and Bingham, 2001; Kathiresan and Qasim, 2005). This is mainly because of the fact that mangroves provide a unique ecological niche to diverse group of microbes which play a major role in transformation of organic matter into nutrient supply to the many organisms associated with the mangrove ecosystem. Microbial processing of litter is an important mechanism for preserving nutrients and energy in the mangrove ecosystem (Holguin et al., 2001a, 2001b; Rajendran and Kathiresan, 2007; Sahoo, 2009; Kathiresan, 2011). The mangrove habitats continue to disappear globally at a rate of 0.66% per year during the 2000–2005 periods (FAO, 2007). Mangroves associated soil bacteria are important participant in carbon, sulfur, nitrogen, and phosphorous cycles in mangroves ecosystem (Toledo et al., 1995; Rojas et al., 2001). Soil phosphate solubilizing bacteria are associated with black mangroves roots systems and are involved in carbon recycling under the both oxic and anoxic conditions (Das et al., 2012). Fungi are prerequisite for the decomposition of the mangroves litter and nutrient conservation. The mangroves associated soil microbe Trichoderma species is known to involved in soil phosphate solubilization and improve the growth of mangroves species *Avicennia marina* (Saravanakumar et al., 2013). In addition, Mangroves habitat loss has put at 16% of mangrove plant species and 40% of the animal species globally at an elevated risk of extinction (Kathiresan, 2010) and such of the data for mangrove associated microbes are yet to be known. In generally, microbial load in the forest ecosystem could changes the properties of the habitat (Zifcakova et al., 2016). It is critically important to understand the microbial ecology of the mangrove sediments in the present context of global warming and sea level rise, besides man made threats to the ecologically sensitive mangrove habitats (Gilman et al., 2008). Soil biochemical and microbial characteristics are important indicators for the vegetations of mangroves (Dinesh et al., 2013). Especially best of our knowledge there is no scientific report about the relationship of the major group of mangroves associated microbes (Cyanobacteria, Actinobacteria, Azotobacters, Lactobacilli, Fungi, Trichoderma, Thraustochytrids and Yeasts) and their relation with physicochemical parameters. In spite of widespread occurrence, marine microorganisms are only poorly understood for their ecology in mangrove biotope. In order to study the relation of physicochemical and microbial variation in mangroves habitat at different soil depth, site, and season's, the present study was undertaken to enumerate microbial loads such as Cyanobacteria, Actinobacteria, Azotobacters, Lactobacilli, Fungi, *Trichoderma*, Thraustochytrids and Yeasts followed by physico-chemical characteristics in mangrove habitat at different soil depth, seasons, and sites. In addition, this study aimed to analysis the relation between microbial load and physicochemical aspects.

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2. Materials and methods

2.1. Description of study area

The study area is Pichavaram, located along the Bay of Bengal on the southeast coast of India (Fig. 1). It is an estuarine type of mangrove habitat, situated at the Vellar-Coleroon estuarine complex. The forest occurs on 51 islets, ranging in size from 10 m^2 to 2 km^2, separated by intricate waterways that connect the Vellar and Coleroon estuaries. The southern part near the Coleroon estuary is predominantly mangrove vegetation, while the northern part near the Vellar estuary is dominated by mud-flats. The Vellar estuary opens into the Bay of Bengal at Parangipettai and links with the Coleroon River, which is a distributary to the River Cauvery. The Pichavaram mangrove is influenced by mixing of three types of waters: (i) neritic water from the adjacent Bay of Bengal through a mouth called 'Chinnavaikkal'; (ii) brackish water from the Vellar and Coleroon estuaries; and, (iii) fresh water from an irrigation channel ('Khan Sahib canal'), as well from the main channel of the Coleroon river.

The mangrove covers and area of about 1100 ha, of which 50% is covered by forest, 40% by water-ways and the remaining filled by sand-flats and mud-flats. The year for convenience is arranged into four seasons: post-monsoon (January–March); summer (April–June); pre-monsoon (July–September); and monsoon (north-east monsoon; October–December). The tides are semi-diurnal and vary in amplitude from about 15–100 cm in different regions during different seasons, reaching a maximum during monsoon and post-monsoon and a minimum during summer. The rise and fall of the tidal waters is through a direct connection with the sea at a river mouth and also through the two adjacent estuaries. The depth of the water-ways ranges from about 0.3–3 m.

2.1.1. Collection of soil samples

Sediment soil samples were collected using a corer (1.5 m long stainless steel corer with 50 cm dia.) during low tide in 10 different depths (10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 cm) from two sites: luxuriant area with dense mangrove forest, (Lat. 11° 25′38.4 N; Long. 79° 47′ 35.5 E) and degrading area with sparse mangrove forest (Lat. 11° 25′55.4 N; Long. 79°49′ 16.2 E) in Pichavaram mangrove forest. The sampling was made for four seasons (pre-monsoon, monsoon, post-monsoon, and summer) respectively during the months of August, November, February and May for the two years of 2010 and 2011.

2.1.2. In situ analysis of temperature, pH, redox potential and pore water salinity

The soil samples were analyzed in the field itself for soil temperature using a thermometer with 0.5 °C accuracy. Hydrogen ion concentration of the soil sample was measured using a pH meter with platinum electrode with an accuracy of ± 0.1, (pH 315i/ SET, Wissenschaftlich Technische Werkstatten, Germany) and calibrated with standard buffer solution prior to use. Redox potential (Eh) was measured by using a milli voltmeter with platinum electrode (pH 315i/ SET, Wissenschaftlich Technische Werkstatten, Germany). Pore water salinity was recorded by using a hand refractometer (Atago hand refractometer, Japan), after crushing a small amount of soil through a Whatman No.1 filter paper by using a syringe. For this, a known amount of sediment samples was moisturized with double distilled water up to the moisture saturation level of the sediment. The soil samples were transferred to laboratory immediately in sterile polythene bags and analyzed for soil texture. The plant roots and other debris were removed from the sediment samples and were ground to fine powder and dried in an oven at 110 °C to a constant weight for further analysis

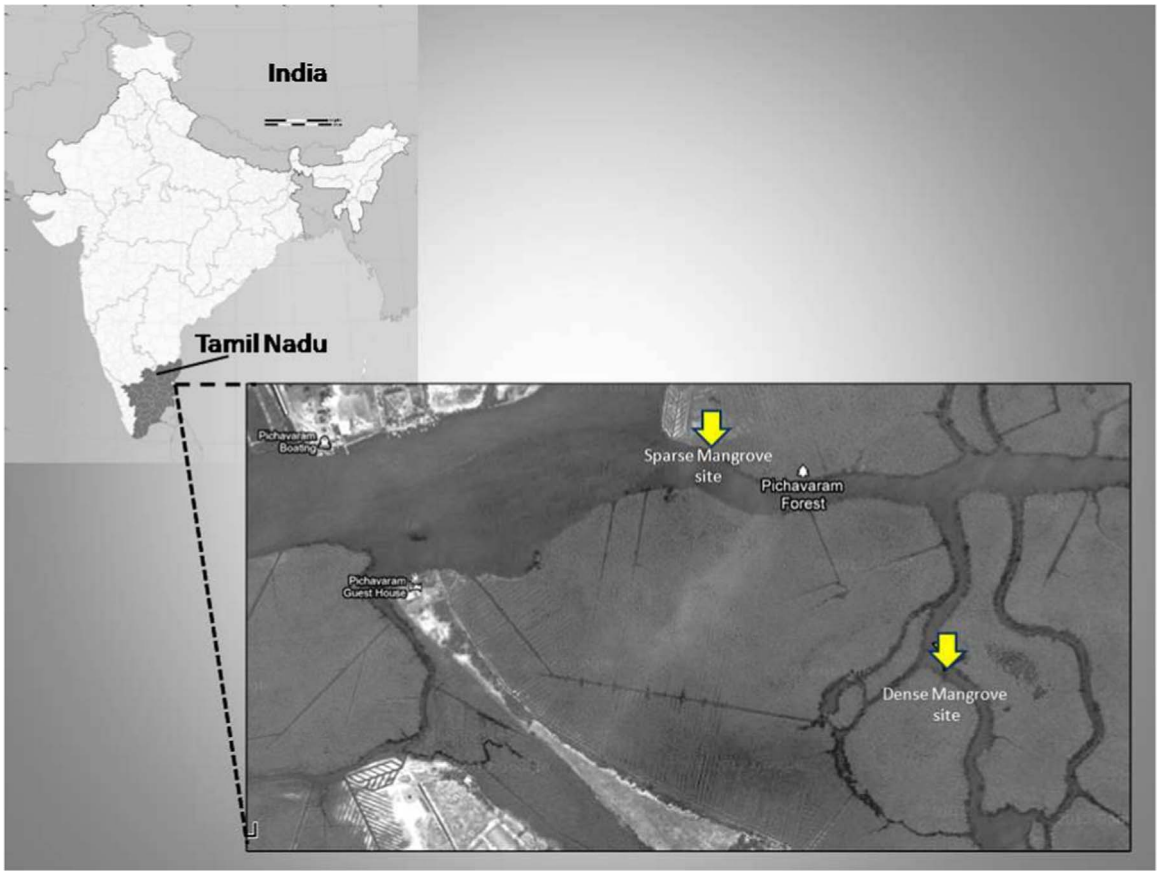

Fig. 1. Study area, located along the Bay of Bengal on the southeast coast of India.

of soil composition, total organic matter, major elements and trace elements.

2.1.3. Soil texture analysis

The soil texture was analyzed in terms of composition of clay, silt and sand using a hydrometer method (Bouyoucos, 1962). Levels of nitrogen phosphorus and Potassium in sediment samples were analyzed using Kjeldahl method (Subbiah and Asija, 1956) and colorimetric method (Olsen et al., 1954), (Guzman and Jimenez, 1992) respectively. Total organic carbon in sediment was estimated by adopting the method of EI Wakeel and Riley (1956). Heavy metals in sediments (Aluminum (Al), Boron (B), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Nickel (Ni), lead (Pb) and Zinc (Zn) was analyzed by using method of Chester and Hughes (1967) in Inductive coupled plasma emission spectrometer (ICP; Jobin Yvon-JY24, France).

2.1.4. Soil microbiological analysis

Fresh soil samples collected were transferred to 4 °C and analyzed for microbial groups within 4–6 h of sampling. The soil samples were serially diluted and specific methods and media were used for enumeration of the microbial counts of different groups of microbial flora: salt nutrient media for cyanobacteira (Waterbury et al., 1986; Waterbury and Willey, 1988). Zobell marine agar for total heterotrophic bacteria (THB), MRS medium for lactobacilli (Deman et al., 1990), starch casein agar medium for actinobacteria (Ravikumar et al., 2004), Winogradsky medium for azotobacters (Bergeys manual, 1974), YM Agar medium for yeasts (Yeast malt Agar) (Fell, 2005) and Potato Dextrose Agar Medium for fungi (Ravikumar et al., 2004), yeast peptone agar medium for thraustochytrids (Raghukumar, 2005), selective medium for *Trichoderma* (Askew and Laing, 1993). Enumeration of all the microbes was done by adopting spread plate method. In this method, sterile media were poured into Petri dishes aseptically and allowed to solidify. One milliliter of the serially diluted sample was pipette out into sterile Petri-dishes. It was made spread in the plate first by rotating it in clockwise and then anti-clockwise directions for three times and then spread with the help of "L" rod. The plates were incubated in an inverted position at 28 ± 2 °C. All the determination was carried out in triplicates. After the incubation period of 2–3 days for THB, 7–10 days for azotobacters, actinobacteria, lactobacilli and yeasts, and 2–3 weeks for cyanobacteria colonies were counted. The plates were examined and counted for the number of colonies per plates. The microbial load in the given sample was calculated using the following formula and it is expressed as Colony Forming Unit (CFU) per gram of the sample.

$$\text{Total microbial load in the given sample (CFU/g)} = \frac{\text{Total number of colonies}}{\text{Sample of volume plated (0.1 ml)} \times \text{Dilution}} \times \text{Total Volume}$$

2.1.5. Statistical analysis

A suite of SPSS 11.5 software (IBM) was used for the statistical analysis to find the significant differences of parameters between soil depths or seasons or soil depths, Univariate 4-way ANOVA was followed by post hoc test (SNK and Tukey's) and to find correlation matrix between the parameters used Pearson's correlation method.

