Original Research

Journal website : www.jeb.co.in ★ E-mail : editor@jeb.co.in

Journal of Environmental Biology

JEB™ p-ISSN: 0254-8704
e-ISSN: 2394-0379
CODEN: JEBIDP

DOI : http://doi.org/10.22438/jeb/42/3(SI)/JEB-07

Effect of dissolved oxygen deficiency on ^{210}Pb content in mussel's tissues at the Johor Strait, Malaysia

N.A.B. Saili and C.A.R. Mohamed*

Department of Earth Sciences and Environment, Faculty of Science and Technology,Universiti Kebangsaan Malaysia, Bangi, 43600, Malaysia

***Corresponding Author Email :** carmohd@ukm.edu.my

Received: 14.11.2020 *Revised*: 17.03.2021 *Accepted*: 26.03.2021

Abstract

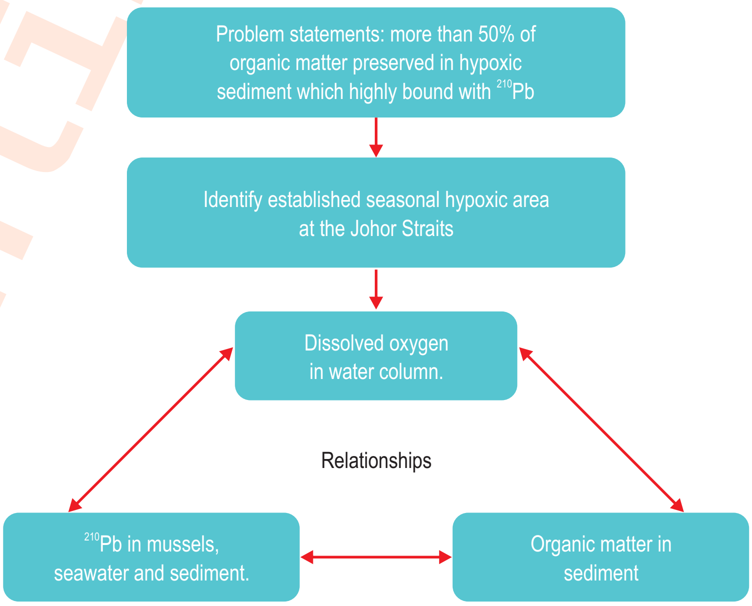
Aim: To investigate the effect of dissolved oxygen deficiency on the level of ^{210}Pb in mussel's tissues, *Perna viridis* which has been reported to be highly tolerant to hypoxia.

Methodology: Mussels (*Perna viridis*), seawater and sediment samples were collected from nine stations along the Johor Straits during North-east monsoon (November 2017), inter-monsoon (March 2018), and South-west monsoon (August 2018). The ^{210}Pb contents were extracted and estimated by Gross Alpha-beta Counter.

Results: The lowest dissolved oxygen was recorded at Station 4 which decreased from 2.14 mg l^{-1} to 2.10 mg l^{-1} and subsequently to 1.63 mg l^{-1} during first to third samplings. In sediment, ^{210}Pb activities increased with the increase in organic matter. Meanwhile, in mussels, the ^{210}Pb activities showed almost similar trend with sediment where ^{210}Pb activities were much higher adjacent to the causeway structure, especially at the East part of Johor Strait. The level of ^{210}Pb in mussel's tissue and sediment also increased with decreasing level of dissolved oxygen.

Interpretation: A causeway structure disrupted the water quality of Johor Straits and caused almost hypoxic conditions nearby. The coverage of oxygen depletion expanded during inter-monsoon. An inverse relationship between ^{210}Pb activities and dissolved oxygen prove that deficiency of dissolved oxygen potentially influenced the bioaccumulation of ^{210}Pb in mussels to correspond to the build-up of concentration factor in their tissues which exceeded the recommended value.

Key words: Dissolved oxygen, Hypoxic, Organic matter, ^{210}Pb, *Perna viridis*



How to cite : Saili, N.A.B. and C.A.R. Mohamed: Effect of dissolved oxygen deficiency on ^{210}Pb content in mussel's tissues at the Johor Strait, Malaysia. *J. Environ. Biol.*, **42**, 782-788 (2021).

Introduction

Marine environment is threatened due to unseen decrease in dissolved oxygen levels. The "dead zones" also known as hypoxia which refer to reduced level of oxygen in the water. The hypoxic zone can develop naturally and created by human activity (Rabalais *et al.,* 1999). The hypoxic zone occurs when the level of dissolved oxygen reduces below 2 mg l^{-1}, meanwhile, the anoxic zone is referred to the absence of dissolved oxygen (Diaz and Rosenberg, 2008). Usually, the hypoxic condition is associated with semi-enclosed water with limited water movement which can cause mass mortality (Breitburg, 2002, Yang *et al*., 2019). The concern arises through current findings on radionuclide binding capacity in anoxic and hypoxic sediment as well as effect of radiotoxic on the environment (Connan *et al*., 2009; Jessen *et al*., 2017).

