Marine Pollution Bulletin 175 (2022) 113363

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Mercury content and consumption risk of 8 species threadfin bream (*Nemipterus* spp.) caught along the Gulf of Thailand

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ARTICLE INFO

Keywords:
Mercury
Threadfin bream
Nemipterus spp.
Consumption risk
Gulf of Thailand

ABSTRACT

Total mercury (T-Hg) was examined in 8 threadfin bream species (*Nemipterus* spp.) caught in the Gulf of Thailand (GoT). The T-Hg contents ranged from 11.3 to 374 μg kg^{-1} wet weight, with the lowest in *Nemipterus peronii* and the highest in *Nemipterus nemurus* and *Nemipterus tambuloides*. Accumulation of T-Hg in fish tissue was found to be related to fish size, trophic levels, feeding habits and habitat. Threadfin bream caught in the upper GoT exhibited significantly ($p < 0.05$) lower T-Hg than those in the middle and lower parts of GoT, which possibly due to local mercury sources e.g., internal anthropogenic activities in the GoT and external from terrestrial input via river discharge. The estimated daily intakes were ranged from 0.03 to 0.07 μg kg^{-1} bodyweight day^{-1}. All threadfin breams in the GoT have HQ <1. To prevent the associated potential risk, the maximum safe daily consumption is recommended at 95.3 g day^{-1}.

1. Introduction

Threadfin breams (*Nemipterus* spp.) are marine fish that usually live in the tropical and subtropical Indo-pacific areas with warm temperatures (Russel, 1993). It is one of the most caught fish species for both local consumption (Pangsorn et al., 2007) and export products, such as surimi (Siriraksophon et al., 2009). In Southeast Asian countries, the surimi production accounted for 347,000 metric ton in 2005, and Thailand was listed as the top production country, followed by Malaysia and Vietnam with the export amount of 150,000, 100,000 and 84,000 metric tons, respectively (Siriraksophon et al., 2009). Threadfin bream is popularly consumed as it contains various nutrients such as amino acids, protein, fat, carbohydrates, minerals, vitamins, and selenium, an antioxidant beneficial for human health (Siong et al., 1987; Wiriyaphan et al., 2012; Tilami and Sampels, 2018). However, they may contain some toxic substances such as mercury (Hg) which is absorbed from the environment and linked to several diseases in humans e.g., neurological, renal, genetic and epigenetic outcomes, cardiovascular, and reproductive outcomes (Kim et al., 2016).

Threadfin breams are often used as an indicator species for monitoring the change of mercury in the environment (Agusa et al., 2007; Saei-Dehkordi et al., 2010; Ahmad et al., 2015). This is because they are demersal carnivores and non-migratory fish that feed on benthic animals thus, allowing threadfin breams to be exposed to and accumulate local pollutants in their bodies (Ahmad et al., 2015; Anual et al., 2018; Mithun et al., 2018). In the environment, mercury is a naturally occurring element found in Earth's crust, atmospheric and volcanos (Driscoll et al., 2013). Additional mercury in the Gulf of Thailand (GoT) is originated from various anthropogenic activities, both internal and external sources. Those activities include deforestation, coastal erosion, and untreated domestic waste (Cheevaporn and Menasveta, 2003; Worakhunpiset, 2018), untreated wastewater from industrial estate and petrochemical complex (Thongra-ar et al., 2008; Tremlová, 2017), oil and gas exploration in the GoT (Yod-In-Lom and Doyle, 2002; Pojtanabuntoeng et al., 2011; Rattanasriampaipong, 2016; Sompongchaiyakul et al., 2019), Coal-fired power plant (Thepanondh and Tunlathorntham, 2020), gold mining activities along Mekong river (Murphy et al., 2009) and irrigation runoff form the agricultural practice using Hg-containing pesticide along the Lower Mekong River Basin (Guédron et al., 2014).

In the aquatic system, dissolved mercury either in sediment or the water column can be transformed into methylmercury (MeHg) by anaerobic bacteria activity (Fuhrmann et al., 2021). MeHg accumulation

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https://doi.org/10.1016/j.marpolbul.2022.113363
Received 26 July 2021; Received in revised form 13 January 2022; Accepted 16 January 2022

in fish was observed with an increase in fish size and the trophic level (Anual et al., 2018; Liu et al., 2019). MeHg is taken up and accumulated in the low trophic organisms and fish. Later, it is thoroughly biomagnified to the higher trophic fish in the pelagic and benthic food webs (Liu et al., 2019). The high T-Hg level in muscle of demersal fish was observed especially in the high trophic fish (Ralston et al., 2019; Grgec et al., 2020). The Atlantic halibut, blue ling, common ling, common pandora, shark, swordfish, mako shark and tusk where the species contained T-Hg in muscle greater than the consumption allowance in standard guidelines (1 μg kg^{-1} for predatory fish) (USEPA, 2000; Ralston et al., 2019; Grgec et al., 2020).