3. Results

3.1. Microbial flora of mangrove sediment

The counts of nine groups of microflora namely cyanobacteria, total heterotrophic bacteria (THB), lactobacilli, azotobacters, actinobacteria, fungi, yeasts, thraustrochytrids and *Trichoderma* as influenced by soil depths of two mangrove sites for four different seasons in two years (2010 and 2011) are shown in Table 1 and Fig. 2a–j. In general, the counts between sites, depths, seasons and years of analysis were highly significant ($p < 0.01$).

Cyanobacterial count was higher in luxuriant site than that in degrading site. It was 1.32×10^3 CFU g^{-1} in luxuriant site and 1.08×10^3 CFU g^{-1} in degrading site (Fig. 2a). Cyanobacterial counts varied from 0.79 to 1.72×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 100 cm depth (Fig. 2j). Cyanobacterial counts ranged between 1.09 and 1.40×10^3 CFU g^{-1} at different seasons. The count was maximum in post-monsoon and minimum in monsoon. Cyanobacterial count was higher (0.80×10^3 CFU g^{-1}) in the year 2010 than that (0.63×10^3 CFU g^{-1}) in 2011 (Table 1).

Total heterotrophic bacteria (THB) counts were higher in luxuriant site than that in degrading site. It was 19.46×10^3 CFU g^{-1} in luxuriant site and 11.71×10^3 CFU g^{-1} in degrading site (Fig. 2b). THB counts varied from 4.75 to 31.16×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 100 cm depth (Fig. 2j). THB counts ranged between 4.92 and 31.04×10^3 CFU g^{-1} at different seasons. The count was maximum in post-monsoon and minimum in monsoon. THB counts were higher (15.92×10^3) in the year 2011 than that (15.25×10^3 CFU g^{-1}) in 2010 (Table 1).

Lactobacilli counts were higher in luxuriant site than that in degrading site. It was 7.06×10^3 CFU g^{-1} in luxuriant site and 5.08×10^3 CFU g^{-1} in degrading site (Fig. 2c). Lactobacillus counts varied from 0.83 to 13.11×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 100 cm depth (Fig. 2j). Lactobacilli counts ranged between 1.87 and 9.89×10^3 CFU g^{-1} at different seasons. The count was maximum in post-monsoon and minimum in monsoon. Lactobacilli counts were higher (6.47×10^3 CFU g^{-1}) in the year 2011 than that (5.66×10^3 CFU g^{-1}) in 2010 (Table 1).

Azotobacters counts were higher in luxuriant site than that in degrading site. It was 4.04×10^3 CFU g^{-1} in luxuriant site and 3.32×10^3 CFU g^{-1} in degrading site (Fig. 2d). Azotobacters counts varied from 0.86 to 6.89×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 100 cm depth (Fig. 2j). Azotobacter counts ranged between 2.12 and 6.23×10^3 CFU g^{-1} at different seasons. The count was maximum in monsoon and minimum in pre monsoon. Azotobacter counts were higher (4.04×10^3 CFU g^{-1}) in the year 2011 than that (3.32×10^3 CFU g^{-1}) in 2010 (Table 1).

Actinobacterial counts were higher in luxuriant site than that in degrading site. It was 6.35×10^3 CFU g^{-1} in luxuriant site and 3.75×10^3 CFU g^{-1} in degrading site (Fig. 2e). Actinobacterial counts varied from 0.72 to 10.46×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 100 cm depth (Fig. 2j). Actinobacterial counts ranged between 1.39 and 12.00×10^3 CFU g^{-1} at different seasons. The count was maximum in premonsoon and minimum in monsoon. Actinobacterial counts were higher (6.69×10^3 CFU g^{-1}) in the year 2010 than that in 2011(Table 1).

Fungal counts were higher in luxuriant site than that in degrading site. It was 7.17×10^3 CFU g^{-1} in luxuriant site and 4.58×10^3 CFU g^{-1} in degrading site (Fig. 2f). Fungal counts varied from 0.88 to 14.74×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 100 cm depth

Table 1
Microbial counts in two mangrove sites at 10 soil depths in four seasons for two years (2010 and 2011).

Source	Soil microbial counts (CFUx 10^3 g^{-1} of soil)								
	Cynobacteria	THB	Lactobacilli	Azotobacters	Actinobacteria	Fungi	Yeasts	Thraustrochytrids	Trichoderma
Mangrove site									
Degrading site	1.11 ± 0.2^{a}	11.72 ± 2.3^{a}	5.08 ± 1.2^{a}	3.33 ± 1.2^{a}	3.75 ± 0.6^{a}	4.58 ± 0.3^{a}	2.84 ± 0.5^{a}	3.89 ± 1.2^{a}	4.82 ± 1.2^{a}
Luxuriant site	1.32 ± 0.3^{b}	19.47 ± 1.2^{b}	7.06 ± 1.2^{b}	4.04 ± 1.2^{b}	6.36 ± 0.3^{b}	7.17 ± 0.4^{b}	4.51 ± 0.4^{b}	6.36 ± 1.5^{b}	6.19 ± 1.4^{b}
Soil depth (cm)									
10	1.73 ± 0.2^{d}	31.16 ± 1.2^{g}	13.11 ± 1.2^{c}	6.90 ± 1.3^{e}	10.47 ± 1.2^{d}	14.75 ± 1.2^{e}	12.64 ± 0.5^{e}	12.17 ± 1.2^{e}	19.43 ± 2.3^{f}
20	1.62 ± 0.3^{c}	27.19 ± 1.3^{g}	11.86 ± 1.2^{c}	6.23 ± 1.4^{e}	8.12 ± 1.3^{d}	12.80 ± 1.2^{e}	7.98 ± 0.3^{b}	10.81 ± 1.4^{e}	12.95 ± 2.4^{e}
30	1.46 ± 0.1^{c}	23.38 ± 1.4^{f}	9.83 ± 1.4^{c}	5.45 ± 1.2^{e}	7.30 ± 1.2^{d}	8.36 ± 1.2^{d}	5.87 ± 0.4^{d}	8.60 ± 1.2^{d}	6.83 ± 2.4^{d}
40	1.37 ± 0.4^{c}	18.83 ± 1.2^{f}	8.81 ± 1.2^{b}	4.77 ± 1.2^{c}	6.20 ± 0.7^{c}	6.76 ± 1.3^{d}	3.23 ± 0.4^{c}	6.51 ± 1.4^{d}	5.22 ± 2.3^{d}
50	1.19 ± 0.3^{c}	15.91 ± 1.3^{e}	6.66 ± 1.2^{b}	4.09 ± 1.1^{c}	5.34 ± 0.7^{c}	5.79 ± 0.8^{c}	2.18 ± 0.3^{c}	4.43 ± 1.2^{c}	3.08 ± 2.5^{c}
60	1.17 ± 0.2^{c}	12.82 ± 1.4^{e}	4.70 ± 1.3^{b}	2.76 ± 1.4^{b}	4.47 ± 0.9^{b}	4.37 ± 0.2^{c}	1.62 ± 0.3^{b}	3.33 ± 1.2^{b}	2.69 ± 2.4^{c}
70	1.03 ± 0.4^{b}	9.55 ± 1.2^{d}	2.59 ± 1.2^{b}	2.25 ± 1.2^{b}	4.86 ± 1.2^{b}	2.03 ± 0.4^{b}	1.07 ± 0.3^{b}	1.66 ± 0.9^{a}	1.56 ± 1.2^{b}
80	0.96 ± 0.3^{a}	6.96 ± 1.3^{c}	1.42 ± 1.1^{a}	2.11 ± 1.1^{a}	2.11 ± 1.9^{a}	1.62 ± 0.9^{a}	0.74 ± 0.4^{a}	1.56 ± 0.7^{a}	1.06 ± 1.4^{b}
90	0.83 ± 0.1^{a}	5.37 ± 1.3^{b}	0.90 ± 0.2^{a}	1.42 ± 1.2^{a}	0.96 ± 0.4^{a}	1.38 ± 0.7^{a}	0.77 ± 0.3^{a}	1.10 ± 0.6^{a}	1.11 ± 2.4^{b}
100	0.79 ± 0.2^{a}	4.75 ± 1.4^{a}	0.84 ± 0.1^{a}	0.87 ± 0.3^{a}	0.72 ± 0.2^{a}	0.89 ± 0.3^{a}	0.64 ± 0.2^{a}	1.11 ± 0.5^{a}	1.13 ± 2.5^{a}
Season of analysis									
Post-monsoon	1.40 ± 0.3^{d}	31.04 ± 1.2^{d}	9.90 ± 1.2^{d}	$2.95 \pm 0.0.8^{a}$	4.52 ± 1.2^{b}	2.63 ± 0.2^{a}	3.81 ± 0.1^{b}	10.81 ± 0.4^{d}	4.65 ± 1.2^{a}
Summer	1.23 ± 0.3^{c}	17.06 ± 1.3^{c}	7.53 ± 1.3^{c}	3.42 ± 0.6^{b}	2.30 ± 0.4^{a}	4.18 ± 0.3^{b}	3.72 ± 0.1^{b}	8.60 ± 0.5^{c}	6.38 ± 1.4^{b}
Pre-monsoon	1.14 ± 0.3^{b}	9.34 ± 1.2^{b}	4.99 ± 1.3^{b}	6.24 ± 1.1^{c}	12.01 ± 0.2^{c}	9.57 ± 0.6^{d}	1.36 ± 0.2^{a}	6.51 ± 0.3^{b}	4.67 ± 1.4^{a}
Monsoon	1.09 ± 0.2^{a}	4.93 ± 1.4^{a}	1.88 ± 1.2^{a}	2.13 ± 0.8^{a}	1.40 ± 0.3^{a}	7.13 ± 0.8^{c}	5.80 ± 0.3^{d}	4.43 ± 0.8^{a}	6.32 ± 1.4^{b}
Year of sampling									
2010	0.80 ± 0.2^{b}	15.26 ± 1.2^{a}	5.67 ± 1.1^{a}	3.32 ± 0.7^{a}	6.70 ± 0.8^{b}	5.54 ± 0.6^{a}	3.27 ± 0.3^{a}	4.60 ± 0.9^{a}	4.57 ± 2.5^{a}
2011	0.63 ± 0.1^{a}	15.93 ± 1.3^{b}	6.48 ± 1.2^{b}	4.05 ± 0.4^{b}	5.41 ± 1.2^{a}	6.21 ± 0.8^{b}	4.08 ± 0.2^{b}	5.65 ± 0.8^{b}	6.45 ± 2.3^{b}
Site	**	**	**	**	**	**	**	**	**
Depth	**	**	**	**	**	**	**	**	**
Season	**	**	**	**	**	**	**	**	**
Year	**	**	**	**	**	**	**	**	**
Site x Depth	NS	**	**	**	**	**	**	**	**
Site x Season	NS	**	**	**	**	**	**	**	**
Depth x Season	NS	**	**	**	**	**	**	**	**
Site x Depth x Season	NS	**	**	**	**	**	**	**	**
Site x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS
Site x Depth x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS
Season x Year	**	**	**	**	**	**	**	NS	NS
Site x Season x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth x Season x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS
Site x Depth x Season x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS

Values not sharing a common superscript differ significantly at $p > 0.05$; **= $p < 0.01$; *= $p < 0.05$; NS= Not Significant.