Lead-210 (^{210}Pb) is a well known reactive radionuclide and limited studies have been conducted on ^{210}Pb, especially on the radiological risk to aquatic organisms. In anoxic sediments, about 5 to 33% of ^{210}Pb is bound to organic matter (Connan*et al*., 2009), meanwhile it is much higher in hypoxic conditions which are more than 50% of organic matter preserved in surface sediments (Jessen *et al*., 2017). High accumulations of ^{210}Pb in hypoxic sediment has triggered a question on the bioavailability of this radionuclide in the aquatic environment under depleted dissolved oxygen level, especially in shallow water regions. Furthermore, hypoxia is a common stressor in high impact environment where green mussels (*Perna viridis*) have been reported to be hypoxic tolerant (Cheung, 1993; Holmes *et al*., 1999; Wendling *et al*., 2013; Huhn*et al*., 2017).

According to Salbu (2009), long term exposure might influence the transfer of radionuclides within a contaminated ecosystem such as weathering processes and remobilization of associated particle reactive radionuclides. Changes in water quality can alter the chemical speciation of waterborne elements, affecting their bioavailability and, consequently, their bioaccumulation in marine organisms. Belivermis *et al*. (2020) reported high level of Pb in the soft tissues of mussels maintained at lower pH conditions using ^{210}Pb radiotracer. Hypoxia exert additive effects of acidification on the physiological energetics of mussels (Gu *et al*., 2019). Most studies on ^{210}Pb content in mussel have been conducted in the temperate regions (Ugur*et al*., 2002; Carvalho *et al*., 2010; Rozmaric *et al*., 2012). Therefore, it is important to study the bioavailability of ^{210}Pb in the mussels and the effect of dissolved oxygen deficiency in the shallow tropical water region.

There is no single study on ^{210}Pb in mussels related to deficiency of oxygen. Therefore, taking into account the behavior of ^{210}Pb which has affinity to particles (Wang *et al.* 2019), it is potentially transported from the surface sediment to water column by shear stress (Kumar Maity and Maiti, 2018). Meanwhile, the mussels in water column are highly tolerant to hypoxia (Huhn *et al*., 2017). In temperate regions, mussels exposed to low oxygen (9 to 2 mg l^{-1}) respond slow due to significant reduction in the respiration rate, while the filtration remains high and constant (Tang and Riisgard, 2018).

Johor Strait is an important waterway for global trades and is the largest source of green mussels' production in Malaysia (DOF, 2018). Unfortunately, the causeway structure separate the water body and limit the water exchange with open water (Wood *et al*., 1997). Dissolved oxygen stimulation and hypoxia prediction indicate that bottom dissolved oxygen decrease during the neap tide (Ismail *et al*., 2016). Therefore, the Johor Strait was selected as a study area to understand the effect of oxygen deficiency on the content of ^{210}Pb in green mussels that might contribute new data base for tropical region under deficiency of DO. Hence, this study was conducted to investigate the relationship of dissolved oxygen on the content of ^{210}Pb in mussels.

Materials and Methods

Study site : Nine stations were selected at the mussel's cages along the Straits. Station 1 to Station 3 were located at the West part of Johor Strait (WJS), meanwhile Station 4 to Station 9 were located at the East part of Johor Strait (EJS). The distance of WJS: EJS from the causeway was 31.86 km: 47.34 km towards open water of the Singapore Strait. According to PHN (2017), the Johor Strait is under semi-diurnal influence. EJS is more longer and narrower than WJS. Consequently, limited water flow due to the causeway structure potentially accumulates higher pollutant at EJS.

Seawater analysis: Water quality parameters such as pH, temperature, dissolved oxygen (DO) were measured *in-situ* at 1 m depth with a calibrated YSI water probe (Professional Plus) in the mussel cages. Chlorophyll-a were extracted from 1 l of seawater in accordance to SCOR Unesco (1980) and the concentration was determined with UV-spectrophotometer (Thermo Scientific Spectronic 20+). Meanwhile, ^{210}Pb content in seawater samples was estimated accordingly to ASTM D7535: 2009: R2015, where 20 l of filtered seawater was acidified with HNO_3, spiked with weighted $Pb(NO_3)_2$ aliquots (20 mg ml^{-1}) as yield monitor and allowed to equilibrate overnight (ASTM, 2015a).

Mussel analyses: Mussels were collected with hand and cleaned before soft tissues were detached from the shell. The gonad maturation was evaluated visually based on > 50% gonad cover. About 20 to 40 soft tissue samples were pooled and dried at 60°C in an oven until constant weight was obtained. Soft tissue samples were homogenized and approximately 0.3 g of tissue from pooled samples were digested with HNO_3 and H_2O_2 for 3 hr until a clear solution was obtained. The solution was filtered and dried before dissolving in 0.5 M HNO_3(ASTM, 2016).