Since threadfin bream is among the popular fish choices for Thai people, mercury biomagnification in the edible muscle from the surrounding environment is a concern. It is necessary to ensure that mercury levels should not exceed the edible allowance concentration (0.5 μg kg^{-1} for commonly fish and fishery products) in standard guidelines (USEPA, 2000) and exposure to mercury via fish does not pose any additional consumption risk. Although several studies reported mercury concentration in fish from the waters of Thailand (Cheevaparanapivat and Menasveta, 1979; Windom and Cranmer, 1998; Cheevaporn and Menasveta, 2003; Hantow et al., 2008; Worakhunpiset, 2018), there is only one report of mercury concentration in different threadfin bream species distribution in the GoT (Agusa et al., 2007). Thus, this study aims to: (1) determine the T-Hg concentration in 8 species of threadfin bream caught during the research survey in different sampling locations in the GoT; (2) evaluate the relationship between T-Hg in fish species with fish size and trophic levels and; (3) assess the risk associated with human dietary intake of T-Hg via threadfin bream consumption.

2. Materials and methods

2.1. Collecting sample and preparation

The collaborative research survey on marine fisheries resources and marine environment in the GoT was conducted during 17 August to 18 October 2018 on board M.V. SEAFDEC-2 (total length = 32.5 m and width = 7.2 m). In this survey, a total of 296 individual threadfin breams (*Nemipterus* spp.) were caught at 63 sampling stations using a bottom trawl net (9.09 to 19.49 m mouth width and 2 in. net mesh). The towing was conducted during daytime at towing speed and depth range between 1.5 and 1.9 m s^{-1} and 19.2–76.0 m, respectively. The haul period was controlled between 15 and 160 min. After hauling, harvested fish were species-separated by staffs from the Department of Fishery (DOF) for the fishery resources survey. Then, all fish were ready for sampling. To avoid contamination, each individual fish were randomly selected, double-wrapped and placed in double plastic zip-lock bags and kept frozen until transported back to laboratory. Until the analysis, samples were stored in the refrigerator at −20 °C.

Each fish sample was thawed at room temperature (±3 h), measured for morphometric information including length and weight, photographed and re-identified and checked with fish identification references (Ahmad et al., 2018; Froese and Pauly, 2019) for its feeding habit and trophic levels (Table S1). The fish was dissected in the laminar flow cabinet. Individually, white tissue was sectioned using ceramic knife and homogenized prior placing into the new zip-lock plastic bag. All homogenized samples were stored at −20 °C for further analysis. The knife was cleaned and rinsed with Milli-Q ultrapure water and 10% HNO_3 before the next use.

2.2. Reagent and glassware

Sub-boiling distillation set up to purify HNO_3 65% (Merck, Germany) for mercury analysis. Milli-Q ultrapure water (18.2 MΩ-cm) was prepared by Millipore Milli-Q lab water system (Merck Millipore, Tokyo, Japan). All glassware in this analysis was soaked in 10% (v/v) HNO_3 overnight, rinsed with Milli-Q ultrapure water, and dried on horizontal laminar airflow cabinet. Standard solution for T-Hg (1000 mg L^{-1}) from Sigma-Aldrich (Taufkirchen, Germany) were freshly prepared by diluting with 3% (w/v) HNO_3 to set up the standard curve ranging from 0.5 ng to 500 ng.

2.3. Mercury analyses

Total mercury (T-Hg) in fish tissue was analysed using the direct thermal decomposition, amalgamation, and atomic absorption spectrophotometry technique based on the USEPA method 7434 (USEPA, 1998), using a NIC® mercury analyzer model MA-3000 at the laboratory of Coax Group Corporation Ltd. Briefly, about ±100 mg of homogenate fresh tissue of known weight (weigh with Sartorius AX224, Sartorius group) was placed on a ceramic sampling boat, then, introduced into the analyzer. Sample was allowed to dry at 150 °C then, decomposed to elemental mercury (Hg^0) at controlled temperature (200–350 °C) under continuously oxygen flow (>90 purity). After that, Hg^0 vapor was trapped at the gold amalgamation unit, then heated to 850 °C. Hg^0 was then released and transferred to a detector and measured for its absorptivity at the wavelength (253.7 nm). The results of T-Hg concentrations were presented as μg kg^{-1} on a wet weight basis.

2.4. Quality control

Limit of detection (LOD) and limit of quantitation (LOQ) was determined from 3 and 10-times of standard deviation of blank analyses. The LOD and LOQ values for mercury analysis were reported at 0.0016 μg kg^{-1} and 0.0050 μg kg^{-1}, respectively. Blanks and certified reference materials (CRMs) namely DORM-4, TORT-3 and BCR-422 were performed in each batch of sample analysis. The percent recovery of CRMs resulted in between 86.9 and 94.2% (Table S2). These indicated that the applied methods for T-Hg analysis were in a satisfactory range with a good quality control. For the method precision, about 45% of the samples were analysed with the replication and the percent relative standard deviation (% RSD) reported for this applied method was not greater than 9% (n = 136).

