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VARIATION IN COMPOSITION OF ORGANIC MARINE DEPOSITS IN SEDIMENTS AND THEIR INFLUENCE ON THE GROWTH OF *RHIZOPHORA* SPP. IN TANJUNG PIAI MANGROVE FOREST

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The mangrove ecosystem is constantly threatened by the accumulation of pollutants along its shoreline. The presence of organic deposits from marine litter is not only a threat to marine ecosystems, but it also harms mangrove stands. This study investigated the chemical properties of the sediment in Tanjung Piai mangrove forest and the their effect on the growth of *Rhizophora* spp. Samples were collected from four separate locations, namely, T1: site without organic deposits, T2: site with new organic deposits, T3: site with decomposed organic deposits, and T4: site with decomposed organic deposits. After one year, the largest growth increment (19 cm) of *Rhizophora* spp. was observed at the site with decomposed organic deposits (T4), compared with sites without organic deposits (T1). The highest levels of nitrogen (N), organic carbon (OC) and cation exchange capacity (CEC) were also found at T4. The growth of *Rhizophora* spp. and the physicochemical parameters have a positive association with the levels of N, OC, CEC and exchangeable magnesium and exchangeable potassium. This study revealed that OC, N, and CEC were released into the sediment at Tanjung Piai mangrove forest when organic deposits decomposed and were physically and chemically degraded.

Keywords: Organic deposits, mangrove ecosystem, *Rhizophora* stand growth, sediment fertility

INTRODUCTION

Mangrove forests are important in coastal areas. Mangrove ecosystems are ecologically and economically important because they maintain critical ecosystem functions with high economic and biomass values such as supporting estuarine fisheries, nutrient filtering, and forming a protective barrier that reduces the chances of low-lying coastal land being damaged by storms and other natural disasters (Lee et al. 2014). Mangrove trees dominate the wetland ecosystems and the trees can physically modify environmental conditions to increase the availability of resources for the entire ecosystem (Wang & Gu 2021). Furthermore, mangrove forests act as coastal buffer zones to protect coastal habitats from natural disasters. Besides being habitats for terrestrial and marine species, mangroves also shape and maintain the intertidal zone, serve as renewable sources of wood and fuel, and act as key accumulation sites for sediments (Kumari et al. 2020).

Human activities produce a lot of waste, which frequently evades management plans and enters the environment through sewage, rainwater, wind and river systems, or may be dumped directly onto beaches and seas (Consoli et al. 2020). Human activities have threatened the mangrove ecosystems in the past century as mangroves are more susceptible to human-induced disturbances than natural perturbations (Gorman 2018). Mangrove wetland systems have experienced environmental changes over the past few decades as a result of various pollutants from anthropogenic activities (Wang & Gu 2021). Human activities, e.g. fisheries, aquaculture, tourism and dumping, that produce impacts on the environment influence the distribution of marine debris. Not only is marine litter a serious threat to marine life and the environment, but it also harms economic sectors as well as human health in the long run (Hua et al. 2018).

Metal, wood, plastic, paper, rubber, and clothing are among the items that have been purposefully or unintentionally dumped into the sea (Galgani et al. 2015). These materials could possibly improve the transport of organic and inorganic contaminants which are known to be detrimental to both human health and aquatic life (Rochman et al. 2013). Natural debris (such as driftwood and drift seeds) has been identified as floating marine debris that is washed ashore and tends to accumulate along the coastlines (Bergmann et al. 2017). The magnitude of the problem related to accumulation of marine debris and its potential to harm biodiversity has not been widely studied (Holmes et al. 2014). However, in 2012, Tanjung Piai National Park was faced with oil spills and marine debris containing organic deposits which killed approximately 7000 mangrove trees. The organic deposits formed toxic materials as they absorbed oil from the cleaning of ships. These organic deposits are not only acidic but also contain high levels of heavy metals, which cause the decay of mangrove roots and will eventually kill the tree (Wan-Rasidah et al. 2015). According to the authors, the death of the trees was due to high acidity and low level of conductivity of organic deposit in the root zone.

The survival of mangrove stands depends on the characteristics of sediments (Salmo et al. 2019, Nguyen et al. 2020). Physical characteristics of mangroves such as sediment texture, salinity, and pH play a vital role in determining the health of the ecosystem (Banerjee et al. 2018). Sediments provide mangroves good sources of nutrients for growth and a sturdy physical structure for stability and anchorage (Gillis et al. 2019). The concentrations of nutrients in mangrove sediments and the growth of mangroves can also be impacted by anthropogenic activities such as sewage discharge or waste disposal (Wang & Gu 2021). Consequently, nutrient depletion threatens the ecological balance in mangrove ecosystems. However, research on the impacts of organic deposits on sediment characteristics and the growth of mangroves are still limited. Therefore, the objective of this research was to understand how organic deposits affected the growth and survival of *Rhizophora* spp. and the sediment chemical composition at Tanjung Piai mangrove forest in Johor.

MATERIALS AND METHODS

Description of study area

Tanjung Piai mangrove forest is one of the Johor National Parks located in the district of Pontian (Figure 1). Tanjung Piai has been designated as a globally important wetland for conservation under the RAMSAR Convention in 2003 due to the value of the site as a wetland in Malaysia. Located strategically between Malaysia, Indonesia and Singapore, this national park sits at the southernmost tip of Mainland Asia. Its location has a significant geographical value that attracts both local and foreign visitors.

Treatment, growth and survival rate

Complete block design with three replications was used to set up the experiment comprising different statuses of organic deposits existing at the research sites in the Tanjung Piai mangrove forest (Table 1). The *Rhizophora* spp. were identified and tagged, and their growth was determined by measuring their heights every three months. Survival rates were calculated based on the percentage of tagged *Rhizophora* spp. that were surviving and growing at the time of the investigation. Data collection on the growth and survival rate of the trees were carried out for one year at intervals of three months.