Sediment analyses: The sediments collected were dried in oven at 105°C until constant weight was obtained and sieved through 63 µm mesh. The organic matter percentage was determined by weight loss on ignition after combustion at 550°C for 4 hrs (Heiri *et al*., 2001). Meanwhile, ^{210}Pb analysis in sediment were prepared in accordance with ASTM D3976-92 where 0.3 g of the sediment powder was acid digested in concentrated HNO_3, HCl, $HClO_4$and HF (3:2:2:1 v/v ratio) in Teflon beaker for total digestion (ASTM, 2015b).

Extraction of ^{210}Pb : ^{210}Pb present in seawater, mussels, and sediments were extracted by separation techniques as described by Narita *et al.* (1989). Finally, the ^{210}Pb content was estimated by Gross Alpha-beta Counter (Tennelec Model Series 5 XLB low background gas-flowing anti-coincidence alpha-beta counter) incorporated with Eclipse software after an equilibrium with ^{210}Bi. The counting efficiency and the minimum detectable activity of Gross Alpha-Beta counter was 43% and 0.01 Bq, respectively.

Concentration factor: In order to evaluate ^{210}Pb uptake by the mussels from water, concentration factor (CF) was calculated (IAEA, 2001).

$$\text{CF (l kg}^{-1}) = \frac{\text{Concentration per unit mass of the organism (Bq kg}^{-1})}{\text{Concentration per unit volume of seawater (Bq l}^{-1})}$$

Quality control: Analytical quality control for ^{210}Pb extraction from mussels and sediment were applied to Certified Reference Material (CRM) IAEA-437 and CRM IAEA-385 with an average recovery yield of 98% and 88%, respectively. Meanwhile, ^{210}Pb extraction from seawater was based on the weighted $Pb(NO_3)_2$ aliquots as internal yield with an average recovery of 84%.

Statistical analysis: Pearson's correlation coefficient (r) was calculated to assess the strength and direction of linear relationship between two continuous variables by SPSS Statistic Version 16 (Allen *et al*., 2014). Pearson's correlation can be either positive or negative and ranged from -1 to +1. The relationship was considered statistically significant at $p < 0.05$.

Results and Discussion

The concentration of dissolved oxygen along the Johor Strait ranged from 1.6 to 7.7 mg l^{-1} (Table 1) which decreased adjacent to the causeway structure. The lowest dissolved oxygen was recorded at Station 4 in the East part of Johor Strait (EJS). The coverage of hypoxic conditions was located near the causeway structure at both sides of West and East parts of Johor Straits, especially during inter-monsoon. Suhaila *et al*. (2010) reported that inter-monsoon period is dry as compared to the North-east and South-west monsoon. Low precipitation limited the water flow and water qualities at the causeway structure deteriorated significantly (Gin *et al*., 2000; Choi *et al*., 2012; Lim *et al*. 2013).

Meanwhile, the highest dissolved oxygen occurred at the WJS (Station 3) during the North-east monsoon. The North-east monsoon carried more precipitation and contributed to high river flow which consisted of well-oxygenated water in the Johor Strait (Bahera *et al*., 2013). Besides that, turbulence and vertical mixing deliver oxygen-rich water resulted due to strong wind during monsoon as well as daily high tide (Vanchon*et al*., 2010). Furthermore, a high dissolved oxygen level might be due to photosynthetic activitiesof algae growth (Wallace *et al*., 2016). The highest concentration (30.8 µg l^{-1}) of chlorophyll-a also occurred at Station 3 (Table 1).

Based on the previous compilation, the means of dissolved oxygen concentration at WJS were 2.75 mg l^{-1}, 5.57 mg l^{-1}, and 3.73 mg l^{-1}during the year 1991, 2006 and 2009, respectively (Hadibrata *et al*., 2012). Meanwhile, the dissolved oxygen at the EJS ranged from 3.2 to 4.4 mg l^{-1}(Othman *et al*., 2015). The present study revealed that the level of dissolved oxygen decreased significantly, especially at EJS creating to hypoxic conditions. In general, about 74% of dissolved oxygen coverage along the Johor Strait satisfied the requirement of Class III (dissolved oxygen = 3 to 5 mg l^{-1}) of the Interim National Water Quality Standard for Malaysia, where only tolerant species survive (DOE, 2006), except for Station 4 to Station 7, especially during inter-monsoon which was classified as polluted (Class IV; dissolved oxygen = <3 mg l^{-1}).