2.5. Statistical analysis

All data were calculated using Microsoft Office Excel (2010) and IBM SPSS Statistics for Windows (Version 19.0. Armonk, New York: IBM Corp). Descriptive statistics were reported for the analysed values including average ± standard deviation and ranges. A non-parametric (Kruskal-Wallis) test was applied to this study after the results of a Shapiro-Wilk test showed a non-normal distribution data set. The Spearman correlation (r) test then was then used for the relationship study between T-Hg and fish size and trophic level. The significance was applied in all cases when $p < 0.05$.

2.6. Risk assessment

Fish consumption contributes to good nutrition and has health benefits. However, overconsumption may be linked to health risks resulting from the bioaccumulation of toxic substances like mercury. Several approaches can be applied to quantify and assess the potential risk of Hg for human health including, the estimation of the daily intake (EDI), hazard quotient (HQ), and maximum safe daily consumption (MSDC). To avoid overconsumption and risk exposure from threadfin breams in the adult population in Thailand, this study predicted the EDI, HQ, and MSDC values based on the equations from the U.S. Environmental Protection Agency (USEPA, 2000) below.

Estimated daily intake (EDI),

$$EDI = \frac{C_m \ x \ FIR \ x \ EF \ x \ ED}{BW \ x \ AT}$$

Risk of T-Hg exposure or hazard quotient (HQ),

$$HQ = \frac{EDI}{RfD}$$

Maximum safe daily consumption (MSDC),

$$MSDC = \frac{PTDI \ x \ BW}{C_m}$$

Where, Cm is a concentration of methylmercury (MeHg) in fish; calculated from 93% of T-Hg concentration (Windom and Cranmer, 1998; Anual et al., 2018). FIR or the daily ingestion rate is accounted for 0.086 kg person^{-1} day^{-1} for the Thai population (Needhan and Funge-Smith, 2015). EF is the exposure frequency (365 year^{-1}). ED; the exposure duration, calculated as the average lifetime between male and female at 72.05 years (Porapakkham et al., 2010). BW; the average body weight for adults (56 kg) in Thailand (Mathuramon et al., 2009). AT; the average time exposed for non-carcinogenic substances (365 days years^{-1} × 72.05 years). RfD; the oral reference dose, is equivalent to 0.1 μg kg^{-1} day^{-1} for MeHg. PTDI; the provisional tolerable daily intake for MeHg, is set by the Joint FAO/WHO Expert Committee on Food Additives (JEFCA, 2007) at value of 0.23 μg kg^{-1} bodyweight day^{-1}. HQ; Hazard quotient, a value less than one, indicates that no systemic effect is posed to human health in fish consumption population.

3. Results and discussion

3.1. The accumulation of T-Hg in threadfin breams

Total mercury (T-Hg) in 8 species of threadfin breams varied from 11.3 to 374 μg kg^{-1} wet weight with an average of 115 ± 71.1 μg kg^{-1} wet weight (Table 1). The average T-Hg accumulated in threadfin breams was in the following order; *Nemipterus nemurus* > *Nemipterus tambuloides* > *Nemipterus japonicus* > *Nemipterus hexodon* > *Nemipterus nematophorus* > *Nemipterus furcosus* > *Nemipterus marginatus* > *Nemipterus peronii* (Fig. 1). The Kruskal-Wallis test (Table S3) for 8 species of threadfin breams resulted in significant differences of T-Hg among species (Chi-Square = 35.2, $p < 0.0001$).

In this survey, threadfin breams contained lower T-Hg than some of the species reported in other (Table 1). T-Hg contents in *N. japonicus* (NJ), *N. marginatus* (NM), *N. nematophorus* (NO) and *N. peronii* (NP) were lower than observed in the upper Andaman Sea (Hantow et al., 2008), Persian Gulf (Saei-Dehkordi et al., 2010), Peninsular, Malaysia (Anual et al., 2018), and Bangkok markets, Thailand (Unpublished result). On the contrary, NJ in the GoT was exhibited higher T-Hg in comparing with the results in the Persian Gulf (Agah et al., 2007) and the Andaman Sea (Hantow et al., 2008). To compare with the dry weight results from Ahmad et al. (2015) study in the Peninsular Malaysia, 77% moisture content (Nurnadia et al., 2011) was applied for wet weight conversion and all reported species of threadfin breams showed higher T-Hg content than in the GoT. This T-Hg variation among different threadfin bream species in comparing with other literatures could be explained by fish size, feeding habit and habitat, trophic position and degree of mercury pollution in each location.

Fish size and trophic level were considered as the most important

Table 1
Summary of T-Hg levels (in μg kg^{-1} wet weight) muscle tissue of threadfin bream (*Nemipterus* spp.) from the Gulf of Thailand and other studies.