Sediment sampling

To determine nutrients in sediments, laboratory analyses were carried out on the sediment samples collected at each study plot at the Tanjung Piai mangrove forest. Sediment samples were collected from two layers of sediments, namely, 0–10 and 10–30 cm in depth using stainless steel auger. These samples were air dried, ground and analysed for pH, organic carbon (OC), available phosphorous (P), total nitrogen (N), and cation exchange capacity (CEC). Using a pH meter, the sediment pH was measured in the supernatant of the mixed sample and distilled water at a ratio 1:2.5. The modified Kjeldahl method was used to calculate total N (Bremner & Mulvaney 1982). The OC was measured using the method by Walkley and Black (1934). Available

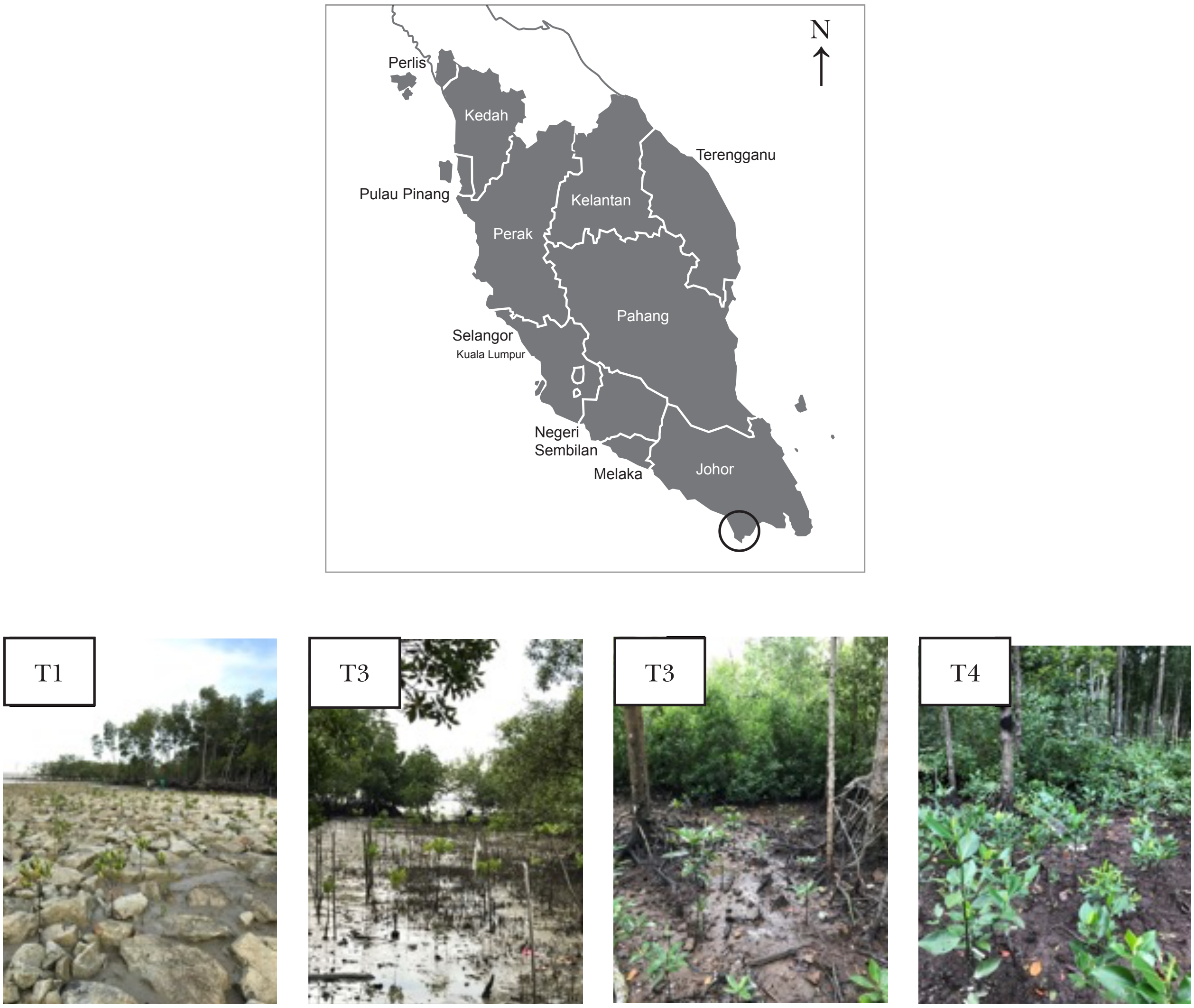

Figure 1 Study area and sample collection; T1 = site without organic deposits, T2 = site with fresh organic deposits, T3 = site with decomposed organic deposits and T4 = site with decomposed organic deposits

Table 1 The description of each plot in Tanjung Piai, Johor

Plot	Description
T1	Site without organic deposit material • There is no organic material present at this plot • 25 m from shoreline
T2	Site with new organic deposit material • The presence of organic deposit on of the sediment • 40 m from shoreline
T3	Site with decomposed organic deposit material • The organic deposit material mixed in the sediment • 90 m from shoreline
T4	Site with decomposed organic deposit material • The organic deposit material mixed in the sediment • 150 m from shoreline

P was determined using the Bray and Kurtz no.2 extract test (Bray & Kurtz 1945) while sediment exchangeable bases (Ca^{2+}, Mg^{2+} and K^+) and CEC were determined following Thomas (1982).

Statistical analysis

Statistical analyses were carried out using SPSS Version 24. Data were expressed as means ± standard deviation. The mean differences of the data between the variables were determined using one-way analysis of variance (ANOVA) and the Tukey test. Values were considered significantly different when $p \leq 0.05$. For bivariate correlations, Pearson's correlation coefficient was used to calculate a correlation between data.

RESULTS

Growth performance

Figure 2 shows the total mean height increment for seedlings of *Rhizophora* spp. at the four study plots for one year. All three species at T1 recorded the lowest increment in a range of 11 to 13 cm. *Rhizophora mucronata* at T1 exhibited the lowest increment after one year of study with a mean increment of 11 cm. However, the highest mean height increment (17 cm) was recorded for *R. mucronata* at T3 and T4. *Rhizophora stylosa* recorded the highest mean of the increment (17 cm) at T2 while *R. apiculata,* at T2 and T3 (15 cm).

Figure 2 depicts the growth of *Rhizophora* spp. under different treatments from the 3rd to the 12th month. At T1, *R. mucronata* exhibited a slow growth during month 3 to month 6, while *R. stylosa* had slow growth from month 9 to month 12. Both species recorded the highest increments at T3 and T4. The highest increment for *R. apiculata* was recorded at T2 from month 3 to month 6 but a slower growth was recorded thereafter, with increments only of 2 to 3 cm.