^{210}Pb activity concentrations in mussels and seawater varied from 11.9 to 41.1 Bq kg^{-1} (d.w) and 2.8 to 5.3 mBq l^{-1}, respectively (Table 2). The ^{210}Pb the content in mussels was slightly higher than Adriatic Coast (Rozmaric *et al*., 2012) but still lower than ^{210}Pb in mussels at the Turkish Coast (Ugur *et al*., 2002) and Costa da Caparica beach, Portugal (Carvalho *et al*., 2010). High ^{210}Pb activities in mussels were established during inter-monsoon and low level in seawater. Pearson's correlation revealed a significant inversed relationship between ^{210}Pb content in mussels and seawater (r=-0.573, N=23, p=0.004). Meanwhile, ^{210}Pb activities and organic matter in sediment ranged from 36.5 to 139.9 Bq kg^{-1} and 6.2 to 19.6%, respectively. ^{210}Pb increased relatively with the organic matter content in sediments at 95% confident level (r=0.437, N=27, p=0.023). Our findings showed similar trend with Venunathan *et al*., (2016) where ^{210}Pb increase was in proportion to organic matter in sediments.

Normally, high pollutant in mussels represents high pollution in the environment. However, this inverse relationship between mussels and seawater (dissolved phase) contradict the nature of these filter feeder organisms. Additional insight of this inverse relationship is potentially related to ^{210}Pb behavior which has an affinity to particles. The removal of ^{210}Pb from the water column is accomplished by aggregation of colloidal material and adsorption onto particulate matter (Smoak *et al*., 1996). Meanwhile, the causeway structure limited the water flow and contributed to the accumulation of non-point sources as a result of ^{210}Pb movement through river runoff, reclamation, fuel burning

Table 1 : Water parameter such as depth, salinity, pH temperature (Temp), dissolved oxygen (DO) and chlorophyll-a (Chl-a) in seawater and organic matter in sediment (OM_{Sed}) at different time of sampling and stations

	Stations		Depth (m)	Salinity (ppt)	pH	Temp (ºC)	DO (mg l^{-1})	Chl-a (µg l^{-1})	OM_{Sed} (%)
29th to 30th Nov 2017	WJS	1	10.13	27	8.27	29.90	7.32	21.99	7
		2	6.33	20	8.05	29.80	5.39	25.69	10.2
		3	8.33	20	8.15	29.80	7.66	30.81	7.9
	EJS	4	11.67	25	7.91	29.80	2.14	16.46	6.2
		5	11.47	24	7.80	29.50	2.16	2.03	17.9
		6	11.07	24	7.93	29.60	3.75	10.49	17.7
		7	15.67	24	7.95	29.60	3.65	3.12	15.3
		8	10.10	24	8.23	29.10	6.02	16.73	13.3
		9	6.70	24	8.15	29.10	5.96	8.21	11.6
28th to 29th Mar 2018	WJS	1	9.70	24	7.98	29.30	4.75	0.53	9.4
		2	3.53	20	7.81	29.30	2.78	2.41	11.1
		3	4.07	20	7.73	29.90	2.13	0.82	12
	EJS	4	9.97	17	7.81	29.90	2.10	14.91	19.6
		5	15.00	21	7.83	29.90	2.10	4.98	15.8
		6	15.70	22	7.92	29.50	2.69	6.82	13.5
		7	16.50	20	7.97	29.40	2.96	1.47	13.3
		8	6.93	25	8.13	29.10	5.05	11.73	14.6
		9	7.53	25	8.11	29.10	6.26	10.20	12.1
1st to 2nd Aug 2018	WJS	1	9.40	22	7.24	29.40	4.61	4.57	5.6
		2	4.50	21	7.28	29.70	3.55	11.30	8.2
		3	4.70	20	7.89	29.70	3.13	11.13	11.3
	EJS	4	5.40	17	7.74	30.00	1.63	4.58	15.4
		5	15.30	20	8.00	30.20	4.17	15.05	17.5
		6	16.70	20	8.01	30.00	3.29	5.43	15.2
		7	15.40	20	8.02	29.90	4.01	5.06	13.5
		8	8.70	20	8.07	29.40	4.52	1.68	12.9
		9	5.90	20	8.09	29.30	4.64	0.59	12.8

from industrial and shipping activities before being scavenged to the surface of sediment.

Therefore, a similar trend of ^{210}Pb content in mussels and sediment was considered due to mixing of water column with the daily tidal changes at the shallow water region which caused sediment resuspension (Sun *et al.*, 2017). The sediment resuspension from the Johor Strait bottom occurred due to higher bed shear stress by strong turbulence during spring tides (Behera *et al.*, 2013). Consequently, ^{210}Pb from the surface sediment is suspended into the water column and filtered by the mussels where they feed on the suspended matter and micro free-floating plankton from water bypassing the water over their gills. Fig. 1 illustrates the occurrence and cycling of ^{210}Pb activities in the Johor Strait.