Species	Code	Location	TL ± SE[a]	n[b]	Length (cm)	Weight (g)	T-Hg (μg kg^{-1})			References
							Mean ± SD	Range	Median	
N. furcosus	NF	Gulf of Thailand	3.7 ± 0.00	34	9.60–23.2	10.3–133	88.0 ± 56.9	26.4–255	70.8	This study
		Peninsular, Malaysia		3	18.2–21.4	102–162	–	286–707	494	(Ahmad et al., 2015)[c]
N. hexodon	NH	Gulf of Thailand	3.9 ± 0.30	8	14.0–23.1	37.2–142	113 ± 113	23.0–282	46.4	This study
N. japonicus	NJ	Gulf of Thailand	4.1 ± 0.30	4	14.2–19.2	32.6–64.9	122 ± 112	48.3–288	75.2	This study
		Persian Gulf, Iran		8	21.0–23.0	104–147	49 ± 25	30–87	–	(Agah et al., 2007)
		Andaman Sea		24	17.6–29.9	54.0–200	81 ± 27	55–153	–	(Hantow et al., 2008)
		Persian Gulf, Iran		5	25.0–27.0	141–162	175 ± 78	–	–	(Saei-Dehkordi et al., 2010)
		Peninsular, Malaysia	4.1 ± 0.76	11	16.9–29.2	63–212	–	164–929	357	(Ahmad et al., 2015)[c]
N. marginatus	NM	Gulf of Thailand	3.5 ± 0.37	30	12.8–19.8	19.3–71.3	82.1 ± 52.7	11.3–192	73.7	This study
		Peninsular, Malaysia		2	23.0–25.5	110–240	–	159–216	188	(Ahmad et al., 2015)[c]
N. nematophorus	NO	Gulf of Thailand	3.8 ± 0.50	103	11.5–25.5	3.95–172	107 ± 59.1	18.2–287	92.7	This study
		Peninsular, Malaysia		2	16.1–25.6	58–154	–	661–1204	932	(Ahmad et al., 2015)[c]
		West Peninsular, Malaysia		1	26.0	–	–	–	645	(Anual et al., 2018)
		Bangkok markets, Thailand		6	24.0–25.0	162–211	320 ± 184	110–597	326	Unpublished results[c]
N. nemurus	NN	Gulf of Thailand	4.0 ± 0.66	31	16.4–30.5	40.1–190	144 ± 85.6	24.6–374	129	This study
		Peninsular, Malaysia		1	17.8	96	–	–	229	(Ahmad et al., 2015)[c]
N. peronii	NP	Gulf of Thailand	3.7 ± 0.30	4	15.5–19.0	39.9–62.4	53.2 ± 20.9	23.5–70.2	59.5	This study
		Andaman Sea		3	19.1–25.9	89.6–206	80 ± 15	65–95	–	(Hantow et al., 2008)
N. tambuloides	NT	Gulf of Thailand	4.0 ± 0.69	82	16.1–29.7	39.5–263	139 ± 74.3	30.9–360	116	This study
		Peninsular, Malaysia	4.0 ± 0.69	2	17.5–21.4	86–109	–	306–350	328	(Ahmad et al., 2015)[c]

[a] Trophic levels assessed from www.fishbase.org (Froese and Pauly, 2019).

[b] Number of individuals tested per species.

[c] T-Hg concentration from Ahmad et al. (2015) was converted from dry weight to wet weight according to Nurnadia et al. (2011) using 77% moister.

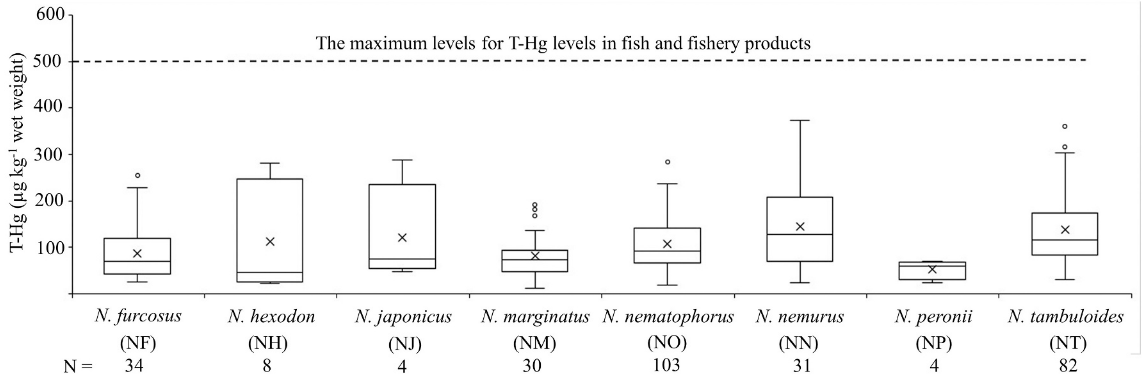

Fig. 1. Mean T-Hg levels in 8 species of threadfin bream (*Nemipterus* spp.) collected in the Gulf of Thailand. The box represents the 25th and 75th percentiles and the horizontal line inside each box represents the 50th percentile. The black cross shows the median values, and the minimum and maximum values are represented by the bars at the end of the whiskers. The small circles (o) represent the outliers of T-Hg levels. The black-dashed horizontal line represents the maximum allowance for mercury in fish and fishery products by the European Commission Regulation (EC, 2006) and the Ministry of Public Health of Thailand (MPH, 2020).