Survival rate

More than 80% of the tagged *Rhizophora* spp. at T4 survived the investigation period of 12 months (Figure 3). In the first three months of the study, all *R. stylosa* at T4 and *R. mucronata* at T3 survived. The second highest survival rate of the three species investigated was recorded at T3 with 75 to 84% survival. Among the three species, *R. mucronata* showed the highest percentage of survival in all study plots. At T2, only 47% of *R. stylosa* survived after 12 months making it the lowest percentage of survival at the study sites. Survival of *R. stylosa* considerably decreased from 100 to 77% in month 3 and continued to drop to 47% in month 12. The highest percentage of survival of *R. stylosa* was recorded at T1 and T4 with 81 and 82% respectively.

Physiochemical properties and nutrient level of sediment

Table 2 shows the physicochemical and textural properties of sediments at the study plots in Tanjung Piai, Johor. The total OC and CEC of the sediments were high at T3 and T4 in both layers, compared with T1 and T2. The pH was slightly acidic at T3 and T4 (4.78 to 5.63).

T3 had the highest percentage of N (0.81%) at 0–10 cm depth followed by T4 with 0.71% in the first month (Table 3a). The highest percentage of N at 10–30 cm depth was recorded at T3 (0.77%) in the first month as shown in Table 3b. The percentage of N at T3 (10–30 cm depth) decreased until month 6, followed by an increase to 0.69% in month 9, and a decrease to 0.43% in month 12. The lowest percentage of N (0.09%) was recorded in month 3 and month 6 at T1 and T2 respectively at the depth of 0–10 cm. At T2, the percentage of N decreased from 0.17 to 0.09% in month 3 and increased until month 9 before decreasing to 0.08% in month 12.

T2 had the most available P at both depths of 0–10 and 10–30 cm (Tables 3a and b). At the former, the highest concentration of available P (23.03 mg kg^{-1}) was recorded in month 12, while the highest concentration at the latter was recorded in month 9 (22.53 mg kg^{-1}). T3 has the least available P at both depths, with 3.47 mg kg^{-1} at the depth of 0–10 cm and 4.30 mg kg^{-1} at 10–30 cm. The level of available P at T2 increased from month 1 to month 12 at both depths. When compared with the other three sites, the level of available P at T2 (10–30 cm) fluctuated with a slight increase and decrease over the 12 months. For example, at the depth of 10–30 cm, the amount of available P increased from 17.59 mg kg^{-1} at month 6 to 22.53 mg kg^{-1} at month 9 and decreased to 20.68 mg kg^{-1} in month 12.

In month 1, T2 at both depths had the highest concentration of exchangeable calcium (Ca). The exchangeable Ca concentration was 27.36 cmol

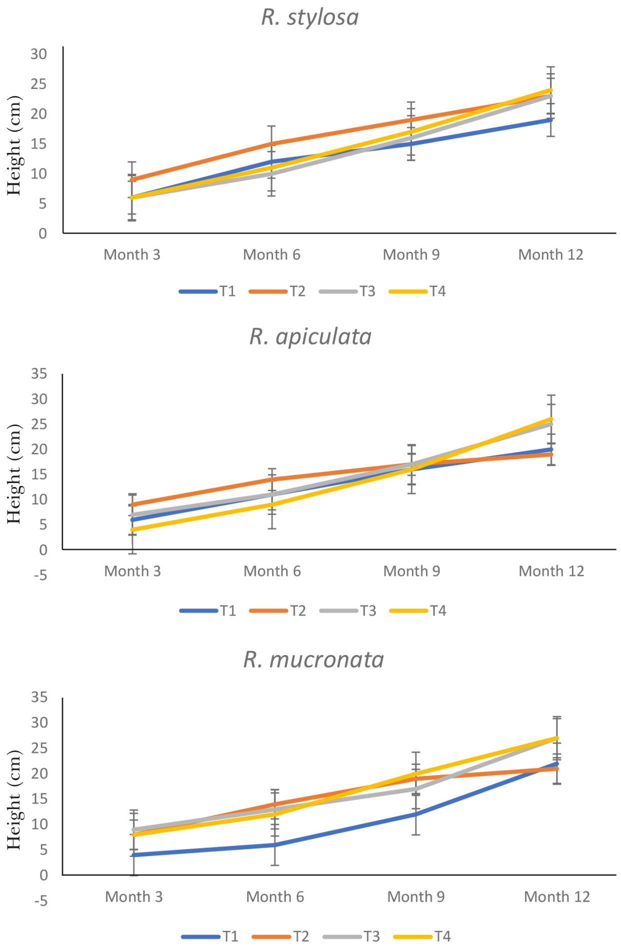

Figure 2 Plant growth performance (mean plant height with standard error) of *Rhizophora* spp. for different treatment from month 3 to month 12; T1 = site without organic deposit, T2 = site with fresh organic deposit, T3 = site with decomposed organic deposit, T4 = site with decomposed organic deposit

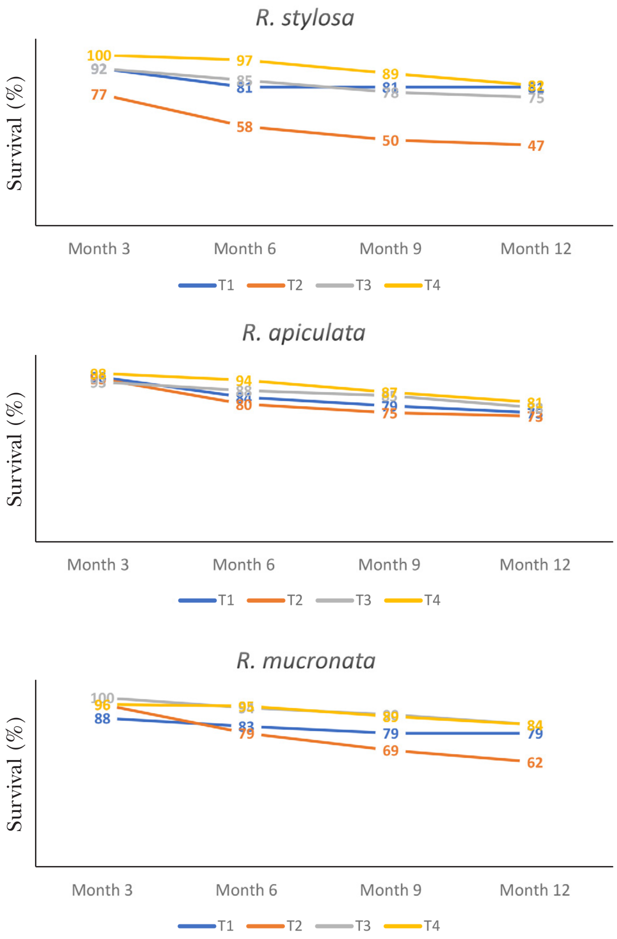

Figure 3 Percentage survival of *Rhizophora* spp. from month 3 to month 12; T1 = site without organic deposit, T2 = site with fresh organic deposit, T3 = site with decomposed organic deposit, T4 = site with decomposed organic deposit