(Fig. 2j). Fungal counts ranged between 2.62 and 9.56×10^3 CFU g^{-1} at different seasons. The count was maximum in pre-monsoon and minimum in post monsoon. Fungal counts were higher (5.54×10^3 CFU g^{-1}) in the year 2011 than that in 2010 (Table 1).

Yeast counts were higher in luxuriant site than that in degrading site. It was 4.51×10^3 CFU g^{-1} in luxuriant site and 2.83×10^3 CFU g^{-1} in degrading site (Fig. 2g). Yeast counts varied from 0.63 to 12.64×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 100 cm depth (Fig. 2j). Yeast counts ranged between 1.36 and 5.80×10^3 CFU g^{-1} at different seasons. The count was maximum in monsoon and minimum in premonsoon. Yeast counts were higher (4.08×10^3 CFU g^{-1}) in the year 2011 than that (3.26×10^3 CFU g^{-1}) in 2010 (Table 1).

Thraustochytrids counts were higher in luxuriant site than that in degrading site. It was 6.36×10^3 CFU g^{-1} in luxuriant site and 3.88×10^3 CFU g^{-1} in degrading site (Fig. 2h). Thraustochytrids counts varied from 1.09 to 12.16×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 90 cm depth (Fig. 2j). Thraustochytrids counts ranged between 3.97 and 6.74×10^3 CFU g^{-1} at different seasons. The count was maximum in monsoon and minimum in premonsoon. Thraustochytrids counts were higher in 2011 than that in 2010. It was 5.64×10^3 CFU g^{-1} in year of 2011 and 4.60×10^3 CFU g^{-1} in year of 2010 (Table 1).

Trichoderma counts were higher in luxuriant site than that in degrading site. It was 6.19×10^3 CFU g^{-1} in luxuriant site and 4.81×10^3 CFU g^{-1} in degrading site (Table 1; Fig. 2i). *Trichoderma* counts varied from 1.13 to 19.43×10^3 CFU g^{-1} at different soil depths. The count was maximum in 10 cm depth and minimum in 90 cm depth (Fig. 2j). *Trichoderma* counts ranged between 4.64and 6.38×10^3 CFU g^{-1} at different seasons. The count was maximum in summer and minimum in postmonsoon. *Trichoderma* counts were higher (6.44×10^3 CFU g^{-1}) in the year 2011 than that in 2010 (Table 1).

3.2. Physical characteristics of mangrove sediment

Temperature, pH, redox potential, pore water salinity as influenced by soil depths of two mangrove sites for four different seasons in two years (2010 and 2011) are shown in Table 2. All the parameters were significant between mangrove sites or seasons or depths or years of analysis. However, temperature, pH and phosphorus were not significant between mangrove sites; and redox potential and pore water salinity did not vary between years of analysis (Table 2).

Soil temperature varied from 26.11 to 28.49 °C at different soil depths. It was maximum in 10 cm depth and minimum in 90 cm depth. It ranged between 24.18 and 28.12 °C at different seasons. It

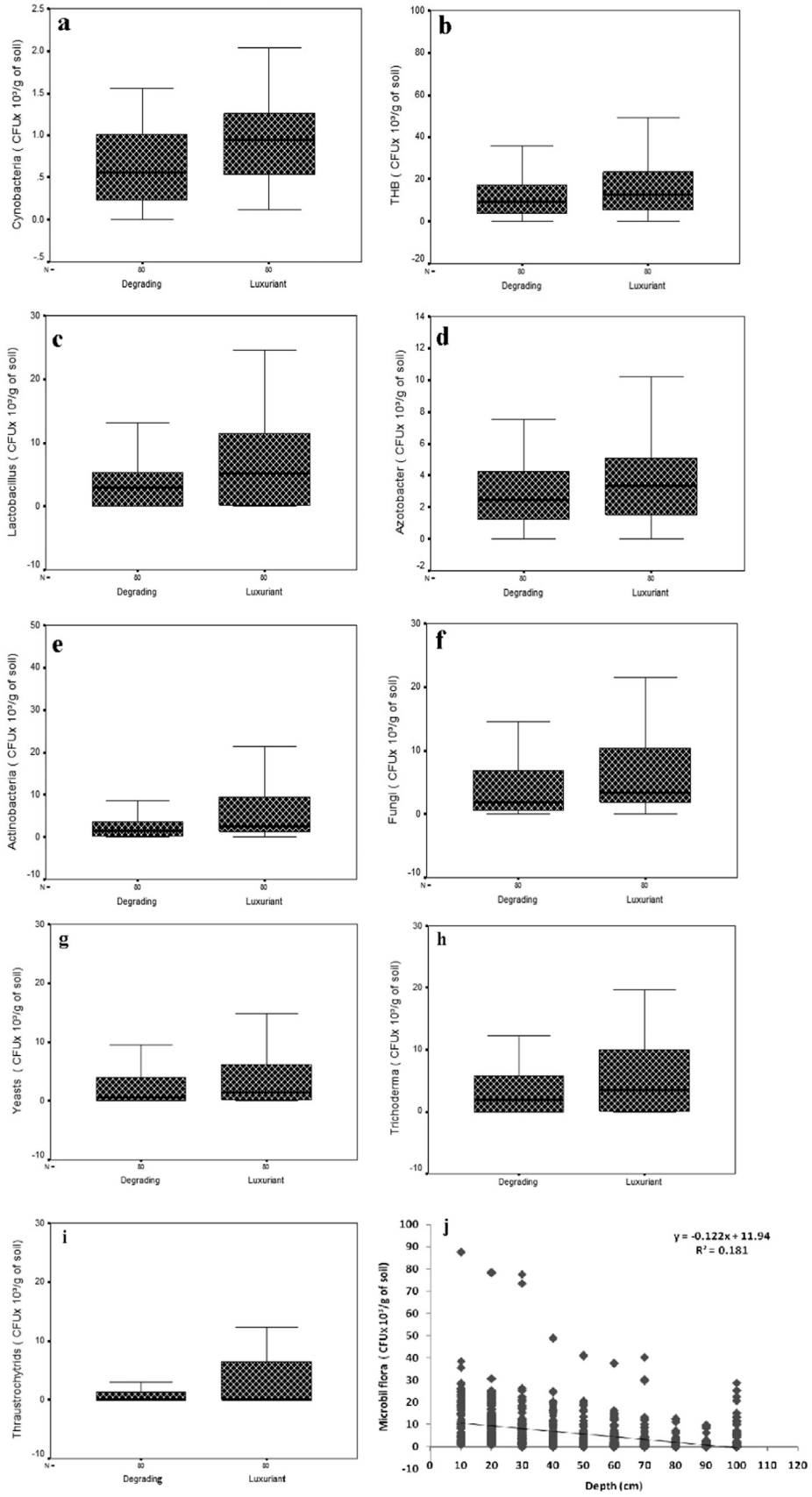

Fig. 2. (a–i) showing microbial counts in degrading or luxuriant mangrove sediments; (j) exhibiting microbial counts as influenced by soil depths.

Table 2
Physical and chemical characteristics of mangrove sediments in two sites at 10 soil depths in four seasons for two years (2010 and 2011).

Source	Temperature (°C)	pH	Redox potential (mV)	Pore water Salinity (ppt)	Silt (%)	Clay (%)	Sand (%)	Nitrogen ($g\ m^{-2}$)	Phosphorus ($g\ m^{-2}$)	Potassium ($g\ m^{-2}$)	TOC ($mgC\ g^{-1}$ soil)
Mangrove site											
Degrading site	26.96 ± 1.1^{a}	7.64 ± 0.4^{bc}	83.25 ± 12.6^{b}	27.52 ± 1.2^{a}	1.62 ± 1.0^{a}	8.77 ± 1.2^{a}	91.34 ± 2.3^{d}	9.73 ± 1.2^{c}	5.03 ± 1.3^{a}	115.64 ± 11.2^{e}	1.90 ± 0.4^{b}
Luxuriant site	27.06 ± 1.5^{a}	7.71 ± 0.5^{bc}	29.81 ± 12.1^{b}	30.49 ± 1.3^{b}	24.76 ± 1.8^{c}	38.99 ± 1.9^{d}	38.71 ± 2.1^{a}	10.17 ± 1.4^{d}	4.97 ± 1.9^{a}	115.02 ± 12.3^{d}	2.89 ± 0.3^{c}
Soil depth (cm)											
10	28.50 ± 1.5^{c}	8.13 ± 0.2^{c}	303.79 ± 27.1^{c}	35.69 ± 1.8^{c}	13.14 ± 2.1^{b}	24.27 ± 2.1^{b}	63.97 ± 2.9^{c}	8.92 ± 1.8^{b}	4.11 ± 1.8^{a}	120.65 ± 11.2^{f}	4.04 ± 0.2^{e}
20	28.24 ± 1.2^{c}	8.01 ± 0.3^{c}	132.82 ± 28.2^{b}	30.22 ± 1.6^{b}	13.60 ± 1.9^{b}	25.07 ± 2.8^{c}	62.91 ± 2.1^{b}	7.72 ± 1.1^{a}	5.57 ± 1.8^{b}	117.57 ± 11.5^{e}	3.92 ± 0.6^{d}
30	27.63 ± 1.1^{bc}	7.67 ± 0.2^{b}	122.22 ± 26.67^{b}	30.94 ± 1.5^{b}	15.05 ± 1.9^{b}	26.09 ± 3.1^{c}	61.88 ± 2.7^{a}	7.68 ± 0.8^{a}	4.45 ± 1.6^{a}	120.56 ± 11.2^{f}	3.36 ± 0.8^{d}
40	27.50 ± 2.3^{bc}	7.68 ± 0.3^{b}	119.28 ± 23.80^{b}	29.86 ± 1.2^{b}	12.98 ± 1.2^{a}	24.34 ± 1.8^{b}	64.23 ± 2.1^{c}	8.25 ± 0.7^{b}	5.41 ± 1.0^{b}	120.67 ± 11.9^{f}	3.06 ± 1.2^{d}
50	27.29 ± 1.2^{bc}	7.52 ± 0.4^{a}	96.25 ± 21.89^{b}	28.89 ± 1.8^{b}	13.66 ± 1.7^{b}	24.59 ± 2.2^{b}	63.55 ± 2.5^{c}	10.94 ± 1.2^{d}	4.86 ± 1.2^{a}	103.57 ± 9.8^{a}	2.51 ± 0.6^{c}
60	27.08 ± 1.5^{bc}	7.55 ± 0.1^{a}	70.55 ± 20.1^{b}	27.57 ± 1.2^{a}	13.00 ± 1.0^{b}	23.62 ± 1.7^{b}	64.84 ± 2.3^{c}	9.88 ± 1.6^{c}	5.72 ± 1.2^{b}	115.52 ± 9.7^{e}	1.96 ± 0.3^{b}
70	26.42 ± 1.4^{a}	7.39 ± 0.2^{a}	-100.26 ± 12.7^{a}	28.94 ± 1.8^{b}	13.09 ± 1.2^{b}	22.46 ± 2.3^{a}	67.08 ± 2.1^{c}	9.36 ± 1.2^{c}	4.82 ± 1.3^{a}	114.14 ± 6.5^{c}	1.71 ± 0.5^{b}
80	25.16 ± 1.9^{a}	7.64 ± 0.2^{b}	-67.03 ± 12.8^{a}	26.29 ± 2.1^{a}	12.49 ± 1.2^{a}	$22.33 \pm 2.^{1a}$	68.54 ± 2.1^{c}	12.50 ± 1.8^{e}	5.22 ± 1.3^{b}	116.33 ± 4.9^{e}	1.60 ± 0.2^{b}
90	26.12 ± 1.8^{ab}	7.61 ± 0.2^{b}	-50.94 ± 22.1^{a}	26.00 ± 1.9^{a}	12.42 ± 1.6^{a}	22.83 ± 1.2^{a}	66.39 ± 2.7^{c}	12.45 ± 1.2^{e}	4.90 ± 1.2^{a}	114.66 ± 7.6^{c}	0.99 ± 0.6^{a}
100	26.16 ± 1.7^{ab}	7.57 ± 0.3^{a}	-61.39 ± 12.9^{a}	25.67 ± 1.8^{a}	12.46 ± 1.2^{a}	23.18 ± 1.3^{b}	66.82 ± 2.1^{c}	11.81 ± 1.7^{e}	4.95 ± 1.4^{a}	109.64 ± 9.7^{b}	0.80 ± 0.2^{a}
Season of analysis											
Post-monsoon	27.74 ± 2.5^{b}	7.82 ± 0.4^{c}	103.28 ± 12.8^{b}	30.13 ± 1.5^{b}	18.40 ± 1.3^{c}	34.57 ± 2.3^{d}	49.54 ± 1.2^{a}	11.44 ± 1.2^{e}	5.09 ± 1.3^{b}	120.03 ± 3.6^{f}	2.47 ± 0.4^{c}
Summer	28.12 ± 1.2^{b}	8.27 ± 0.2^{c}	35.75 ± 8.9^{b}	33.23 ± 1.9^{c}	11.70 ± 1.7^{a}	25.75 ± 1.8^{b}	65.77 ± 1.7^{c}	8.96 ± 1.3^{b}	5.52 ± 0.8^{b}	117.50 ± 4.5^{e}	2.34 ± 0.6^{c}
Pre-monsoon	24.18 ± 1.1^{a}	7.25 ± 0.7^{a}	16.34 ± 12.3^{b}	27.39 ± 2.1^{a}	1.80 ± 1.6^{a}	3.33 ± 1.2^{a}	96.04 ± 2.3^{d}	8.38 ± 1.2^{b}	4.67 ± 0.6^{a}	110.36 ± 5.4^{a}	2.81 ± 0.6^{c}
Monsoon	27.99 ± 2.1^{b}	7.37 ± 0.2^{a}	70.75 ± 11.12^{b}	25.26 ± 1.9^{a}	20.87 ± 1.6^{c}	31.86 ± 1.2^{d}	48.74 ± 1.9^{a}	11.03 ± 1.4^{e}	4.72 ± 0.5^{a}	113.44 ± 8.9^{c}	1.96 ± 0.6
Year of analysis											
2010	26.69 ± 1.7^{a}	7.35 ± 0.3^{a}	55.92 ± 11.1^{b}	28.67 ± 1.8^{b}	12.75 ± 1.8^{a}	23.46 ± 1.7^{b}	64.70 ± 2.3^{c}	9.63 ± 1.9^{c}	4.68 ± 1.8^{a}	115.00 ± 9.9^{d}	2.06 ± 0.5^{c}
2011	27.33 ± 2.5^{b}	8.00 ± 0.5^{c}	57.14 ± 7.8^{b}	29.34 ± 1.9^{b}	13.63 ± 1.7^{b}	24.30 ± 1.9^{b}	65.34 ± 2.7^{c}	10.28 ± 1.8^{d}	5.32 ± 1.2^{b}	115.66 ± 8.0^{d}	2.74 ± 0.3^{c}
Site	NS	NS	**	**	**	**	**	**	NS	**	**
Depth	**	**	**	**	**	**	**	**	**	**	**
Season	**	**	**	**	**	**	**	**	**	**	**
Year	**	**	NS	NS	**	**	**	**	**	**	**
Site x Depth	*	NS	**	*	**	**	**	**	**	**	**
Site x Season	**	**	NS	*	**	**	**	**	NS	**	NS
Depth x Season	**	NS	**	**	**	**	**	**	**	**	NS
Site x Depth x Season	**	NS	NS	**	**	**	**	**	**	**	NS
Site x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Site x Depth x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Seasons x Year	NS	NS	NS	NS	**	**	**	**	**	**	**
Site x Season x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth x Season x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Site x Depth x Season x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Values not sharing a common superscript differ significantly at $p > 0.05$; **$p < 0.01$; *$p < 0.05$; NS=Not Significant.