factors influencing Hg accumulation in fish tissues. While fish size is a reliable parameters to estimate fish age (Costa et al., 2020; Grgec et al., 2020), the trophic position in the food webs reflected the degree of Hg accumulation in fish (Ali and Khan, 2019). The Spearman correlation test between T-Hg and fish length (Fig. 2B) and trophic levels (Fig. 2C) has indicated that fish size and trophic level influence the T-Hg accumulation in threadfin bream. In this survey, *N. tambuloides* (NT) and *N. nemurus* (NN) were positioned in the higher trophic levels (4.0). Their fish size was also the biggest and contained the highest mean T-Hg. While *N. marginatus* (NM) and *N. peronii* (NP) were positioned in the lower trophic level, they contained the lowest mean T-Hg and had the smallest fish size. This result was similar to the Bangkok markets, Thailand report (Unpublished result) where the highest T-Hg observed in fish positioned in the higher trophic levels e.g., yellowfin tuna (*Thunnus albacores*). The variation of T-Hg with fish size and trophic level was also observed in other studies (Ahmad et al., 2015; Azad et al., 2019; Grgec et al., 2020) where the high trophic levels fish had the bigger fish size and the higher tendency to accumulate more level of T-Hg. Interestingly, among threadfin beam species observed in the Ahmad et al. (2015), the positive relation between the increase in T-Hg content with fish size and trophic level were observed except for the *N. nematophorus* (NO). This could be related to the less number of samples.

Since, all threadfin breams are classified as non-migratory demersal fish for their feeding habit (Table S1), prey selection (Eryalcin, 2018; Froese and Pauly, 2019) and local mercury source (Sirirattanachai and Utoomprurkporn, 2005; Liu et al., 2014) may contribute to these differences in T-Hg content. Specific diet selection (size of prey) has been observed among different threadfin bream species. The most piscivorous species like *N. nemurus* (NN) fed mostly on the high trophic positioned preys like *Nemipterus mesoprion*, mantis shrimp, shrimp, and other crustaceans (Eryalcin, 2018; Froese and Pauly, 2019). While *N. peronii* (NP) main diet is crustaceans, cephalopods, polychaeta, and smaller fish (Froese and Pauly, 2019). These diet selections are suggested to be based on their body size (i.e. length) and mouth size (Paul et al., 2017). The study of Agusa et al. (2007) in South East Asia and Liu et al. (2014) in South China Sea (SCS) suggested the connection of geographic location and the Hg content in fish. The human activities in the coastal area of SCS indicated as the possible sources for Hg accumulation in fish (Liu et al., 2014).

Moreover, the accumulation of T-Hg in threadfin breams is influenced by their habitat, family group, geographic locations (Saei-Dehkordi et al., 2010; Ahmad et al., 2015; Anual et al., 2018; Azad et al., 2019) as well as seasonal variation in their environment including salinity, dissolved oxygen, total organic carbon and suspended particulate matter and local mercury source (Sirirattanachai and Utoomprurkporn, 2005). The application of stable isotope (δ^{15}N and δ^{13}C) in the future study is suggested to assist in the estimation of the trophic position of threadfin bream and their prey in marine food web in the GoT and enable to track the predator and prey relationship more precisely (Chouvelon et al., 2018). In turn, this could provide even more accurate information on the pathway of T-Hg accumulation and safety caution for fish consumption.

Though, all threadfin bream examined in this survey had T-Hg concentration less than 500 µg kg^{-1} wet weight or the T-Hg maximum concentration allow in fish and fishery products from the standard guidelines of the European Commission Regulation (EC, 2006) and Ministry Public Health of Thailand (MPH, 2020). This screening result indicated the safe consumption of threadfin breams caught in the GoT.

3.2. Distribution of 8 threadfin bream species in the Gulf of Thailand (GoT)

The GoT was divided into the upper, the middle, and the lower GoT. In the middle GoT, the survey was conducted on both in Thai and Cambodian waters (Fig. S1). Threadfin bream caught in this research survey were examined for the T-Hg distribution patterns over the GoT. The average T-Hg concentration in threadfin bream accounted for 60.8 ± 47.9, 121 ± 67.5, 126 ± 76.0 µg kg^{-1} wet weight in the upper, the middle, and the lower GoT, respectively (Fig. S1). The Kruskal-Wallis test showed a significant difference (Chi-Square = 41.8, $p < 0.0001$) of T-Hg in these 3 locations in the GoT (Table S4A). When testing the differences of T-Hg between the middle and the lower GoT (Table S4B) and between Thai and Cambodian waters (Table S5) with Mann Whitney test, the results were not significantly different ($p > 0.05$).