Table 2 Sediment physicochemical properties in study plots at Tanjung Piai, Johor

Site	Parameter								
	Depth (cm)	TOC (%)	CEC (cmol kg^{-1})	pH	Coarse sand	Fine sand	Silt	Clay	Textural class
TI	0–10	1.76 ± 0.13 c	11.65 ± 0.13 c	7.78 ± 0.13 a	2	46	28	27	Sandy clay loam
	10–30	1.86 ± 0.04 c	11.65 ± 0.04 c	7.82 ± 0.04 a	1	51	27	24	Sandy clay loam
T2	0–10	3.80 ± 0.46 b	12.73 ± 0.46 c	7.72 ± 0.46 a	15	54	8	24	Sandy clay loam
	10–30	3.60 ± 0.08 b	12.73 ± 0.08 c	7.66 ± 0.08 a	14	52	10	25	Sandy clay loam
T3	0–10	16.52 ± 0.16 a	40.63 ± 0.16 a	4.78 ± 0.16 b	19	10	21	50	Clay
	10–30	17.98 ± 0.26 a	40.63 ± 0.26 a	5.12 ± 0.26 b	17	12	24	48	Clay
T4	0–10	16.77 ± 0.48 a	30.20 ± 0.48 b	5.19 ± 0.48 b	23	9	21	47	Clay
	10–30	18.70 ± 0.08 a	30.20 ± 0.08 b	5.63 ± 0.08 b	19	10	24	48	Clay

Means ± standard error of mean value followed by different letters in column are significantly different using repeated measures ANOVA at $p < 0.05$; TOC = total organic carbon, CEC = cation exchange capacity; T1 = site without organic deposit, T2 = site with fresh organic deposit, T3 = site with decomposed organic deposit, T4 = site with decomposed organic deposit

Table 3a Nitrogen content and exchangeable cations of the sediments in the 0–10 cm sediment depth

Site	Parameter	Month 1	Month 3	Month 6	Month 9	Month 12
		Sediment depth (0–10 cm)				
TI	Nitrogen (%)	0.18 ± 0.13 b	0.16 ± 0.14 c	0.09 ± 0.15 c	0.17 ± 0.02 c	0.19 ± 0.04b
	Avail. P. (mg kg^{-1})	7.19 ± 0.47 b	4.11 ± 0.28 c	6.55 ± 0.35 c	9.77 ± 0.88 b	9.45 ± 0.32c
	Exch. Ca. (cmol kg^{-1})	13.96 ± 0.53 b	12.61 ± 0.43 b	12.54 ± 0.27 b	16.62 ± 0.52 b	9.49 ± 0.28b
	Exch. Mg. (cmol kg^{-1})	16.89 ± 0.61 c	16.38 ± 0.14 b	15.45 ± 0.32 c	16.72 ± 0.20 c	13.46 ± 0.30d
	Exch. K (cmol kg^{-1})	1.98 ± 0.04 a	2.64 ± 0.12 a	3.19 ± 0.03 ab	2.94 ± 0.06 a	2.89 ± 0.38a
T2	Nitrogen (%)	0.17 ± 0.46 b	0.09 ± 0.46c	0.12 ± 0.21b	0.14 ± 0.02 c	0.08 ± 0.07b
	Avail. P (mg kg^{-1})	15.39 ± 0.30 a	15.57 ± 0.30a	16.51 ± 0.17a	21.00 ± 0.88 a	23.03 ± 0.33a
	Exch. Ca (cmol kg^{-1})	27.36 ± 0.58 a	25.22 ± 0.24 a	23.44 ± 0.48 a	18.74 ± 0.73 a	12.02 ± 0.41 a
	Exch. Mg (cmol kg^{-1})	18.58 ± 0.20 b	14.51 ± 0.13 d	16.36 ± 0.38 b	12.76 ± 0.20 d	10.70 ± 0.28 e
	Exch. K (cmol kg^{-1})	1.75 ± 0.01 b	1.53 ± 0.06 c	1.42 ± 0.20 d	1.22 ± 0.11 c	1.24 ± 0.42 b
T3	Nitrogen (%)	0.81 ± 0.16 a	0.81 ± 0.35 a	0.67 ± 0.06 a	0.78 ± 016 a	0.48 ± 0.27 a
	Avail. P (mg kg^{-1})	3.62 ± 1.06 c	3.51 ± 0.31 c	3.47 ± 0.25 d	4.42 ± 0.46 c	4.44 ± 0.28 d
	Exch. Ca (cmol kg^{-1})	6.38 ± 0.44 d	5.76 ± 0.11 d	7.43 ± 0.45 c	9.02 ± 0.43 d	8.69 ± 0.22 bc
	Exch. Mg (cmol kg^{-1})	16.42 ± 0.37 c	15.61 ± 0.23 c	15.58 ± 0.34 bc	23.74 ± 0.23 b	27.88 ± 0.03 b
	Exch. K (cmol kg^{-1})	0.96 ± 0.03 c	1.29 ± 0.06 d	2.55 ± 0.66 bc	2.20 ± 0.15 b	2.28 ± 0.19 a
T4	Nitrogen (%)	0.71 ± 0.48 a	0.66 ± 1.05 b	0.66 ± 0.47 a	0.70 ± 0.51 b	0.46 ± 0.32 b
	Avail. P (mg kg^{-1})	7.87 ± 0.51 b	8.21 ± 0.65 b	7.13 ± 0.13 bc	5.19 ± 0.18 c	11.84 ± 0.75 b
	Exch. Ca (cmol kg^{-1})	8.25 ± 0.12 c	8.43 ± 0.19 c	7.01 ± 0.81 c	8.50 ± 0.31 d	7.92 ± 0.82 c
	Exch. Mg (cmol kg^{-1})	22.34 ± 0.30 a	21.47 ± 0.11 a	22.48 ± 0.18 a	30.30 ± 0.20 a	28.90 ± 0.08 a
	Exch. K (cmol kg^{-1})	1.94 ± 0.05 a	1.84 ± 0.05 b	2.42 ± 0.32 c	2.58 ± 0.36a b	2.29 ± 0.05a