was maximum in summer and minimum in premonsoon. It was higher (27.33 °C) in the year 2011 than that (26.68 °C) in 2010 (Table 2).

Soil pH varied from 7.38 to 8.13 at different soil depths. It was maximum in 10 cm depth and minimum in 70 cm depth. It was ranged between 7.25 and 8.26 different seasons. It was maximum in summer and minimum in premonsoon. It was higher (8.0) in the year 2011 than that (7.35) in 2010 (Table 2).

Redox potential was higher in degrading site than that in luxuriant site. It was in luxuriant site 29.81 mV in luxuriant site and 83.24 mV in degrading site. It was varied from −50.93 to 303.79 mV at different soil depths. It was maximum in 10 cm depth and minimum in 90 cm depth. It ranged between 16.33 and 103.28 mV different seasons (Table 2).

Pore water salinity was higher in luxuriant site than that degrading site. It was in luxuriant site 30.48 ppt in luxuriant site and 27.52 (ppt) in degrading site. It varied from 25.67 to 35.68 ppt at different soil depths. It was maximum in 10 cm depth and minimum in 100 cm depth. It ranged between 25.26 and 30.13 ppt in four different seasons. It was maximum in postmonsoon and minimum in monsoon (Table 2).

3.3. Mangrove soil composition

Silt, clay and sand as influenced by soil depths of two mangrove sites for four different seasons for two years (2010 and 2011) are shown in Table 2. The soil composition was found significant between site or depths or seasons or years of analysis.

Silt was higher in luxuriant site than that in degrading site. It was 24.76% [in] luxuriant site and 1.62% in degrading site. It varied from 12.41 to 13.66% at different soil depths. It was maximum in 50 cm depth and minimum in 90 cm depth. It ranged between 1.80 and 20.86 at different seasons. It was maximum in monsoon and minimum in premonsoon. It was higher (13.2%) in the year 2011 than that (12.75%) in 2010 (Table 2).

Clay was higher in luxuriant site than that in degrading site. It was 38.98% in luxuriant site and 8.76% in degrading site. It varied from 22.32 to 26.08% at different soil depths. It was maximum in 30 cm depth and minimum in 80 cm depth. It ranged between 3.32% and 34.56% at different seasons. It was maximum in postmonsoon and minimum in premonsoon. It was higher (24.29%) in 2011 than that (23.45%) in 2010 (Table 2).

Sand was higher in luxuriant site than that in degrading site. It was 38.70% in luxuriant site and 91.33% in degrading site. It varied from 61.88 to 68.53% at different soil depths. It was maximum in 80 cm depth and minimum in 30 cm depth. It ranged between 48.73% and 96.01% at different seasons. It was maximum in premonsoon and minimum in monsoon. It was higher (65.33%) in the year 2011 than that (64.70%) in 2010 (Table 2).

3.4. Nitrogen, phosphorus, potassium and total organic carbon in mangrove sediment

Nitrogen, phosphorus, potassium and total organic carbon as influenced by soil depths at two mangrove sites for four different seasons in two years (2010 and 2011) are shown in Table 2. The parameters were found in general significant between site or depths or seasons or years of analysis. However, soil phosphorus did not vary between mangrove sites.

Soil nitrogen was higher in luxuriant site than that in degrading site. It was 10.17 g m^{-2} in luxuriant site 9.73 g m^{-2} in degrading site (Fig. 3b). It varied from 7.68 to 12.49 g m^{-2} at different soil depths. It was maximum in 80 cm depth and minimum in 30 cm depth. It ranged between 8.38 and 11.43 g m^{-2} at different seasons. It was maximum in postmonsoon and minimum in premonsoon. It was higher (10.27 g m^{-2}) in the year 2011 than that (9.62 g m^{-2}) in 2010 (Table 2).

Soil phosphorus varied from 4.10 to 5.71 g m^{-2} at different soil depths. It was maximum in 60 cm depth and minimum in 10 cm depth. It ranged between 4.66 and 5.51 g m^{-2} at different seasons. It was maximum in summer and minimum in premonsoon. It was higher (5.32 g m^{-2}) in the year 2011 than that (4.67 g m^{-2}) in 2010 (Table 2).

Soil potassium was higher in degrading site than that in luxuriant site. It was 115.02 g m^{-2} in luxuriant site and 115.64 g m^{-2} in degrading site. It varied from 103.57 to 120.66 g m^{-2} at different soil depths. It was maximum in 40 cm depth and minimum in 50 cm depth. It ranged between 113.43 and 120.03 g m^{-2} at different seasons. It was maximum in postmonsoon and minimum in monsoon. It was higher (115.66 g m^{-2}) in the year 2011 than that (115.00 g m^{-2}) in 2010 (Table 2).

Total organic carbon was higher in luxuriant site than that in degrading site. It was 2.89 mgC g^{-1} in luxuriant site and 1.89 mgC g^{-1} in degrading site (Fig. 3a). It varied from 0.80 to 4.04 mgC g^{-1}at different soil depths. It was maximum in 10 cm depth and minimum in 100 cm depth. It ranged between 1.95 and 2.81 mgC g^{-1} at different seasons. It was maximum in premonsoon and minimum in monsoon. It was higher (2.73 mgC g^{-1}) in the year 2011 than that (2.05 mgC g^{-1}) in 2010 (Table 2).

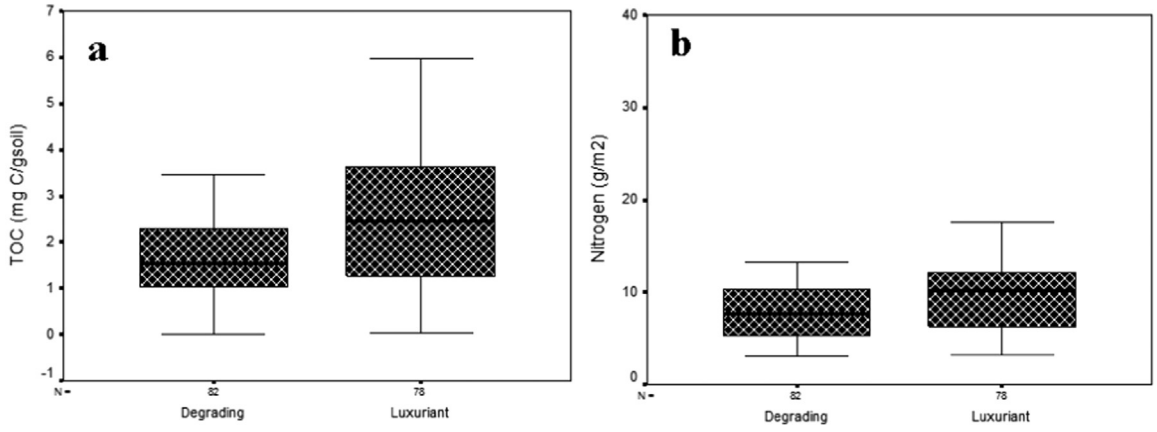

Fig. 3. Levels of total organic carbon (a) TOC; mgC/g^{-1})and (b) Nitrogen (g m^{-2}) in luxuriant and degrading mangroves.

3.5. Micronutrients in mangrove sediments

Aluminum (Al), Boron (B), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Nickel (Ni), lead (Pb) and Zinc (Zn) as influenced by soil depths at two mangrove sites for four different seasons in two years (2010 and 2011) are shown in Table 3. All the micronutrients except Cd, Mn, Ni varied significantly between mangrove sites. Micronutrients such as Al, Cd, Co, Fe, Mg and Pb varied significantly between soil depths, but not others. Micronutrients such as Al, Cr, Cu, Fe, Mg, Mn and Zn varied significantly between seasons, but not others. All micronutrients varied significantly between the years of analysis.