The low T-Hg content in threadfin breams often observed in sampling stations in the upper GoT and in the near coastline stations. While, the higher T-Hg content in threadfin breams were observed in the sampling stations in the middle and the lower parts GoT. As aforementioned, threadfin bream is a non-migratory fish, therefore their feeding habit near seawater-sediment interface could lead to T-Hg accumulation from their prey and environment. The variation in T-Hg in threadfin bream could be related to the local mercury sources in the GoT (Yod-In-Lom and Doyle, 2002; Cheevaporn and Menasveta, 2003; Thongra-ar et al., 2008; Murphy et al., 2009; Pojtanabuntoeng et al., 2011; Guédron et al., 2014; Rattanasriampaipong, 2016; Tremlová, 2017; Wor-akhunpiset, 2018; Sompongchaiyakul et al., 2019; Thepanondh and Tunlathorntham, 2020). The water circulation pattern in the upper GoT dominated by river discharge and was distinguished from the circulation in the middle and the lower GOT, whereby are influenced by the South China Sea waters (Sirirattanachai and Utoomprurkporn, 2005; Buranapratheprat et al., 2016; Asokbunyarat and Sirivithayapakorn, 2020;

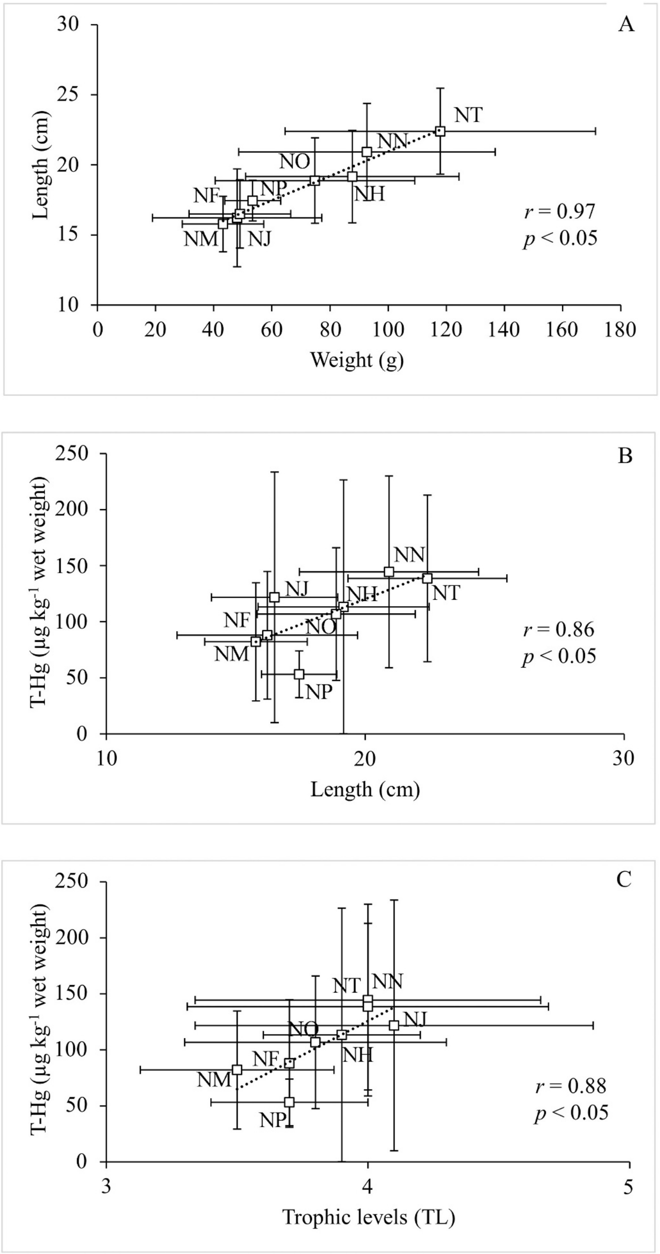

Fig. 2. Position of species in relation to their value: A) mean length against mean weight; B) mean T-Hg levels against length; and C) mean T-Hg levels against mean trophic levels. (Error bars represent the standard deviation). NF – *N. furcosus* (n = 34), NH – *N. hexodon* (n = 8), NJ – *N. japonicus* (n = 4), NM – *N. marginatus* (n = 30), NO – *N. nematophorus* (n = 103), NN – *N. nemurus* (n = 31), NP – *N. peronii* (n = 4), NT – *N. tambuloides* (n = 82).

Higuchi et al., 2020).

The average T-Hg of each threadfin bream species by station was displayed in the T-Hg classification plot (Fig. 3). For *N. furcosus* (NF), this species was found in sampling locations near the river runoff in the upper GoT, the middle GoT in Cambodian waters, and the lower GoT near Songkhla Lake. Among NF caught stations, Cambodian waters showed relatively higher T-Hg in samples. Whereas *N. marginatus* (NM) and *N. nemurus (*NN) were found to be distributed only in specific location i.e. the middle GoT in Cambodian waters and the lower GoT, *N. nematophorus* (NO) and *N. tambuloides* (NT) were found to be distributed in all areas of the GOT. Still, the higher T-Hg tended to be observed in sampling stations in the middle GoT. The rarest caught species in this survey were *N. hexodon* (NH), *N. japonicus* (NJ) and *N. peronii* (NP) which were reported in stations near coastal areas.