Samples were collected at the end of the experiment; means ± standard error of mean value followed by different letters in column are significantly different using repeated measures ANOVA at $p < 0.05$; Avail. P = Available P, Exch. Ca, Mg and K = exchangeable Ca, Mg and K; T1 = site without organic deposit, T2 = site with fresh organic deposit, T3 = site with decomposed organic deposit, T4 = site with decomposed organic deposit

kg^{-1} at 0–10 cm and 27.70 cmol kg^{-1} at 10–30 cm. The value of exchangeable Ca in T2 decreased with time over 12 months at the depth of 0–10 cm, and only slightly decreased at the depth of 10–30 cm, from 27.70 to 26.75 cmol kg^{-1}. The second highest concentration of exchangeable Ca was recorded at T1, with the values from 9.49 to 16.62 cmol kg^{-1} at the depth of 0–10 cm and 10.42 to 18.27 cmol kg^{-1} at 10–30 cm. T3 had the lowest concentrations of exchangeable Ca, and the lowest were recorded in month 3 at 0–10 and 10–30 cm depths with values of 5.76 and 5.49 cmol kg^{-1} respectively. The highest (9.02 and 8.70 cmol kg^{-1}) values were recorded in the 9th month at 0–10 cm and 10–30 cm respectively. The concentration of exchangeable Ca at T4 was the same at both depths, with the value decreasing from the first to the 6th month, followed by an increase in month 9, and decreasing thereafter. The maximum concentration at T4 was 8.50 cmol kg^{-1} at the depth of 0–10 cm and 11.94 cmol kg^{-1} at 10–30 cm.

The highest concentration of exchangeable magnesium (Mg) was discovered at T4 and the lowest at T2. At 0–10 cm, the concentration of exchangeable Mg at T4 increased from 22.34 cmol kg^{-1} in month 1 to 30.30 cmol kg^{-1} in month 9, followed by a decrease to 28.90 cmol kg^{-1} in month 12. The concentration at T4 increased from month 1 to month 9 at the depth of 10–30 cm, followed by a decrease in month 12. T3 had the second highest exchangeable Mg concentration ranging from 15.61 to 27.88 cmol kg^{-1} at the depth of 0–10 cm and 18.46 to 29.22 cmol kg^{-1} at 10–30 cm. At T2, the concentration of exchangeable Mg decreased from month 1 to month 12 at the depth of 0–10 cm and increased from month 1 to month 12 at 10–30 cm. The concentration of exchangeable Mg at T1 was nearly the same as from month 1 to

Table 3b Nutrient content of the sediments in the 10–30 cm sediment depth

Site	Parameter	Month 1	Month 3	Month 6	Month 9	Month 12
		Sediment depth(10–30 cm)				
T1	Nitrogen (%)	0.18 ± 0.04 c	0.17 ± 0.06 c	0.11 ± 0.10 b	0.18 ± 0.02 b	0.19 ± 0.01 b
	Avail. P (mg kg^{-1})	6.23 ± 1.02 c	3.56 ± 0.32 d	8.47 ± 0.38 c	7.41 ± 0.13 c	8.49 ± 0.37 c
	Exch. Ca (cmol kg^{-1})	12.85 ± 0.44 c	12.26 ± 0.15 c	10.42 ± 0.19 b	18.27 ± 0.20 b	13.11 ± 0.64 c
	Exch. Mg (cmol kg^{-1})	16.59 ± 0.61 c	16.53 ± 0.05 d	16.71 ± 0.24 c	16.58 ± 0.23 e	16.25 ± 0.35 e
	Exch. K (cmol kg^{-1})	1.91 ± 0.08 b	2.86 ± 0.11 a	3.31 ± 0.18 a	2.94 ± 0.37 ab	2.85 ± 0.13 a
T2	Nitrogen (%)	0.14 ± 0.08 c	0.14 ± 0.53 c	0.13 ± 0.12 b	0.18 ± 0.25 b	0.15 ± 0.17 bc
	Avail. P (mg kg^{-1})	19.57 ± 0.19 a	18.83 ± 0.13 a	17.59 ± 0.25 a	22.53 ± 0.36 a	20.68 ± 0.40 a
	Exch. Ca (cmol kg^{-1})	27.70 ± 0.14 a	27.27 ± 0.27 a	26.89 ± 0.48 a	25.57 ± 0.53 a	26.75 ± 0.40 a
	Exch. Mg (cmol kg^{-1})	17.61 ± b0.24 c	17.64 ± 0.22 c	17.72 ± 0.02 c	18.70 ± 0.18 c	24.63 ± 0.29 c
	Exch. K (cmol kg^{-1})	1.56 ± 0.03 c	1.51 ± 0.06 c	1.55 ± 0.22 c	2.08 ± 0.32 c	1.41 ± 0.54 c
T3	Nitrogen (%)	0.77 ± 0.26 a	0.64 ± 0.21 a	0.56 ± 0.29a	0.69 ± 0.22a	0.43 ± 0.17a
	Avail. P (mg kg^{-1})	5.53 ± 0.35 c	5.26 ± 0.88 c	6.23 ± 0.20 d	6.75 ± 0.57cd	4.30 ± 0.40d
	Exch. Ca (cmol kg^{-1})	6.27 ± 0.31 e	5.49 ± 0.15 e	7.49 ± 0.10 d	8.70 ± 0.24 e	7.37 ± 0.19e
	Exch. Mg (cmol kg^{-1})	18.46 ± 0.42 b	19.65 ± 0.20 b	21.5 ± 0.53 b	29.22 ± 0.20 b	27.72 ± 0.31 b
	Exch. K (cmol kg^{-1})	1.25 ± 0.04 c	1.64 ± 0.05 c	2.53 ± 0.17 b	2.58 ± 0.28 bc	2.38 ± 0.69 b
T4	Nitrogen (%)	0.55 ± 0.08 b	0.43 ± 0.29 b	0.54 ± 0.34 b	0.61 ± 0.63 a	0.39 ± 0.20 a
	Avail. P (mg kg^{-1})	8.71 ± 0.37 b	8.86 ± 0.59 b	9.89 ± 0.10 b	5.62 ± 0.52 d	13.63 ± 0.70 b
	Exch. Ca (cmol kg^{-1})	10.06 ± 0.53 d	9.66 ± 0.35 d	8.78 ± 0.32 c	11.94 ± 0.56 d	10.24 ± 0.20 d
	Exch. Mg (cmol kg^{-1})	23.11 ± 0.60 a	23.59 ± 0.06 a	23.19 ± 0.76 a	34.74 ± 0.40 a	32.38 ± 0.09 a
	Exch. K (cmol kg^{-1})	2.76 ± 0.27 a	2.54 ± 0.05 b	3.39 ± 0.29 a	2.93 ± 0.05 ab	2.96 ± 0.65 a

Samples were collected at the end of the experiment; means ± standard error of mean value followed by different letters in column are significantly different using repeated measures ANOVA at $p < 0.05$; Avail. P = Available P, Exch. Ca, Mg and K = exchangeable Ca, Mg and K; T1 = site without organic deposit, T2 = site with fresh organic deposit, T3 = site with decomposed organic deposit, T4 = site with decomposed organic deposit

month 12 at the sediment depth of 0–10 cm, with slightly different values recorded at 10–30 cm.