Aluminum were found higher (13.918 mg g^{-1}) in degrading site than that (8.804) in luxuriant site. It varied from 5.35 to 16.13 mg g^{-1} at different soil depths. It was maximum in 10 cm depth and minimum in 60 cm depth. It was ranged between 8.75 and 15.24 mg g^{-1} at different seasons. It was maximum in monsoon and minimum in summer. It was higher (11.68 mg g^{-1}) in the year 2011 than that (11.03 mg g^{-1}) in 2010 (Table 3).

Boron was found significantly higher (0.635) in degraded site than that (0.605) in luxuriant site. It was higher (1.19 mg g^{-1}) in the year 2011 than that (1.04 mg g^{-1}) in 2010 (Table 3). Cadmium varied from 5.35 to 16.13 mg g^{-1} at different soil depths. It was maximum in 10 cm depth and minimum in 60 cm depth at the four seasons of two years. It was higher (11.68 mg g^{-1}) in 2011 than that (11.03 mg g^{-1}) in 2010 (Table 3). Cobalt was higher (0.607) in degrading site than that (0.582) in luxuriant site. It varied from 0.53 to 0.64 mg g^{-1} at different soil depths. It was maximum in 70 cm depth and minimum in 10 cm depth. It was higher (0.008 mg g^{-1}) in 2011 than that (0.007 mg g^{-1}) in 2010 (Table 3).

Chromium was higher (0.633) in degrading site than that (0.599) in luxuriant site. It ranged between 0.59 and 0.64 mg g^{-1} at different seasons. It was maximum in postmonsoon and minimum in premonsoon. It was higher (0.01 mg g^{-1}) in 2010 than that (0.03 mg g^{-1}) in 2011 (Table 3). Copper was higher (0.762) in degrading site than that (0.608) in luxuriant site. It ranged between 0.63 and 0.72 mg g^{-1} at different seasons. It was maximum in summer and minimum in premonsoon. It was higher (0.24 mg g^{-1}) in 2011 than that (0.12) in 2010 (Table 3).

Iron was higher (7.392 in degrading site than that (6.323)) in luxuriant site. It varied from 3.65 to 9.60 mg g^{-1} at different soil depths. It was maximum in 10 cm depth and minimum in 60 cm depth. It ranged between 5.73 and 8.25 mg g^{-1} at different seasons. It was maximum in monsoon and minimum in summer. It was higher (7.19 mg g^{-1}) in 2011 than that (6.52 mg g^{-1}) in 2010 (Table 3). Magnesium was higher (2.817) in degrading site than that (2.501) in luxuriant site. It varied from 1.48 to 3.67 mg g^{-1} at different soil depths. It was maximum in 10 cm depth and minimum in 60 cm depth. It was ranged between 2.12 and 3.14 mg g^{-1} at different seasons. It was maximum in monsoon and minimum in summer. It was higher (3.03 mg g^{-1}) in 2011 than that (2.28 mg g^{-1}) in 2010 (Table 3).

Manganese ranged between 0.62 and 0.68 mg g^{-1} at different seasons. It was maximum in post monsoon and minimum in premonsoon. It was higher (0.22 mg g^{-1}) in 2011 than that (0.08 mg g^{-1}) in 2010 (Table 3). Nickel was higher in 2011 than that in 2010. It was (0.18 mg g^{-1}) in 2011 and (0.02 mg g^{-1}) in 2010 (Table 3). Lead was higher (0.612) in degrading site than that (0.582) in luxuriant site. It varied from 0.60 to 0.64 mg g^{-1} at different soil depths. It was maximum in 70 cm depth and minimum in 40 and 60 cm. It was higher (0.18 mg g^{-1}) in 2011 than that (0.01 mg g^{-1}) in 2010 (Table 3). Zinc was higher (0.636) in degrading site than that (0.597) in luxuriant site. It ranged between 0.58 and 0.64 mg g^{-1} at different seasons. It was maximum in summer and minimum in premonsoon. It was higher (0.19 mg g^{-1}) in 2011 than that (0.03) in 2010 (Table 3).

3.6. Correlation between microbial flora and sediment characteristics

The values of correlation coefficient and their level of significance between any two variables are shown in Table 4. The microbial counts reduced in counts significantly ($p < 0.01$) with increasing depth of soil (Fig. 2j). There was a high negative correlation between soil depths and density of any particular microbial flora.

Microbial density (except actinobacteria) increased in counts significantly ($p < 0.01$) with increasing redox potential value of soil. There was a high positive correlation between redox potential and density of microbes (Table 4). A narrow increase in soil temperature increased significantly ($p < 0.01$) the density of cyanobacteria, THB, lactobacilli, yeasts, thraustochytrids, *Trichoderma* and these groups of microbes seemed to be tolerant to temperature variation. However, actinobacteria appeared to be sensitive to temperature as evident by a negative correlation between actinobacterial density and soil temperature (Table 4).

A narrow increase in soil pH significantly ($p < 0.01$) increased the density of cyanobacteria, THB, lactobacilli, azotobacter, yeasts, thraustochytrids, T*richoderma* and these groups of microbial flora seemed to be tolerant to pH variation (Table 4). A narrow increase in pore water salinity increased significantly ($p < 0.01$) the density of all microbes studied. This revealed that the microbial flora were salinity tolerant (Table 4).

Silt increased the density of cyanobacteria, THB, yeast, thraustochytrids, but reduced the density of azotobacters and actinobacteria. Clay increased the density of cyanobacteria, THB, lactobacilli, yeasts, thraustochytrids and *Trichoderma*, but reduced the density of azotobacters and actinobacteria, similar to clay. Sand reduced the density of cyanobacteria, THB, lactobacillus, yeasts, thraustochytrids, *Trichoderma* and increased azotobacters and actinobacteria contrary to clay or silt (Table 4).

Soil nitrogen reduced the counts of azotobacters, fungi, yeasts, thraustochytrids and *Trichoderma*. Soil phosphorus increased the density of cyanobacteria but reduced aztobacters, fungi and *Trichoderma*. Potassium increased the density of THB, lactobacillus, yeasts, thraustochytrids and *Trichoderma* (Table 4). Total organic carbon increased significantly ($p < 0.01$) the density of all microbial flora studied. This revealed that the microbial flora was stimulated by the TOC (Table 4).

Density of cyanobacterial density increased with increasing concentrations of micronutrients such as boron, cadmium, cobalt, chromium, copper, manganese, nickel, lead and zinc. Other trace metals also increased the microbial flora, as evident by correlation coefficients. For instance, iron increased cyanobacteria, THB, azotobacters, actinobacteria, fungi, yeasts, traustochytrids, *Trichoderma*. Magnesium increased the counts of cyanobacteria, THB, lactobacilli, azotobacters, actinobacteria, fungi, yeasts, thraustochytrids and *Trichoderma*. Aluminum increased counts of thraustochytrids, *Trichoderma* and yeasts (Table 4).

3.7. Discussion

Mangroves provide a unique ecological environment for diverse microbial communities, which are fundamental to the functioning of the habitats. In the mangrove system, activities of microbes are predominant in decomposing organic matter, making protein rich detritus food for fishes, recycling of nutrients, carbon fluxes as well as climate change. A variety of abiotic and biotic factors influenced the density of microorganisms. All these factors change with time and spatial heterogeneity. The microbes are

Table 3
Levels of micronutrients in mangrove sediments of two sites at 10 soil depths under four seasons for two years (2010 and 2011).