In the middle and the lower GoT, higher T-Hg content in threadfin breams was observed, especially in NM, NO and NT. This could have been elucidated by human activities in the middle GoT such as petroleum and gas exploration and production. Although, mercury concentration in seawater did not exceed the standard guidelines from the Thailand seawater quality (100 ng L^{-1}), stations in the middle and offshore showed high mercury contents which ranged from 0.2 to 33.1 and 0.1 to 47.7 ng L^{-1} in surface and bottom seawater, respectively (Sompongchaiyakul and Sanesith, 2013). Surface sediment (0–5 cm) in the lower GoT has been reported to have an increase in T-Hg overtime (2003 to 2013) from 24.4 ± 9.00 to 41.4 ± 15.3 µg kg^{-1} in concordance with the intensity of the petroleum and gas operations in the middle of the Gulf (Sompongchaiyakul et al., 2019). In addition, seawater and sediment supply from rivers in the southern part of Thailand and Malaysia rivers plus the atmospheric deposition and seawater from adjacent areas may play a part in contribution, transportation, and distribution mercury content in the middle and lower GoT (Fu et al., 2010; Hajeb et al., 2012; Buranapratheprat et al., 2016; Liu et al., 2016). Accordingly, this relatively higher mercury in seawater and sediment may lead to bioaccumulation in benthic organisms (Thongra-Ar and Parkpian, 2002) and transfer to higher trophic positioned organisms in the GoT like observed in NM, NO and NT. Particularly high T-Hg in NN in Cambodian waters may relate also from locally runoff and discharge from several human activities. Toxic waste dumping in Sihanoukville, Cambodia from Taiwan Ship in 1998 was an example of such an event probably allows Hg-contained waste runoff and exposed both residents and the environment to Hg (Hess and Frumkin, 2000).

3.3. Risk assessment

The risk of mercury exposure from fish consumption is one concerning factor in balancing food nutrition. To estimate mercury exposure for consumption threadfins breams caught in the GoT, the estimation of the daily intake (EDI), hazard quotient (HQ) and maximum safe daily consumption (MSDC) were evaluated using the mean concentration of mercury of each species for calculation.

The EDI value was compared with the provisional tolerable daily intake (PTDI) standard guideline (JEFCA, 2007). All EDI of 8 species were lower than the PTDI values or less than 0.23 µg kg^{-1} bodyweight day^{-1}. The highest EDI was exhibited in *N. nemurus* (NN) and *N. tambuloides* (NT) at 0.07 µg kg^{-1} bodyweight day^{-1}, while the lowest was in *N. peronii* (NP) at 0.03 µg kg^{-1} bodyweight day^{-1} (Table S6, Fig. 4A). The HQ was reported from 0.25 in NP to 0.69 in NN and NT and none of them exceed the HQ limit (HQ > 1). The EDI and HQ estimation indicates that consumption threadfin breams caught in the GoT does not pose any additional health risks for T-Hg exposure in adults.

To protect dietary Hg exposure associated with fish consumption for adults, the value of maximum safe daily consumption (MSDC) for each species was calculated (Table S6, Fig. 4B). The result showed that fish with low T-Hg like *N. peronii* (NP) could be consumed up to 259 g $person^{-1}$ day^{-1} while higher T-Hg fish like *N. nemurus* (NN) and *N. tambuloides* (NT), should not be consumed more than 95.3 g $person^{-1}$ day^{-1}. To minimalize high mercury exposure for the human body, adults should consume less than the calculated MSDC of each species. However, in serving table, it is not possible to recognize the differences among 8 species of threadfin bream. Thus, the recommend MSDC of threadfin breams caught in GoT should follow the MSDC of NN and NT. One strategy to reduce mercury exposure via fish consumption is to consume fish of various species. The best fish choice is small-size species positioned at a lower trophic level.

4. Conclusion

Eight species of threadfin breams in the Gulf of Thailand (GoT) sampling from different locations during the research survey exhibited