For the exchangeable potassium (K), the recorded concentrations were generally lower than that of exchangeable Ca and Mg. The concentration of exchangeable K at both depths, ranged from 0.96 to 3.46 cmol kg^{-1}. The highest concentration of exchangeable K is at T2 at both sediment depths. At T2, the concentration at the depth of 0–10 cm decreased from month 1 to month 12, with only minor differences between readings. The highest concentration recorded at the depth of 10–30 cm was 2.08 cmol kg^{-1} in month 9, which dropped to 1.41 cmol kg^{-1} in month 12. The concentration of exchangeable K at T3 was from 0.96 to 2.55 cmol kg^{-1} at 0–10 cm in depth and 1.25 to 2.58 cmol kg^{-1} at 10–30 cm. At T4, the concentration ranged from 1.84 to 2.58 cmol kg^{-1} at 0–10 cm in depth and 2.54 to 3.39 cmol kg^{-1} at 10–30 cm.

Correlation analysis

The correlation analysis (Table 4) shows that the growth of *R. apiculata* was positively correlated with the concentration of available P but negatively correlated with CEC. There was no significant correlation between the growth of *R. stylosa* and all parameters representing sediment fertility investigated in this study. In addition, the growth of *R. mucronata* had positive correlation with CEC, C and N but was negatively correlated with the pH of sediment.

DISCUSSION

The decomposition of organic compounds in the soil layers at T3 and T4 have led to an increase in nutrient availability thus enhancing sediment fertility. In this study, the highest mean height increment of *Rhizophora* seedlings was 17 cm,

Table 4 Correlation between *Rhizophora* spp. growth and sediment fertility

	pH	Avail. P	N	C	CEC	Exch. K	Exch. Ca	Exch. Mg
R. stylosa	ns	ns	ns	ns	ns	ns	ns	ns
R. apiculata	ns	0.573**	ns	ns	-0.215*	ns	ns	ns
R. mucronata	-0.702**	ns	0.793*	0.567**	0.735**	ns	ns	ns

Correlation is significant at the 0.05 level (2-tailed), **correlation is significant at the 0.01 level (2-tailed); ns = not significant; *Avail. P = available P, Exch. Ca, Mg and K = exchangeable Ca, Mg and K, CEC = cation exchange capacity

although Wechakit (1990) reported an annual increment of 45 cm for one-year-old stands. The height of *R. apiculata* normally exceeds 100 cm two years after propagules are seeded (Matsui et al. 2008). The relatively low tree height might be due to the inadequate growth of the plants. Mangrove species have certain attributes to adapt to the highly dynamic and harsh coastal wetland environment. The poor growth of *Rhizophora* spp. had most likely led to the low average tree height. The highest growth was recorded from month 1 to month 3 (Figure 3), with less rain recorded from June (month 1) to September (month 3) compared to month 6 to month 9, which was rainy season in Malaysia, i.e. from December (month 6) to March (month 9). Topographic factors such as duration and frequency of tidal inundation affect oxidation states, sediment nutrient availability, and salinity, resulting in complex patterns in nutrient supply and demand, which contribute to the variation in the structure of mangrove forests (Reef et al. 2010). The pattern of mangrove seedlings may be explained by the seasonal variation in light availability, which favours maximal growth rates near the end of the dry season when rainfall is low and solar radiation is probably high (Padilla et al. 2004).

T3 and T4 are located more landward than T1, which is in the seaward zone (Table 1). Physical conditions are critical for mangrove survival and growth. According to Basyuni et al. (2018), *R. mucronata* growing in the landward zone has a 96% growth rate compared with that of the seaward and middle zones. High mortality of *Rhizophora* spp. seedling at T2 was most probably due to physical damage caused by fallen trees and driftwood around the plot as a result of the big tidal before collecting data in month 6. This has caused survival to drop from 93 to 74%. Massive structure (low permeability) of the top sediment was one of the factors affecting *Rhizophora* spp. seedling survival during the big tidal. Some of the *Rhizophora* spp. seedlings did not survive, which could be due to poor growth caused by sediment properties at the study sites. Some seedlings died naturally due to changes in nutrient availability and salinity spikes, which are often attributed to natural runoffs and leaf loss, whereby the remaining leaves may not be able to photosynthesise at a level to support the tree (Sippo et al. 2018).

The mechanical disturbance associated with wave exposure at T1 and T2 in this study might be one of the causes for the higher mean mortality rate, as it caused a lower percentage of silt in the sediments compared with other soil structure as in Table 2 (Thampanya et al. 2002, Padilla et al. 2004). Table 2 shows that the silt at T2 is the lowest at both sediment depths compared with the rest of the study sites. By addressing the geomorphic site, ecological condition, salinity concentration and recommended species, successful tree restoration and survival can be increased (Basyuni et al. 2018).

The total OC in the sediments in Tanjung Piai was high at T3 and T4 at both depths, contributing to the growth of *Rhizophora* spp. Carbon is the key component of healthy sediment conditions and sediment productivity (Schlesinger & Andrews 2000). The presence of organic matter in the sediment increases its level of total OC (Havlin et al. 2016). Carbon sources in mangrove forests include pure mangrove litter, organic materials carried in by tides or rivers and deposited alongside mangrove detritus, decomposed materials, etc. (Kristensen et al. 2008). Quantifying C accumulation in sediments is a useful technique for estimating C storage in mangrove ecosystems. T1 and T4 had different densities of mangrove species, which could translate into different vegetation growth within the ecosystem.