^{210}Pb is a non-essential element for mussels. However, the hypoxic bottom water condition potentially preserves the organic matter in surface sediment which is highly bound to ^{210}Pb (Jessen *et al.*, 2017). The significant correlation between ^{210}Pb and organic matter in surface sediment (r=0.437, N=27, p=0.023) concurrently with significant inversed relationship between dissolved oxygen and ^{210}Pb (r=0.589, N=27, p=0.001) as well as organic matter (r=0.432, N=27, p=0.025) proved that the co-occurrence of ^{210}Pb and organic matter were expected to be associated to depleting level of dissolved oxygen. Thus, ^{210}Pb might be released from the sediment *via* resuspension and, subsequently ingested by the mussels (Sun *et al.*, 2017; Behera *et al.*, 2013).

Although, the mussels are susceptible to hypoxic conditions (Huhn*et al.*, 2017), they have selective ingestion behaviour. In fact, some species are able to select living particles from non-living detritus (Ward *et al.*, 1997). The ^{210}Pb concentration factor ranged from 10^3 to 10^4, which exceeded the permissible limit of, $1x10^3 l\ kg^{-1}$ (IAEA, 2001). High CF values were observed during inter-monsoon with a mean of $8.6{\times}10^3 l\ kg^{-1}$.

Table 3: Distribution of ^{210}Pb activity concentrations in mussels, seawater and sediment at different stations and sampling period

	Stations		$^{210}Pb_{Sediment}$ (Bq kg^{-1})	$^{210}Pb_{mussel}$ (Bq kg^{-1})	$^{210}Pb_{seawater}$ (mBq l^{-1})
29th-30th Nov 2017	WJS	1	62.5 ± 1.8	11.9 ± 5.6	4.6 ± 2.0
		2	65.9 ± 1.9	11.9 ± 3.1	4.6 ± 1.6
		3	36.5 ± 2.0	13.9 ± 2.5	3.7 ± 1.8
	EJS	4	124.2 ± 2.8	-	3.5 ± 1.3
		5	139.9 ± 4.3	-	4.1 ± 1.7
		6	80.0 ± 1.9	16.8 ± 2.8	5.1 ± 2.3
		7	92.8 ± 1.8	-	5.3 ± 2.4
		8	73.8 ± 3.1	13.6 ± 4.0	5.3 ± 2.3
		9	74.9 ± 3.4	14.9 ± 0.4	4.8 ± 1.9
28th-29th March 2018	WJS	1	36.9 ± 1.0	24.1 ± 6.8	3.5 ± 1.2
		2	53.9 ± 1.5	22.8 ± 12.0	3.8 ± 1.7
		3	61.0 ± 1.5	21.9 ± 5.3	2.8 ± 1.2
	EJS	4	98.2 ± 1.8	31.0 ± 8.3	4.0 ± 1.6
		5	113.8 ± 1.8	32.8 ± 5.1	3.7 ± 1.4
		6	99.7 ± 1.4	36.5 ± 19.0	3.1 ± 1.4
		7	81.9 ± 1.4	41.1 ± 15.3	3.5 ± 1.6
		8	63.1 ± 1.4	29.3 ± 7.6	3.1 ± 1.3
		9	71.0 ± 1.3	24.6 ± 5.8	3.7 ± 1.6
1st-2nd Aug 2018	WJS	1	53.1 ± 1.0	13.0 ± 0.7	5.0 ± 2.3
		2	77.6 ± 1.6	17.9 ± 9.9	3.8 ± 1.7
		3	69.6 ± 1.4	19.6 ± 13.8	3.9 ± 1.6
	EJS	4	78.1 ± 1.3	-	3.3 ± 1.4
		5	79.0 ± 1.2	18.7 ± 9.0	3.8 ± 1.7
		6	83.1 ± 1.5	18.2 ± 3.4	3.4 ± 1.6
		7	60.9 ± 1.1	19.9 ± 6.2	5.3 ± 2.8
		8	72.3 ± 1.5	13.2 ± 8.4	5.2 ± 2.1
		9	46.5 ± 1.4	14.6 ± 4.4	3.4 ± 1.7

*November 2017 – Mussel cages at Station 4, 5 and 7, the line were covered by unidentified mussels which believed as an invasive species; *August 2018 – Mussel cages at Station 4 have been removed due to reclamations activities.

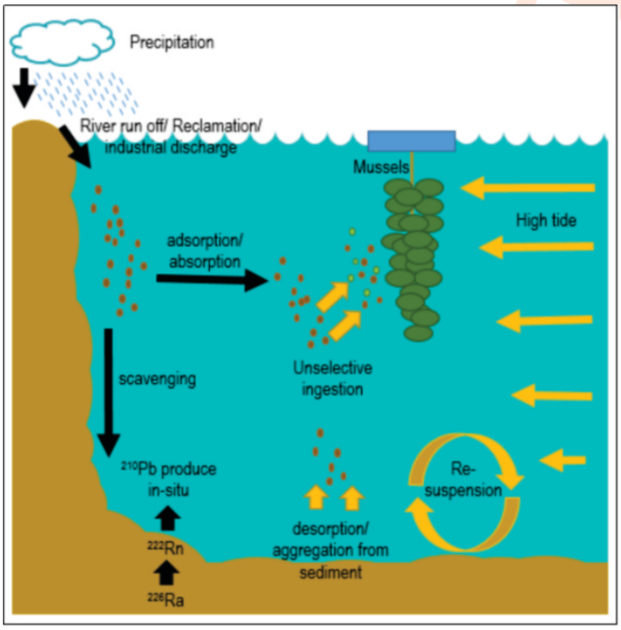


Fig. 1 : Occurrence and cycling of ^{210}Pb in the environment.