Source	Micro nutrients (mg g^{-1})											
	Al	**B**	**Cd**	**Co**	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Ni**	**Pb**	**Zn**
Degrading site	13.92 ± 1.2^{d}	0.64 ± 0.2^{b}	0.60 ± 0.1^{a}	0.61 ± 0.2^{b}	0.63 ± 0.1^{b}	0.76 ± 0.2^{b}	7.39 ± 0.1^{c}	2.82 ± 1.4^{c}	0.67 ± 0.2^{a}	0.62 ± 0.3^{a}	0.61 ± 0.1^{b}	0.64 ± 0.02^{b}
Luxuriant site	8.80 ± 1.5^{c}	0.61 ± 0.2^{a}	0.58 ± 0.2^{a}	0.58 ± 0.1^{a}	0.60 ± 0.2^{a}	0.61 ± 0.1^{a}	6.33 ± 0.2^{b}	2.50 ± 1.1^{b}	0.64 ± 0.2^{a}	0.60 ± 0.2^{a}	0.58 ± 0.2^{a}	0.60 ± 0.01^{a}
Soil depth (cm)												
10	16.14 ± 1.3^{e}	0.59 ± 0.1^{a}	0.53 ± 0.2^{a}	0.53 ± 0.1^{a}	0.55 ± 0.1^{b}	0.64 ± 0.1^{a}	9.61 ± 0.3^{d}	3.67 ± 2.3^{c}	0.62 ± 0.2^{a}	0.55 ± 0.3^{a}	0.54 ± 0.1^{a}	0.58 ± 0.2^{a}
20	12.02 ± 1.4^{d}	0.59 ± 0.2^{a}	0.56 ± 0.3^{a}	0.57 ± 0.1^{a}	0.60 ± 0.2^{b}	0.66 ± 0.2^{a}	8.17 ± 0.1^{d}	3.10 ± 1.9^{c}	0.63 ± 0.3^{a}	0.62 ± 0.2^{a}	0.57 ± 0.2^{a}	0.59 ± 0.1^{a}
30	13.08 ± 1.5^{d}	0.62 ± 0.2^{a}	0.60 ± 0.1^{b}	0.60 ± 0.2^{b}	0.62 ± 0.2^{b}	0.68 ± 0.1^{a}	6.33 ± 1.2^{b}	3.00 ± 1.3^{c}	0.64 ± 0.1^{a}	0.62 ± 0.2^{a}	0.61 ± 0.2^{b}	0.62 ± 0.2^{a}
40	12.62 ± 1.8^{d}	0.64 ± 0.2^{a}	0.61 ± 0.1^{b}	0.62 ± 0.2^{b}	0.62 ± 0.1^{b}	0.68 ± 0.1^{a}	7.87 ± 1.1^{c}	2.98 ± 1.1^{b}	0.69 ± 0.3^{a}	0.61 ± 0.2^{a}	0.61 ± 0.2^{b}	0.62 ± 0.1^{a}
50	7.72 ± 1.5^{b}	0.59 ± 0.3^{a}	0.56 ± 0.1^{a}	0.57 ± 0.1^{a}	0.60 ± 0.2^{b}	0.67 ± 0.2^{a}	5.22 ± 1.3^{a}	1.82 ± 0.8^{a}	0.66 ± 0.2^{a}	0.57 ± 0.1^{a}	0.57 ± 0.1^{a}	0.58 ± 0.2^{a}
60	5.36 ± 1.2^{a}	0.62 ± 0.2^{a}	0.60 ± 0.2^{b}	0.60 ± 0.2^{b}	0.62 ± 0.1^{b}	0.71 ± 0.1^{a}	3.66 ± 2.1^{a}	1.49 ± 0.3^{a}	0.63 ± 0.2^{a}	0.61 ± 0.1^{a}	0.61 ± 0.2^{b}	0.62 ± 0.1^{a}
70	8.95 ± 1.2^{c}	0.66 ± 0.3^{a}	0.64 ± 0.2^{b}	0.64 ± 0.2^{b}	0.66 ± 0.2^{b}	0.69 ± 0.1^{a}	6.18 ± 1.2^{b}	2.22 ± 0.2^{b}	0.68 ± 0.3^{a}	0.66 ± 0.2^{a}	0.64 ± 0.2^{b}	0.67 ± 0.2^{a}
80	11.54 ± 1.4^{d}	0.63 ± 0.2^{a}	0.60 ± 0.2^{b}	0.60 ± 0.2^{b}	0.63 ± 0.1^{b}	0.72 ± 0.2^{a}	7.99 ± 2.1^{c}	2.90 ± 0.5^{b}	0.67 ± 0.2^{a}	0.61 ± 0.2^{a}	0.61 ± 0.1^{b}	0.63 ± 0.2^{a}
90	12.25 ± 1.4^{d}	0.62 ± 0.1^{a}	0.60 ± 0.2^{b}	0.61 ± 0.2^{b}	0.63 ± 0.1^{b}	0.68 ± 0.2^{a}	5.68 ± 2.1^{a}	2.51 ± 0.3^{b}	0.64 ± 0.2^{a}	0.62 ± 0.1^{a}	0.61 ± 0.1^{b}	0.62 ± 0.2^{a}
100	13.93 ± 1.3^{d}	0.64 ± 0.2^{a}	0.60 ± 0.2^{b}	0.60 ± 0.2^{b}	0.63 ± 0.2^{b}	0.73 ± 0.2^{a}	7.92 ± 2.1^{c}	2.90 ± 0.2^{b}	0.69 ± 0.1^{a}	0.63 ± 0.2^{a}	0.62 ± 0.2^{b}	0.65 ± 0.3^{a}
Season of analysis												
Post-monsoon	11.51 ± 1.2	0.64 ± 0.3^{b}	0.60 ± 0.2^{b}	0.61 ± 0.2^{a}	0.64 ± 0.2^{b}	0.72 ± 0.1^{b}	7.13 ± 1.2^{c}	2.93 ± 0.3^{b}	0.68 ± 0.3^{b}	0.63 ± 0.1^{a}	0.61 ± 0.2^{a}	0.63 ± 0.2^{c}
Summer	8.75 ± 1.6^{c}	0.64 ± 0.2^{b}	0.60 ± 0.2^{b}	0.60 ± 0.2^{a}	0.62 ± 0.2^{b}	0.73 ± 0.1^{b}	5.73 ± 1.2^{a}	2.12 ± 0.2^{b}	0.68 ± 0.2^{b}	0.61 ± 0.2^{a}	0.61 ± 0.2^{a}	0.64 ± 0.1^{c}
Pre-monsoon	9.94 ± 1.2^{c}	0.59 ± 0.2^{a}	0.57 ± 0.2^{b}	0.57 ± 0.1^{a}	0.59 ± 0.2^{a}	0.63 ± 0.2^{a}	6.33 ± 1.3^{b}	2.44 ± 0.4^{b}	0.63 ± 0.3^{a}	0.58 ± 0.1^{a}	0.58 ± 0.1^{a}	0.59 ± 0.2^{a}
Monsoon	15.24 ± 1.4^{e}	0.61 ± 0.1^{b}	0.59 ± 0.1^{b}	0.59 ± 0.1^{a}	0.61 ± 0.1^{b}	0.66 ± 0.2^{a}	8.26 ± 2.1^{d}	3.15 ± 0.1^{c}	0.64 ± 0.3^{a}	0.61 ± 0.2^{a}	0.60 ± 0.2^{a}	0.61 ± 0.2^{b}
Year of analysis												
2010	11.03 ± 1.2^{d}	1.04 ± 0.3^{c}	0.01 ± 0.001^{a}	0.01 ± 0.001^{a}	0.04 ± 0.001^{b}	0.12 ± 0.01^{a}	6.53 ± 1.2^{b}	2.28 ± 0.2^{b}	0.09 ± 0.2^{a}	0.03 ± 0.01^{a}	0.01 ± 0.01^{a}	0.04 ± 0.1^{a}
2011	11.69 ± 1.3^{d}	1.20 ± 0.2^{c}	0.18 ± 0.01^{b}	0.01 ± 0.001^{a}	0.02 ± 0.001^{a}	0.25 ± 0.01^{b}	7.20 ± 1.1^{c}	3.04 ± 0.1^{c}	0.22 ± 0.5^{b}	0.19 ± 0.02^{b}	0.18 ± 0.01^{b}	0.20 ± 0.2^{b}
Site	**	*	NS	*	**	**	**	**	NS	NS	*	*
Depth	**	NS	**	*	NS	NS	**	**	NS	NS	*	NS
Season	**	NS	NS	NS	*	**	**	**	*	NS	NS	*
Year	**	*	**	**	**	**	**	**	**	*	**	**
Site x Depth	**	*	*	*	*	NS	**	**	NS	NS	*	*
Site x Season	**	NS	NS	NS	NS	NS	**	**	NS	NS	NS	NS
Depth x Seasons	**	*	**	**	**	**	**	**	**	*	*	**
Site x Depth x Season	**	**	**	**	**	NS	**	**	*	*	**	**
Site x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth x Year	NS	*	*	*	*	NS	NS	NS	NS	NS	*	*
Site x Depth x Year	NS	NS	*	*	NS	NS	NS	NS	NS	**	*	NS
Seasons x Year	**	*	NS	NS	*	**	**	**	*	**	NS	*
Site x Season x Year	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth x Season x Years	NS	**	**	**	**	NS	NS	NS	*	*	*	*
Site x Depth x Season x Year	NS	*	**	**	**	NS	NS	NS	*	*	*	**

Values not sharing a common superscript are differ significantly at $p > 0.05$; **= $p < 0.01$; *= $p < 0.05$; NS= Not Significant.

Table 4
Correlation coefficient values between microbial counts and physicochemical variables.

	Microbial counts (CFUx 10^3 g^{-1} of soil)								
Sources	Cynobacteria	THB	Lactobacilli	Azotobacters	Actinobacteria	Fungi	Yeasts	Thraustrochytrids	Trichoderma
Depth	−.406(**)	−.526(**)	−.703(**)	−.712(**)	−.457(**)	−.714(**)	−.673(**)	−.739(**)	−.676(**)
Temperature (°C)	0.316(**)	0.275(**)	0.282(**)	−0.032	−.175(**)	0.032	0.393(**)	0.283(**)	0.248(**)
pH	0.698(**)	0.281(**)	0.366(**)	0.235(**)	−0.01	0.078	0.269(**)	0.171(**)	0.209(**)
Redox potential (mV)	0.215(**)	0.365(**)	0.435(**)	0.280(**)	0.046	0.306(**)	0.447(**)	0.416(**)	0.402(**)
Pore water Salinity (ppt)	0.327(**)	0.468(**)	0.471(**)	0.363(**)	0.167(**)	0.251(**)	0.347(**)	0.361(**)	0.379(**)
Silt (%)	0.185(**)	0.340(**)	0.095	−.152(**)	−.143(*)	0.008	0.291(**)	0.273(**)	0.089
Clay (%)	0.199(**)	0.406(**)	0.149(**)	−.184(**)	−.204(**)	−0.028	0.298(**)	0.265(**)	0.120(*)
Sand (%)	−.158(**)	−.381(**)	−.122(*)	0.180(**)	0.178(**)	0.01	−.301(**)	−.271(**)	−.115(*)
Nitrogen (g m^{-2})	0.012	−0.015	−0.078	−.190(**)	−0.092	−.204(**)	−.196(**)	−.141(*)	−.141(*)
Phosphorus (g m^{-2})	0.391(**)	0.023	0.047	0.004	−0.089	−.150(**)	−0.109	−0.098	−.127(*)
Potassium (g/m^{-2})	0.109	0.209(**)	0.171(**)	0.054	0.032	0.063	0.161(**)	0.159(**)	0.117(*)
TOC (mgC g^{-1} soil)	0.732(**)	0.571(**)	0.704(**)	0.799(**)	0.586(**)	0.696(**)	0.573(**)	0.676(**)	0.528(**)
Al (mg g^{-1})	0.091	0.039	0.041	0.038	0.026	0.09	0.115(*)	0.150(**)	0.150(**)
B (mg g^{-1})	0.580(**)	0.022	0.06	0.097	0.015	0.004	0.082	0.066	0.102
Cd (mg g^{-1})	0.546(**)	0.01	0.047	0.083	0.01	−0.004	0.07	0.054	0.091
Co (mg g^{-1})	0.547(**)	0.013	0.051	0.08	0.008	−0.008	0.07	0.053	0.09
Cr (mg g^{-1})	0.563(**)	0.021	0.056	0.08	0.007	−0.012	0.072	0.055	0.09
Cu (mg g^{-1})	0.581(**)	0.007	0.062	0.078	−0.015	−0.035	0.053	0.033	0.087
Fe (mg g^{-1})	0.206(**)	0.164(**)	0.106	0.149(**)	0.129(*)	0.189(**)	0.174(**)	0.202(**)	0.199(**)
Mg (mg g^{-1})	0.430(**)	0.189(**)	0.163(**)	0.214(**)	0.154(**)	0.209(**)	0.203(**)	0.248(**)	0.215(**)
Mn (mg g^{-1})	0.596(**)	0.041	0.071	0.1	0.018	0.005	0.083	0.06	0.092
Ni (mg g^{-1})	0.562(**)	0.027	0.055	0.087	0.01	0.005	0.084	0.072	0.099
Pb (mg g^{-1})	0.548(**)	0.01	0.048	0.081	0.008	−0.008	0.069	0.052	0.089
Zn (mg g^{-1})	0.559(**)	0.012	0.052	0.082	0.001	−0.007	0.071	0.054	0.097
Cyanobacteria	1	0.404(**)	0.492(**)	0.492(**)	0.297(**)	0.355(**)	0.405(**)	0.403(**)	0.319(**)
THB	0.404(**)	1	0.835(**)	0.342(**)	0.302(**)	0.154(**)	0.468(**)	0.442(**)	0.362(**)
Lactobacilli	0.492(**)	0.835(**)	1	0.555(**)	0.426(**)	0.347(**)	0.484(**)	0.509(**)	0.485(**)
Azotobacters	0.492(**)	0.342(**)	0.555(**)	1	0.799(**)	0.804(**)	0.322(**)	0.497(**)	0.478(**)
Actinobacteria	0.297(**)	0.302(**)	0.426(**)	0.799(**)	1	0.575(**)	0.072	0.253(**)	0.257(**)
Fungi	0.355(**)	0.154(**)	0.347(**)	0.804(**)	0.575(**)	1	0.591(**)	0.690(**)	0.610(**)
Yeasts	0.405(**)	0.468(**)	0.484(**)	0.322(**)	0.072	0.591(**)	1	0.792(**)	0.677(**)
Thraustochytrids	0.403(**)	0.442(**)	0.509(**)	0.497(**)	0.253(**)	0.690(**)	0.792(**)	1	0.691(**)
Trichoderma	0.319(**)	0.362(**)	0.485(**)	0.478(**)	0.257(**)	0.610(**)	0.677(**)	0.691(**)	1

Significant at $p > 0.05$; **= $p < 0.01$; *= $p < 0.05$; NS= Not Significant.

adapted to varied physical and chemical conditions of mangrove systems (Kathiresan, 2000; Holguin et al., 2001a, 2001b; Kathiresan and Bingham, 2001; Kathiresan and Qasim, 2005; Rajendran and Kathiresan, 2007; Sahoo and Dhal, 2009; Kathiresan, 2011). Microbial density in relation to soil depth and type of mangrove forests are largely unknown for mangrove sediment, although it is known for seasonal changes. Bearing this in mind the present study was undertaken to analyze the microbial density in relation to the soil physical and chemical characteristics in a mangrove forest, located in southeast coast of India.

Mangrove is a detritus-based ecosystem and hence is colonized with a rich population of saprophytic microorganisms, distributed all through the seasons in order to decompose the organic matter, available in the biotope. For instance, the highest counts of azotobacters or fungi were recorded in premonsoon, yeasts or thraustochytrids in monsoon, *Trichoderma* in summer, and THB or lactobacilli in postmonsoon. The counts of nitrogen fixing autotrophic cyanobacteria were recorded maximum in postmonsoon and the nitrogen fixing azotobacters in monsoon (Table 1). In general wet seasons appeared to be favourable for microbial colonization. This is accordance with the fact that the degree of wetness is an important factor regulating microbial cycling of organic matter in the mangrove soil (Alongi et al., 1993, 2005a, 2005b).