Total OC content of the sediments was high at T3 and T4 at both depths, contributing to the growth of the *Rhizophora* spp. there. Mangrove ecosystems are significant natural C sinks, which accumulate and store large amounts of OC, especially in sediments. As stored C in sediment increases, the risk of other nutrients being lost due to erosion and leaching decreases, resulting in increased agricultural productivity (Schlesinger & Andrews 2000). In comparison to plots T1 and T2, the amounts of CEC in T3 and T4 were the highest, as shown in Table 3. The majority of the nutrients in the nutrient pool of the mangrove forest are stored in the sediment rather than in the trees (Alongi 2014). A high CEC reduces the mobility and availability of metal cations in the sediment as more nutrients are attached to soil particles (Del Refugio Cabañas-Mendoza et al. 2020).

The exchangeable Ca, K and Mg are typically referred to as major ions linked to CEC in soils (Rayment & Higginson 1992). The primary core of the chlorophyll molecule in plant tissue is Mg. As a result, if Mg is inadequate, the lack of chlorophyll causes poor and stunted plant growth. Magnesium also assists in the activation of particular enzyme systems in plant (Wang & Gu 2021). Potassium is classified as a macronutrient because it is an essential nutrient for plant growth and plants take up a significant amount of K during their life cycle (Alongi 2014). Calcium in plants is essential for signalling the activation of specific enzymes for the establishment of a proper root system in plants (Mitsui et al. 2008). Besides that, Ca also provides the best soil structure which influences plant growth by extent of root distribution and how water percolates and infiltrates through the soil (Havlin et al. 2016)

Decomposition of organic matter improves nutrient availability and is a major source of nutrients in the mangrove ecosystem (Milne et al. 2015). Organic matter is likely to play a key role in promoting tree growth by improving sediment properties, which include improving sediment structure and facilitating root growth, while organic matter decomposition provides nutrients to trees (Matsui et al. 2008). The decomposition of organic deposits in sediment at T3 and T4 has liberated N as ammonia, which is then converted into nitrate or soluble form that is readily available and usable by plants (Kida & Fujitake 2020). More study is required for better understand the N cycle in organic sediment in mangrove ecosystems.

To determine the pairwise association, Pearson's correlation matrix was used between sediment nutrient content and development of mangrove species. Plant growth and development in natural conditions are influenced by various factors including the availability of micronutrients and macronutrients in the soil (Rahman et al. 2019, 2021). Subtle changes in the growth factor of the mangrove will have an impact on the overall mangrove density. Thus, nutrient status should be investigated not by determining the impacts of shortage of a single nutrient on the physiological condition of the plant, but by examining the consequences of several nutrients in a particular environment (Kalaji et al. 2018). Differences in nutrient contents have a substantial impact on the photochemical process such as photosynthesis, which is important for plant growth and development. Nutrient deficiency stunts plant growth, and causes plant tissue death, or yellowing of leaves due to decreased production of chlorophyll, which is required for photosynthesis. Besides the status of nutrients in the sediments, tidal cycles and seasonality associated with the geographical location are also linked to the mangrove vegetation and overall productivity of the ecosystem (Taillardat et al. 2019). Mangrove species such as *Rhizophora* spp. grow well near wide river mouth, muck and sand-rich streams (Hossain & Nuruddin 2016). Therefore, future studies that investigate the link between the factors that are present in different mangrove locations and the nutrient status of sediments there will provide a thorough understanding of the development of site-specific species.

CONCLUSION

The growth of *Rhizophora* spp. in Tanjung Piai is the highest at the study sites rich in decomposed organic deposits (T3 and T4), which reflects the vast nutrient availability and enhanced sediment fertility that support the development of the plant. The percentages of N and C are also higher in the study plots having decomposed organic deposit (T3 and T4).

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REFERENCES

Alongi DM. 2014. Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science* 6: 195–219. https://doi.org/10.1146/annurev-marine-010213-135020

Banerjee K, Bal G & Mitra A. 2018. How soil texture affects the organic carbon load in the mangrove ecosystem? A case study from Bhitarkanika, Odisha. Pp 329–341 in *Environmental Pollution*. Springer, Singapore.

Basyuni M, Telaumbanua T, Wati R, Sulistyono N & Putri L. 2018. Evaluation of *Rhizophora* mucronata growth at first-year mangrove restoration at abandoned ponds, Langkat, North Sumatra. *IOP Conference Series: Earth and Environmental Science* 126: 012118. doi:10.1088/1755-1315/126/1/012118

Bergmann M, Lutz B, Tekman MB & Gutow L. 2017. Citizen scientists reveal: marine litter pollutes Arctic beaches and affects wild life. *Marine Pollution Bulletin* 125: 535–540. https://doi.org/10.1016/j.marpolbul.2017.09.055

Bray RH & Kurtz LT. 1945. Determination of total organic and available forms of phosphorus in soils. *Soil Science* 59: 39–45. http://dx.doi.org/10.1097/00010694-194501000-00006

Bremner J & Mulvaney C. 1982. Nitrogen—total. Pp 595–624 in Page AL et al. (eds) *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. Agronomy Monograph 9. Second Edition. Soil Science Society of America, Madison.

Consoli P, Scotti G, Romeo T et al. 2020. Characterization of seafloor litter on Mediterranean shallow coastal waters: evidence from dive against debris, a citizen science monitoring approach. *Marine Pollution Bulletin* 150: 110763. doi: 10.1016/j.marpolbul.2019.110763

Del Refugio Cabañas-Mendoza M, Santamaría JM, Sauri-Duch E, Escobedo-Graciamedrano RM & Andrade JL. 2020. Salinity affects pH and lead availability in two mangrove plant species. *Environmental Research Communications* 2: 061004. https://doi.org/10.1088/2515-7620/ab9992

Galgani F, Hanke G & Maes T. 2015. Global distribution, composition and abundance of marine litter. Pp 29–56 in Bergmann M et al. (eds) *Marine Anthropogenic Litter*. Springer, Cham. https://doi.org/10.1007/978-3-319-16510-3_2

Gillis LG, Hortua DA, Zimmer M, Jennerjahn TC & Herbeck LS. 2019. Interactive effects of temperature and nutrients on mangrove seedling growth and implications for establishment. *Marine Environmental Research* 151: 104750. https://doi.org/10.1016/j.marenvres.2019.104750

Gorman D. 2018. Historical losses of mangrove systems in South America from human-induced and natural impacts. Pp 155–171 in Makoeski C & Finki CW (eds) *Threats to Mangrove Forests—Hazards, Vulnerability, and Management*. Springer, Cham. doi:10.1007/978-3-319-73016-5_8

Havlin JL, Tisdale SL, Nelson WL & Beaton JD. 2016. *Soil Fertility and Fertilizers*. Pearson Education, India.