It is presumed that high CF during inter-monsoon might be related to the feeding behavior of mussels at crucial stages. According to Lopes-Lima *et al.* (2014), the selective ingestion behaviour of *Perna viridis* was significantly higher during gametogenesis and growth stages. However, *Perna viridis* appeared to be less selective and consumed all the available food after spawning to restore their energy. This study demonstrated that the lowest gonad development in mussels occurred during inter-monsoon (end of March 2018), where only 21% out of 394 mussels were covered by gonad. According to Tan and Ransangan (2016), no selective ingestion was observed by *Perna viridis* during the the lowest gonad development stages in Marudu Bay, especially in March and April, where less than 25% of population covered by gonad.

Pearson's correlation demonstrated a significant inverse relationship at 99% confidence level between ^{210}Pb content in mussel and dissolved oxygen (r=0.587, N=23, p=0.003), which proved that the deficiency of dissolved oxygen influenced bioaccumulation of ^{210}Pb by mussels. The hypoxic event at the bottom water contributes to high preservation of organic matter in surface sediment, which is highly bound to ^{210}Pb. The vertical mixing water column causes resuspension at the seabed as well as reclamation, river runoff, and industrial discharge significantly contribute ^{210}Pb into the water column. At the same time, the mussels probably at critical stage restore their energy by unselectively ingestion. A long exposure during this period subsequently corresponded to the build-up of ^{210}Pb concentration in their tissues.

Oxygen deficiency due to limited water flow potentially influenced the bioavailability of ^{210}Pb in mussels. The concurrent event obviously during inter-monsoon were reduced dissolved oxygen level contribute to increased ^{210}Pb content in sediments vertical water mixing of shallow Johor Strait contribute to suspension of ^{210}Pb in the water column, and the unselective ingestion during crucial stages contribute to high particle reactive ^{210}Pb in mussels, subsequently corresponding to high concentration factor. The study on ^{210}Pb activity in mussels is important, especially at potential hypoxic region. The bioavailbility of ^{210}Pb from mussels can be transferred to humans through consumption of seafood. Therefore, an assessment of ^{210}Pb dose to human population is highly recommended in the future for food safety.

Acknowledgment

This research is supported by ST-2017-001 and DPK-2017-010 grants. Besides, the authors would like to thank all the members of Land-Atmospheric-Ocean Interaction Research (LAOI) of Faculty of Science and Technology, Universiti Kebangsaan Malaysia for their help during sampling and samples analysis.

Add-on Information

Authors' contribution : N.A.B. Saili: Laboratory work and experimental, data analysis and manuscript writing; **C.A.R. Mohamed:** Idea of the research, experimental design.

Research content : The research content of manuscript is original and has not been published elsewhere.

Ethical approval : Not Applicable

Conflict of interest : The authors declare that there is no conflict of interest.

Data from other sources : Not Applicable

Consent to publish : All authors agree to publish the paper in Journal of Environmental Biology.

References

Allen, P., K. Bennett and B. Heritage: SPSS Statistics Version 22: A Practical Guide. 3rd Edn., Cengage Learning Australia, Australia, pp. 328 (2014).

ASTM D7535: 2009: R2015: Standard Test Method for Lead-210 in Water. American Society for Testing and Materials, SAI Global Standard Legislation, Sydney, Australia (2015a).

ASTM D3976-92 2015: Standard Practice for Preparation of Sediment Samples for Chemical Analysis, ASTM International, West Conshohocken, PA (2015b).

ASTM D4638-16: Standard Guide for Preparation of Biological Samples for Inorganic Chemical Analysis, ASTM International, West Conshohocken, PA (2016).

Bahera, M.R., C. Chun, S. Palani and P. Tkalich: Temporal variability and climatology of hydrodynamic, water property and water quality parameters in the West Johor Strait of Singapore. *Mar. Pollut. Bull.*, **77**, 380-395 (2013).

Belivermis, M., M. Besson, P.W. Swarzenski, F. Oberhansli, A. Taylor and M. Metian: Influence of pH on Pb accumulation in the blue mussel, *Mytilus edulis*. *Mar. Pollut. Bull.*, **156**, 111203 (2020).

Breitburg, D.: Effect of hypoxia and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries*, **25**, 767-781 (2002).