Saprophytic fungi and bacteria contribute to decomposition of the mangrove material and to the transformation of cycling of nutrients. Fungi are the primary litter invaders in the mangrove sediment, reaching their peak in the early phases of decomposition. Bacterial colonies appear shortly after the litter has been colonized by fungi. The bacteria grow quickly and can reach very high densities (Rajendran and Kathiresan, 2007). Zhuang and Lin (1993) have measured bacterial densities from 2×10^5 to 10×10^5 g^{-1} on *Kandelia candel* leaves that decomposed for 2–4 weeks in the sediment. This is about 100 times higher than densities of filamentous fungi. This finds support of our data that the density of total heterotrophic bacteria was higher than that of fungi in mangrove sediment (Table 1). In spite of variations in densities of microorganisms, they are living together in association within the mangrove biotope. Individual group of microorganisms increased the counts of other microbial floras. For instance, total heterotrophic bacteria (THB) or lactobacilli or cyanobacteria or azotobacters or fungi or actinobacteria increased the density of all other microbial flora studied (Table 4). This was also evident that the dense mangrove sediment exhibited significantly higher microbial counts than the sparse mangrove sediment did (Table 1). Based on the counts of microbes in dense mangrove over sparse mangrove sediments, it was inferred that the dense mangroves influenced the microorganisms in a decreasing order: Actinobacteria > THB > Thraustochytrids > Yeasts > Fungi > Lactobacilli > *Trichoderma* > Azotobacters > Cyanobacteria respectively with 69.5%, 66.1%, 63.5%, 58.9%, 56.6%, 38.9%, 28.4%, 21.4% and 19.4% higher counts over sparse mangrove sediment. This can be attributed to litter decomposition process which releases the nutrients which in turn help in multiplication of both autotrophic and heterotrophic microorganisms in the mangrove sediment (Rajendran and Kathiresan, 2004, 2007).

Actinobacteria are Gram positive bacteria and produce cotton-like structures and they are best known for their ability to produce antibiotics, vitamins, enzymes, pigments, nutrients and also in decomposition of mangrove litter (Zhuang and Lin, 1993).

Mangrove habitat, by virtue of its fluctuating physical and chemical conditions are a potential source for isolating the actinobacteria (Kala and Chandrika, 1993; Kathiresan et al., 2005; Kathiresan and Manivannan, 2007; Balagurunathan et al., 2010).

Thraustochytrids are perhaps the only group of eukaryotes of an obligate marine occurrence. Starting from 1950s, substantial evidences for the presence of thraustochytrids in marine sediments have been known (Raghukumar, 2002). They can be isolated from various substrates and appear to be abundant in the sediments of coastal and estuarine environments (Ulken, 1981; Bongiorni, 1999; Raghukumar and Schaumann, 1993). Such widespread occurrence, together with their density and ability to feed on diverse complex organic substrata, suggests that thrautochytrids play an important ecological role within the microbial loop and in the carbon cycle of marine ecosystems.

Yeasts are ubiquitous saprophytic microorganisms and they also form part of the microbiota of mangrove ecosystems. The counts ranged from 0.63 to 12.64×10^3 CFU g^{-1} in the present study. Our laboratory has earlier enumerated their counts in a range from 1×10^2 to 1.4×10^4 CFU g^{-1} of rhizosphere soil of Pichavaram in the same study area (Manivannan and Kathiresan, 2009). This reduction in yeast density might be due to sampling at different soil depths in the present study. Maximum counts of yeasts were recorded during monsoon in the present study (Table 1), similarly to the previous study (Manivannan and Kathiresan, 2009).

Marine cyanobacteria are an important component of microbiota in the mangrove ecosystem. The dense mangrove site was found colonized with higher counts of cyanobacteria than the sparse mangrove site in Pichavaram (Table 1). Besides density, our previous study recorded that the diversity also varies with mangrove forests. The luxuriant mangrove forest in Pichavaram are represented with 63 species of cyanobacteria; whereas the degrading mangroves in Ariyankuppam is colonized with 40 species of cyanobacteria (Palaniselvam and Kathiresan, 1998). The present study recorded the cyanobacteria in a range of $0.630 \times 10^3 - 1.725 \times 10^3$ CFU g^{-1} (Table 1). Our laboratory has earlier enumerated their counts in a range between 3.1×10^3 and 4.1×10^4 CFU g^{-1} of rhizosphere soil in the same study area (Nabeel et al., 2009). The reduction in cyanobacterial density might be due to sampling at different soil depths in the present study. Cyanobacterial density was maximum in post-monsoon and minimum in monsoon, in contrast to the previous report that summer has recorded the maximum and postmonsoon does the minimum count of cyanobacteria (Nabeel et al., 2009).

Lactobacilli are beneficial bacteria that occur abundant in the root-soil of mangroves (Kathiresan and Thiruneelakandan, 2008). The present study recorded the lactobacilli in a range of $0.838 \times 10^3 - 13.111 \times 10^3$ (Table 1). Our laboratory has earlier enumerated their counts in a range between 3×10^2 and 3.1×10^4 colony forming units per gram of rhizosphere soil of Pichavaram in the same study area. The reduction in cyanobacterial density might be due to sampling at different soil depths in the present study Similar to the present study, lactobacilli density has been reported to be the maximum in post monsoon (November).

The microbial counts reduced in counts significantly ($p < 0.01$) with increased depth of soil, as was also evident by a high negative correlation between soil depths and density of any particular microbial flora (Tables 1 and 4). This reduction of the microbial density in the deep soil is due to oxygen deficiency for proliferation of the aerobic microbes, as evident by a high positive correlation between redox potential (availability of oxygen) and density of microbial flora (Table 4). The mangrove substrate is unique to be rich in anaerobic domain which may be colonized by anaerobic bacteria such as sulphur reducers, methanogens, iron reducers, manganese reducers etc. (Alongi et al., 2000) and these anaerobes are likely to contribute greatly to the productivity of anaerobic domain of mangrove ecosystem, which deserve a special study.

Physical factors of mangrove sediment exhibited profound effects on microorganisms. In general, the microbial density increased with soil temperature, pH, salinity, silt and clay compositions, as evident by significant correlation between them (Table 4). This revealed the tolerance of soil microbes to temperature, pH and salinity and hence, the microbial density may not be affected with the sea level rise and global warming issues in the mangrove sediment. However, actinobacteria appeared to be sensitive to temperature as evident by a negative correlation between them (Table 4). All the microbial density increased with increasing levels of silt and clay and decreased with increasing level of sand, but the density of azotobacters and actinobacteria exhibited a reverse trend. It is not clear why the sand increased their density, in contrast to clay or silt (Table 4).

Chemical factors of mangrove sediment also exhibited profound effects on microorganisms. Mangrove habitats are naturally nitrogen-deficient as the salinity reduces the availability of nitrogen (Kathiresan, 2000) and hence the system is dependent on the nitrogen fixing microorganisms such as cyanobacteria and azotobacters (Alongi et al., 1993; Vazquez et al., 2000; Bashan and Holguin, 2002). In the present study, soil nitrogen reduced the counts of azotobacters, fungi, yeasts, thraustochytrids and *Trichoderma*. Soil phosphorus increased the density of cyanobacteria but reduced aztobacters, fungi and *Trichoderma*. Soil potassium increased the density of THB, lactobacillus, yeasts, thraustochytrids and *Trichoderma* (Table 4).

Soil micronutrients also increased the microbial flora, as evident by correlation coefficients. For instance, iron increased cyanobacteria, THB, azotobacters, actinobacteria, fungi, yeasts, traustochytrids, *Trichoderma*. Magnesium increased the counts of cyanobacteria, THB, lactobacilli, azotobacters, actinobacteria, fungi, yeasts, thraustochytrids and T*richoderma*. Aluminum increased counts of thraustochytrids, T*richoderma* and yeasts (Table 4). The sparse mangrove sediment had significantly higher levels of Al, B, Co, Cr, Cu, Mg, Fe, Pb and Zn than the dense mangrove did (Table 3). This may be attributed to the higher microbial count in the luxuriant site which perhaps accumulate and process the metals. In general, monsoon and post monsoon recorded the maximum levels of micronutrients in the sediment, while summer did the maximum levels of Zn and Cu (Table 3).

Sub-surface bacterial communities may sequester nutrients and bind them within nutrient-limited mangrove mud (Kathiresan and Bingham, 2001). Thus the microbes are important in controlling the chemical environment of the mangrove system (Holguin et al., 2001a, 2001b; Iwamoto et al., 2000; Jiang et al., 2007; Zhang et al., 2008). However, physical factors appeared to have strong influence on the microbial density rather than chemical factors as evident by correlation analysis among the factors (Table 4). Among the physical factors, the dense mangrove sediment exhibited 15.3 fold higher silt, 4.4 fold more clay, 2.9 fold increasing redox potential, 42.3% lower sand and 10.8% higher pore water salinity than the sparse mangrove sediment did. Among the chemical factors, TOC was 52% higher in dense mangrove sediment than that in sparse mangrove sediment and soil nitrogen was4.5% higher in the former than in the latter.

Total organic carbon increased significantly ($p < 0.01$) the density of all microbes studied, as most of them were heterotrophically dependent upon the external source of carbon (Table 4). The mangroves are able to store large amounts of organic carbon several meters in depth (Alongi, 1998; Matsui, 1998; Lallier-Verges et al., 1998; Fujimoto et al., 1999; Chmura et al., 2003). Organic carbon in sediment is a crucial indicator for productivity of the coastal area (Hasrizal et al., 2009). The mangroves are significantly rich in total organic carbon due to the supply of organic

matter derived from mangrove litter fall and associated microorganisms (Alongi, 1998; Volkman et al., 2000; Bouillon et al., 2004; Kristensen et al., 1998). The mangrove sediment is rich in the microbial counts due to the availabilities of the higher quantities of organic matters (Rajendran and Kathiresan, 2004, 2007; Kathiresan and Masilamani, 2005; Nabeel et al., 2010). Thus the microorganisms appeared to play vital role as a net carbon sink in the mangrove sediments. Maintenance of a high microbial density through conservation of dense mangrove forests is essential to store carbon in the tropical mangrove habitats, in the present context of increasing level of carbon dioxide in the atmosphere.