Holmes LA, Turner A & Thompson RC. 2014. Interactions between trace metals and plastic production pellets under estuarine conditions. *Marine Chemistry* 167: 25–32.

Hossain M & Nuruddin A. 2016. Soil and mangrove: a review. *Journal of Environmental Science and Technology* 9: 198–207. https://dx.doi.org/10.3923/jest.2016.198.207

Hua C, Doheny PW, Ding B, Chan B, Yu M, Kepert CJ & D'alessandro DM. 2018. Through-space intervalence charge transfer as a mechanism for charge delocalization in metal–organic frameworks. *Journal of the American Chemical Society* 140: 6622–6630. https://doi.org/10.1021/jacs.8b02638

Kalaji HM, Bąba W, Gediga K et al. 2018. Chlorophyll fluorescence as a tool for nutrient status identification in rapeseed plants. *Photosynthesis Research* 136: 329–343.

Kida M & Fujitake N. 2020. Organic carbon stabilization mechanisms in mangrove soils: a review. *Forests* 11: 981. https://doi.org/10.3390/f11090981

Kristensen E, Bouillon S, Dittmar T & Marchand C. 2008. Organic carbon dynamics in mangrove ecosystems: a review. *Aquatic Botany* 89: 201–219. https://doi.org/10.1016/j.aquabot.2007.12.005

Kumari P, Singh JK & Pathak B. 2020. Potential contribution of multifunctional mangrove resources and its conservation. Pp 1–26 in Patra et al. (eds) *Biotechnological Utilization of Mangrove Resources*. Academic Press, London.

Lee SY, Primavera JH, Dahdoh-Guebas F et al. 2014. Ecological role and services of tropical mangrove ecosystems: a reassessment. *Global Ecology and Biogeography* 23: 726–743.

Matsui N, Suekuni J, Havanond S, Nishimiya A, Yanai J & Kosaki T. 2008. Determination of soil-related factors controlling initial mangrove (*Rhizophora apiculata* BL.) growth in an abandoned shrimp pond. *Soil Science & Plant Nutrition* 54: 301–309.

Milne E, Banwart SA, Noellemeyer E et al. 2015. Soil carbon, multiple benefits. *Environmental Development* 13: 33–38. http://dx.doi.org/10.1016/j.envdev.2014.11.005

Nguyen LTM, Hoang HT, Ta HV & Park PS. 2020. Comparison of mangrove stand development on accretion and erosion sites in Ca Mau, Vietnam. *Forests* 11: 615. https://doi.org/10.3390/f11060615

Padilla C, Fortes MD, Duarte CM, Terrados J & Kamp-Nielsen L. 2004. Recruitment, mortality and growth of mangrove (*Rhizophora* sp.) seedlings in Ulugan Bay, Palawan, Philippines. *Trees* 18: 589–595. https://doi.org/10.1007/s00468-004-0351-x

Rahman MS, Hossain MS, Ahmed MK et al. 2019. Assessment of heavy metals contamination in selected tropical marine fish species in Bangladesh and their impact on human health. *Environmental Nanotechnology, Monitoring & Management* 11: 100210. https://doi.org/10.1016/j.enmm.2019.100210

Rahman MS, Saha N, Ahmed AS et al. 2021. Depth-related dynamics of physicochemical characteristics and heavy metal accumulation in mangrove sediment and plant: *Acanthus ilicifolius* as a potential phytoextractor. *Marine Pollution Bulletin* 173: 113160. http://dx.doi.org/10.1016/j.marpolbul.2021.113160

Rayment GE & Higginson FR. 1992. Electrical conductivity. *Australian Laboratory Handbook of Soil and Water Chemical Methods.* Inkata Press, Melbourne.

Reef R, Ball MC, Feller IC, & Lovelock CE. 2010. Relationships among RNA: DNA ratio, growth and elemental stoichiometry in mangrove trees. *Functional Ecology* 24: 1064–1072. https://doi.org/10.1111/j.1365-2435.2010.01722.x

Rochman CM, Hoh E, Kurobe T & Teh SJ. 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific Reports* 3: 3263. https://doi.org/10.1038/srep03263

Salmo SG, Tibbetts IR, & Duke NC. 2019. Recolonization of mollusc assemblages in mangrove plantations damaged by Typhoon Chan-hom in the Philippines. *Estuarine, Coastal and Shelf Science* 228: 106365. https://doi.org/10.1016/j.ecss.2019.106365

Schlesinger WH & Andrews JA. 2000. Soil respiration and the global carbon cycle. *Biogeochemistry* 48: 7–20. https://doi.org/10.1023/A:1006247623877

Sippo JZ, Lovelock CE, Santos IR, Sanders CJ & Maher DT. 2018. Mangrove mortality in a changing climate: an overview. *Estuarine, Coastal and Shelf Science* 215 241–249. doi:10.1016/j.ecss.2018.10.011

Taillardat P, Ziegler AD, Friess DA et al. 2019. Assessing nutrient dynamics in mangrove porewater and adjacent tidal creek using nitrate dual-stable isotopes: a new approach to challenge the Outwelling Hypothesis? *Marine Chemistry* 214: 103662. https://doi.org/10.1016/j.marchem.2019.103662

Thampanya U, Vermaat JE & Duarte CM. 2002. Colonization success of common Thai mangrove species as a function of shelter from water movement. *Marine Ecology Progress Series* 237: 111–120. http://dx.doi.org/10.3354/meps237111

Thomas GW. 1982. Exchangeable cations. Pp 159–165 in Page AL et al. (eds) *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties.* Agronomy Monograph 9. Second Edition. Soil Science Society of America, Madison

Walkley AJ & Black IA. 1934. Estimation of soil organic carbon by the chromic acid titration method. *Soil Science* 37: 29–38.

Wan-Rasidah K, Mohamad-Zaki MI & Mohd-Fakhri I. 2015. *Muddy Substrates of Malaysia Coast.* Forest Research Institute of Malaysia, Kepong.

Wang YS & Gu JD. 2021. Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities. *International Biodeterioration & Biodegradation* 162: 105248. https://doi.org/10.1016/j.ibiod.2021.105248

Wechakit D. 1990. Growth and survival of private mangrove plantation (*Rhizophora apiculata*) at Amphoe Amphawa, Changwat Samut Songkhram. *Thai Journal of Forestry* 9: 93–100.