Carvalho, F.P., M.O. Joao, G. Alberto and J.V. Battle: Allometric relationships of ^{210}Po and ^{210}Pb and their application to environmental monitoring. *Mar. Poll. Bull.,* **60**, 1734-1742 (2010).

Cheung, S.G.: Population dynamics and energy budgets of green-lipped mussel *Perna viridis* (Linnaeus) in a polluted harbour. *J. Exp. Mar. Biol. Ecol.*, **168**, 1-24 (1993).

Choi, K.H., Y.O. Kim, J.B. Lee, S.Y. Wang, M.W. Lee, P.G. Lee, D.S. Ahn, J.S. Hong and H.Y. Song: Thermal impacts of coal power plant on the plankton in an open coastal water environment. *J. Mar. Sci. Technol.*, **20**, 187-194 (2012).

Connan, O., D. Boust, G. Billon, L. Solier, M. Rozet and S. Bouderbala: Solid partitioning and solid-liquid distribution of ^{210}Po and ^{210}Pb in marine anoxic sediments: Roads of Cherbourg at the Northern France. *J. Environ. Radioact.*, **100**, 905-913 (2009).

Diaz, R.J. and R. Rosenberg: Spreading deadzones and consequences for marineecosystems. *Science*, **321**, 926 (2008).

DOE: Development of water quality criteria standard of Malaysia Department of Environment Malaysia, Malaysia (2006).

DOF: Annual Fisheries Statistic. Vol. 1, Department of Fisheries Malaysia, Malaysia (2018).

Gin, K.Y.H., X. Lin and S. Zhang: Dynamics and size structure of phytoplankton in the coastal waters of Singapore. *J. Plankton Res.,* **22**, 1465-1484 (2000).

Gu, H., Y. Shang, J. Clements, S. Dupont, T. Wang, S. Wei, X. Wang, J. Chen, W. Huang, M. Hu and Y. Wang: Hypoxia aggravates the effects of ocean acidification on the physiological energetics of the blue mussel *Mytilus edulis*. *Mar. Pollut. Bull.*, **149**, 110538 (2019).

Hadibrata, T., F. Abdullah, A.R.M. Yusoff, R. Ismail, S. Azman and N. Adnan: Correlation study between land use, water quality and heavy metals (Cd, Pb and Zn) content in water and green lipped mussel *Pernaviridis* (Linnaeus.) at the Johor Strait. *Water Air Soil Pollut.*, **223**, 3125-3136 (2012).

Heiri, O., A.F. Lotter and G. Lemcke: Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *J. Paleolimnol.*, **25**, 101-110 (2001).

Holmes, M.J., S.L.M. Teo, F.C. Lee and H.W. Khoo: Persistent low concentrations of diarrhetic shellfish toxins in green mussels *Perna viridis* from the Johor Strait, Singapore: First record of diarrhetic shellfish toxins from South-east Asia. *Mar. Ecol. Prog. Ser.*, **181**, 257-268 (1999).

Huhn, M., N.P. Zamani and M. Lenz: Tolerance to hypoxia in Asian green mussels, *Pernaviridis*, collected from ship hull in the non-native range in eastern Indonesia. *Manag. Biol. Invasion*, **8**, 227-233 (2017).

IAEA: Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment, Safety Reports Series No. 19. IAEA, Vienna (2001).

Ismail, M., N.N. Hashim and Z. Kazemi: Estimating dissolved oxygen depletion in inner Western Johor Strait, Malaysia using a three dimensional water quality model. *MJCE*, **28**, 240-251 (2016).

Jessen, G.L., A. Lichtschlag, A. Ramette, S. Pantoja, P.E. Rossel, C.J. Schubert, U. Struck and A. Boetius: Hypoxia causes preservation of labile organic matter and changes seafloor microbial community composition (Black Sea). *Sci. Adv.*, **3**, 1-14 (2017).

Kumar Maity S. and R. Maiti: Available and aritical shear stress for sediment entrainment. In: Sedimentation in the Rupnarayan River. Springer Briefs in Earth Sciences. Springer, Cham (2018).

Lim, P.T., G. Usup and C.P. Leaw: Harmful algal blooms in Malaysian waters. *Sains Malays.*, **41**, 1509-1515 (2013).

Lopes-Lima, M., P. Lima, M. Hinzmann and A. Rocha: Selective feeding by *Anodonta cygnea* (Linnaeus, 1771): The effect of seasonal changes and nutritional demands. *Limnologica*, **44**, 18-22 (2014).

Narita, H., K., Harada, W. Burnett, S. Tsunogai and W.J. McCabe: Determination of ^{210}Pb, ^{210}Bi and ^{210}Po in natural waters and other materias by electrochemical separation. *Talanta,* **36**, 925-929 (1989).