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References

Alongi, D.M., 1998. Coastal Ecosystems Processes. CRC Press, Boca Raton, Florida, USA.
Alongi, D.M., Christoffersen, P., Tirendi, F., 1993. The influence of forest type on microbial-nutrient relationships in tropical mangrove sediments. J. Exp. Mar. Biol. Ecol. 171, 201–223.
Alongi, D.M., Clough, B.F., Robertson, A.I., 2005a. Nutrient-use efficiency in arid-zone forests of the mangroves *Rhizophora stylosa* and *Avicennia marina*. Aquat. Bot. 82, 121–131.
Alongi, D.M., Trott, L.A., Wattayakorn, G., Clough, B.F., 2000. Below-ground nitrogen cycling in relation to net canopy production in mangrove forests of southern Thailand. Mar. Biol. 140, 855–864.
Alongi, D.M., Ramanathan, A.L., Kannan, L., Tirendi, F., Trott, L.A., Bala Krishna Prasad, M., 2005b. Influence of human-induced disturbance on benthic microbial metabolism in the Pichavaram mangroves, Vellar-Coleroon estuarine complex, India. Mar. Biol. 147, 1033–1044.
Balagurunathan, R., Radhakrishnan, M., Somasundaram, S., 2010. L-glutaminase producing Actinomycetes from marine sediments-selective isolation, semi quantitative assay and characterization of potential strain. Aust. J. Basic Appl. Sci. 4, 698–705.
Bashan, Y., Holguin, G., 2002. Plant growth-promoting bacteria: a potential tool for arid mangrove reforestation. Trees 16, 159–166.
Bongiorni, L., 1999. Ecology of Thraustochytrids (Fungi-like Marine Protists) from Mediterranean Coasts and Their Secondary Metabolites Production (Dissertation). University of Pisa.
Bouillon, J., Medel, M.D., Pages, F., Gili, J.M., Boero, F., Gravili, C., 2004. Fauna of the Mediterranean Hydrozoa. Sci. Mar. 68 (2), 5–438.
Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analysis of soils. Agron. J. 54, 464–465.
Buchanan, R.E., Gibbons, N.E., 1974. Bergey's Manual of Determinative Bacteriology, 8th ed. Williams & Wilkins Co., Baltimore, Pp xxvi-1246.
Chester, R., Hughes, M.J., 1967. A chemical technique for the separation of ferromanganese minerals, carbonate minerals and adsorbed trace elements for pelagic sediments. Chem. Geol. 2, 249–262.
Chmura, G.L., Anisfeld, S.C., Cahoon, D.R., Lynch, J.C., 2003. Global carbon sequestration in tidal, saline wetland soils. Global Biogeochem. Cycles, 17. http://dx.doi.org/10.1029/2002GB001917.
Das, S., De, M., Ganguly, D., Maiti, T.K., Mukherjee, A., Jana, T.K., De, T.K., 2012. Depth integrated microbial community and physico-chemical properties in mangrove soil of Sundarban. India Adv. Microbiol. 2, 234–240.
Deman, J.C., Rogosa, M., Sharpe, M.E., 1990. A medium for the cultivation of lactobacilli. J. Appl. Bacteriol. 23, 130.
Dinesh, R., Chaudhuri, S.G., 2013. Soil biochemical/microbial indices as ecological indicators of land use change in mangrove forests. Ecol. Indic. 32, 253–258.
FAO., 2007. Aquaculture Development FAO Technical Guidelines For Responsible Fisheries Health Management For Responsible Movement Of Live Aquatic Animals Food And Agriculture Organization Of The United Nations. 5(2), pp. 1–37.
Fell, J.W., 2005. The role of nucleotide analysis in the systematics of the yeast genera Cryptococcus sp. and Rhodotorula sp. Stud. Mycol. 38, 129–146.
Fujimoto, K., Imaya, A., Tabuchi, R., Kuramoto, S., Utsugi, H., Murofushi, T., 1999. Below ground carbon storage of Micronesian mangrove forests. Ecol. Res. 14, 409–413.
Gilman, E., Ellison, J., Duke, N.C., Field, C., 2008. Threats to mangroves from climate change and adaptation options: a review. Aquat. Bot. 89 (2), 237–250.
Guzman, G.N., Jimenez, C.E., 1992. Contamination of coral reef by heavy metals along the Carrribean coast of Central America (Coasta Rica and Panama). Mar. Poll. Bull. 24 (11), 554–561.
Hasrizal, S., Kamaruzzaman, B.Y., Sakri, I., Ong, M.C., Azhar, M.S.N., 2009. Seasonal distribution of organic carbon in the surface sediments of the Terengganu Nearshore coastal area. Am. J. Environ. Sci. 5, 111–115.
Holguin, G., Vazquez, P., Bashan, Y., 2001a. The role of sediment microorganisms in the productivity, conservation, and rehabilitation of the mangrove ecosystems: an overview. Biol. Fertil. Soils 33, 265–278.
Holguin, G., Vazquez, P., Bashan, Y., 2001b. The role of sediment microorganisms in the productivity, conservation, and rehabilitation of the mangrove ecosystems: an overview. Biol. Fertil. Soils 33, 265–278.
Iwamoto, T., Tani, K., Nakamura, K., Suzuki, Y., Kitagawa, M., 2000. Monitoring impact of in situ biostimulation treatment on groundwater bacterial community by DGGE. FEMS Microbiol. Ecol. 32, 129–141.
Jiang, J.G., Wu, S.G., Shen, Y.F., 2007. Effects of seasonal succession and water pollution on the protozoan community structure in a eutrophic lake. Chemosphere 66, 523–532.
Kala, R.R., Chandrika, V., 1993. Effect of different media for isolation, growth and maintenance of actinomycetes from mangrove sediments. Indian J. Mar. Sci. 22, 297–299.
Kathiresan, K., 2000. A review of studies on Pichavaram mangrove, Southeast India. Hydrobiologia 430, 185–205.
Kathiresan, K., 2010. Globally threatened mangrove species in India. Curr. Sci. 98 (12), 1551.
Kathiresan, K., 2011. Eco-biology of Mangroves. In: Metras, J.N. (Ed.), Mangroves: Ecology, Biology and Taxonomy. Nova Science Publishers, New York, pp. 1–50.
Kathiresan, K., Bingham, B.L., 2001. Biology of mangrove and mangrove ecosystems. Adv. Mar. Biol. 40, 81–251.
Kathiresan, K., Qasim, S.Z., 2005. Biodiversity of Mangrove Ecosystems. Hindustan Publishing Corporation Limited, New Delhi, 251 pp.
Kathiresan, K., Masilamani, M., 2005. Evaluation of beneficial bacteria from mangrove soil. Bot. Mar. 49, 86–88.
Kathiresan, K., Manivannan, S., 2007. Production of alkaline protease by *Streptomyces* sp. isolated from coastal mangrove sediment. Res. J. Environ. Sci. 1, 173–178.
Kathiresan, K., Thiruneelakandan, G., 2008. Prospects of lactic acid bacteria of marine origin. Ind. J. Biotech. 7, 170–177.
Kathiresan, K., Balagurunathan, R., Masilamaniselvam, M., 2005. Fungicidal activity of marine actinomycetes against phytopathogenic fungi. Ind. J. Biotech. 4, 71–276.
Kristensen, E., Jensen, M.H., Banta, G., Hansen, K., Holmer, M., King, G.M., 1998. Transformation and transport of inorganic nitrogen in sediments of a southeast Asian mangrove forest. Aquat. Microb. Ecol. 15, 165–175.
Lallier-Verges, E., Perrussel, B.P., Disnar, J., Baltzer, F., 1998. Relationships between environmental conditions and the diagenetic evolution of organic matter derived from higher plants in a modern mangrove swamp system (Guadeloupe, French West Indies). Org. Geochem. 29, 1663–1686.
Manivannan, S., Kathiresan, K., 2009. Marine Yeasts from Rhizosphere Soil of Mangroves along the East Coast of India. Conservation and Management of Mangroves in India. Zoological Survey of India, pp. 269–274.
Matsui, N., 1998. Estimated stocks of organic carbon in mangrove roots and sediments in Hinchinbrook Chennel, Australia. Mangroves Salt Marshes 2, 199–204.
Nabeel, M.A., Kathiresan, K., Rajendran, N., Ohnishi, H., Hamaoka, H., Omori, K., 2010. Contribution by microbes to the foodweb of a mangrove biotope: the approach of carbon and nitrogen stable isotopes. Afr. J. Mar. Sci. 32 (1), 65–70.
Olsen, S.R., Cole, C.V., Watanable, F.S., Dean, D.A., 1954. Estimation of available phosphorus in soil by the extraction with sodium bicarbonates. USDA, Circular No. 939.
Palaniselvam, M., Kathiresan, K., 1998. *Phormidium tenue*: a potent source of biofertilizer for mangrove seedlings Cyanobacterial. In: Subramanian, G., Kaushik, B.D., Venkataraman, G.S. (Eds.), Biotechnology. Oxford & IBH publishing Co. Pvt. Ltd, New Delhi, pp. 377–382.
Raghukumar, C., 2005. Marine fungi and their enzymes for decolorization of coloured effluents. In: Ramiah, N. (Ed.), Marine Lignolytic Fungi. National Institute Oceanography, Goa, pp. 145–158.
Raghukumar, S., 2002. Ecology of the marine protists, the Labyrinthulomycetes (Thraustochytrids and Labyrinthulids). Eur. J. Protistol. 38, 127–145.
Raghukumar, S., Schaumann, K., 1993. An epifluorescence microscope method for direct detection of and enumeration of the fungi-like marine protists: the thraustochytrids. Limnol. Oceanogr. 38 (1), 182–187.
Rajendran, N., Kathiresan, K., 2004. How to increase juvenile shrimp in mangrove water? Wetl. Ecol. Manag. 12 (3), 179–188.
Rajendran, N., Kathiresan, K., 2007. Microbes associated with submerged leaf litter of mangroves. Rev. Biol. Trop. 55, 393–400.
Ravikumar, S., Kathiresan, K., Shanthy, S., Ignatiammal, S.T.M., Prakash, S., 2004. Quantification of Azotobacters from semi-intensive prawn culture system and their possible utility as marine biofertiliser. J. Appl. Fish. Aquat. 4, 1–4.
Rojas, A., Holguin, G., Glick, B.R., Bashan, Y., 2001. Synergism between Phyllobacterium sp. (N2-Fixer) and *Bacillus licheniformis* (*p*-Solubilizer), both from a semiarid mangrove rhizosphere. FEMS Microbiol. Ecol. 35, 181–187. http://dx.doi.org/10.1111/j.1574–6941.2001.tb00802.
Sahoo, K., Dhal, N.K., 2009. Potential microbial diversity in mangrove ecosystems: a review. Indian J. Mar. Sci. 38 (2), 249–256.
Saravanakumar, K., Shanmuga Arasu, V., Kathiresan, K., 2013. Effect of *Trichoderma* on soil phosphate solubilization and growth improvement of *Avicennia marina*. Aquat. Bot. 104, 101–105.
Subbiah, B.V., Asija, G.L., 1956. A rapid procedure for estimation of available nitrogen in soils. Curr. Sci. 25 (8), 259–260.
Toledo, G., Bashan, Y., Soeldner, A., 1995. Cyanobacteria and black mangroves in Northwestern Mexico: colonization, and diurnal and seasonal nitrogen fixation

on aerial roots. Can. J. Microbiol. 41 (11), 999–1011. http://dx.doi.org/10.1139/m95-139.
Ulken, A., 1981. On the role of phycomycetes in the food web of different mangrove swamps with brackish waters and waters of high salinity. Kiel. Meeresforsch., Sonderhal 5, 425–428.
Vazquez, P., Holguin, G., Puente, M.E., Lopez-Cortes, A., Bashan, Y., 2000. Phosphate-solubilizing microorganisms associated with the rhizosphere of mangroves in a semiarid coastal lagoon. Biol. Fertil. Soils 30, 460–468.
Volkman, J.K., Rohjans, D., Rullkötter, J., Scholz-Böttcher, B.M., Liebezeit, G., 2000. Sources and Diagenesis of Organic Matter in Tidal Flat Sediments from the German Wadden Sea. Continental Shelf Waterbury and Willey.
Wakeel, El, Riley, J.R., 1956. The determination of organic carbon in marine mud. J. du Cons. Perm. Int. Pourl Explor. Mer. 22, 180–183.
Waterbury, J.B., Watson, S.W., Valois, F.W., Franks, D.G., 1986. Biological and ecological characterization of the marine unicellular cyanobacterium *Synechococcus*. In: *Photosynthetic Picoplankton*, Platt, T., L., W.K. W., (Eds) Can. Bull. Fish. Aquat. Sci. 214, Otawa, pp. 71–120.
Zhang, K., Simard, M., Ross, M.S., Rivera-Monroy, V., Houle, P., Ruiz, P.L., Twilley, R. R., Whelan, K.R.T., 2008. Air-borne laser scanning quantification of disturbances from hurricanes and lightning strikes to mangrove forests in Everglades National Park, USA. Sensors 8, 2262–2292.
Zhuang, T., Lin, P., 1993. Soil microbial amount variations of mangroves (*Kandelia candel*) in process of natural decomposition of litter leaves. J. Xiamen Univ. Nat. Sci. 32 (3), 365–370.
Zifcakova, L., Vetrovsky, T., Howe, A., Baldrian, P., 2016. Microbial activity in forest soil reflects the changes in ecosystem properties between summer and winter. Environ. Microbiol. 18 (1), 288–301.