Rabalais, N.N., R.E. Turner, J.D. Justic, Q. Dortch, J. William and Jr. Wiseman: Characterization of Hypoxia: Topic 1 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico. NOAA Coastal Ocean Program Decision Analysis Series No. 15. NOAA Coastal Ocean Program, Silver Spring, MD. 167 pp (1999).

Othman, Z., M.A. Wahid, W.K. Lee and Z.D. Mohamed Basri: Water quality observation on Johor River Estuary and East Tebrau Strait, Malaysia. *J. Teknol.*, **72**, 1-4 (2015).

PHN: Jadual Pasang Surut Malaysia-Singapura 2017, Jilid 1. Pusat Hidrografi Nasional, Malaysia (2017).

Rozmaric, M., M. Rogic., L. Benedic, M. Strok, D. Barisic and A.G. Ivsic: ^{210}Po and ^{210}Pb activity concentration in *Mytilus galloprovincialis* from Croatian Adriatic coast with the related dose assessment to the coastal, population. *Chemosphere*, **87**, 1295-1300 (2012).

Salbu, B.: Challenges in radioecology. *J. Environ. Radioact.*, **100**, 1086-1091 (2009).

SCOR Unesco: Determination of chlorophyll in seawater. Unesco Technical Papers in Marine Science 35, Division of Marine Sciences, Unesco, Paris, France (1980).

Smoak, J.M., D.J. DeMaster, S.A. Kuehl, R.H. Pope and B.A. McKee: The behavior of particle-reactive tracers in a high turbidity environment: ^{234}Th and ^{210}Pb on the Amazon continental shelf. *Geochim. Cosmochim. Acta*, **60**, 2123-2137 (1996).

Suhaila, J., S. Mohd Deni, W.Z. Wan Zin and A.A. Jemain: Trends in Peninsular Malaysia rainfall data during the Southwest monsoon and Northeast monsoon seasons: 1975-2004. *Sains Malays.*, **39**, 533-542 (2010).

Sun, Y., E. Eltahir and P. Malanotte-Rizzoli: The bottom water exchange between the Singapore Strait and the West Johor Strait. *Cont. Shelf Res.*, **145**, 32-42 (2017).

Tan, K.S. and J. Ransangan: Feeding behaviour of green mussels, *Pernaviridis* farmed in Marudu Bay, Malaysia. *Aquac. Res.*, **48**, 1-16 (2016).

Tang, B. and H.U. Riisgard: Relationship between oxygen concentration, respiration and filtration rate in blue mussels Mytilus edulis. *J. Ocean. Limnol.* **36**, 395-404 (2018).

Ugur, A., Y. Gungor and A. Bassari: Trace metals and ^{210}Po (^{210}Pb) concentrations in mussels (*Mytilus galloprovincialis*) consumed in Western Anatolia. *Appl. Radiact. Isot.,* **57**, 565-571 (2002).

Vanchon, D., Y.T. Prairie and J.J. Cole: The relationship between near-surface turbulence and gas transfer velocity in freshwater systems and its implications for floating chamber measurements of gas exchange. *Limnol. Oceanogr.*, **55**, 1723-1732 (2010).

Venunathan, N. and Y. Narayana: Activity of ^{210}Po and ^{210}Pb in the riverine environs of coastal Kerala on the Southwest coast of India. *J. Radiat. Res. Appl. Sci.*, **9**, 392-399 (2016).

Wallace, J., P. Champagne and G. Hall: Time series relationships between chlorophyll-a, dissolved oxygen, and pH in three facultative wastewater stabilization ponds. *Environ. Sci. Water. Res. Technol.*, **2**, 1032-1040 (2016).

Wang, J., Q. Zhong, M. Baskaran and J. Du: Investigations on the time-series partitioning of ^{210}Pb , ^{207}Bi and ^{210}Po between marine particles and solution under different salinitsy and pH conditions. *Chem. Geol.*, **528**, 119275 (2019).

Ward, J.E., J.S. Levinton, S.E. Shumway and T. Cucci: Site of particle selection in a bivalve mollusk. *Nature*, **390**, 131-132 (1997).

Wendling, C., M. Huhn, N. Ayu, R. Bachtiar, K. von Juterzenka and M. Lenz: Habitat degradation correlates with tolerance to climate-change related stressors in the green mussel *Perna viridis* from West Java, Indonesia. *Mar. Pollut. Bull.*, **71**, 222-229, (2013).

Wood, A.K., Z. Ahmad, N.A.M. Shazili, R. Yaakob and R. Carpenter: Geochemistry of sediments in Johor Strait between Malaysia and Singapore. *Cont. Shelf Res.*, **17**, 1207-1228 (1997).

Yang, L., C. Linlin, L. Xiaojing, Z. Zhengquan, L. Bo, S. Bo, L. Bingjun and L. Baoquan: Effect of seasonal hypoxia on macrobenthic communities in the Muping Marine Ranch, Yantai, China. *Biodiver. Sci.*, **27**, 200-210 (2019).