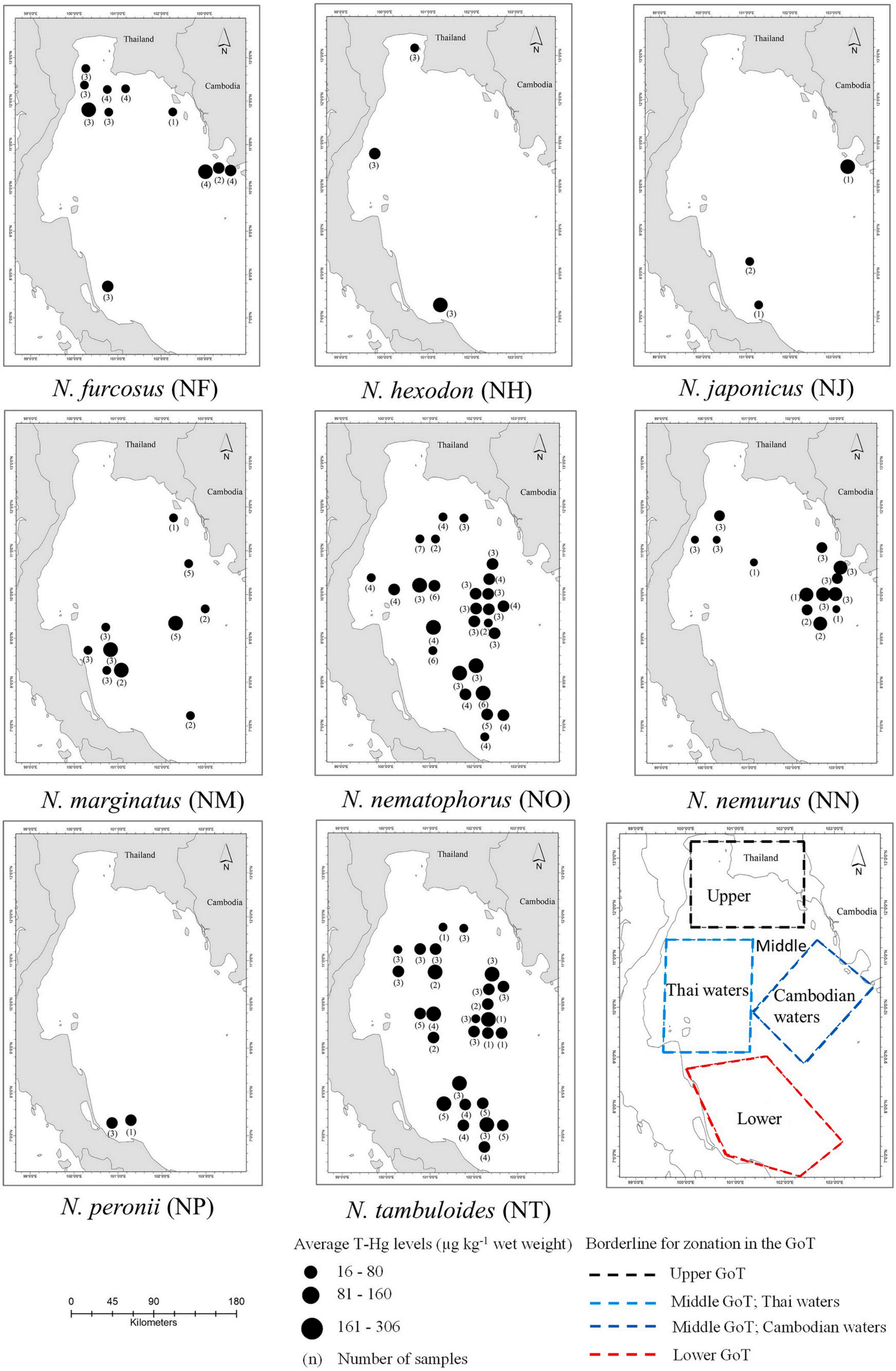

Fig. 3. Classification plot of T-Hg concentrations (μg kg^{-1} wet weight) in 8 species of threadfin bream (*Nemipterus* spp.) caught during the research survey in the Gulf of Thailand (GoT) in 2018.

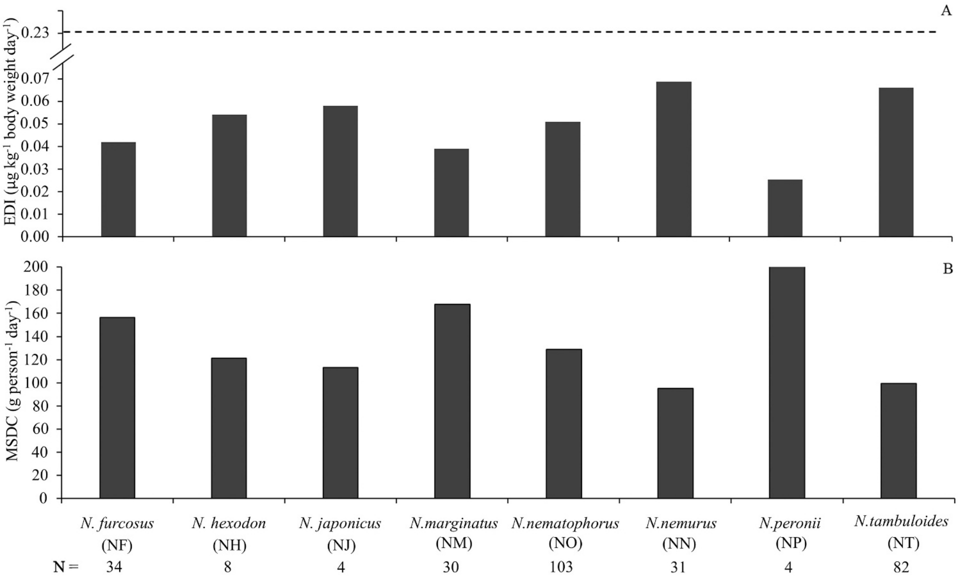

Fig. 4. The values of A) Estimated daily intake (EDI) in μg kg^{-1} bodyweight day^{-1} and B) Maximum safe daily consumption (MSDC) in g person^{-1} day^{-1} of threadfin bream (*Nemipterus* spp.) in the Gulf of Thailand. The black-dashed horizontal line in EDI represents the provisional tolerable daily intake (PTDI) standard guidelines at 0.23 μg kg^{-1} body weight day^{-1} (JEFCA, 2007).

the variation in T-Hg contents by species and locations. T-Hg in fish was ranged from 11.3 to 374 μg kg^{-1} wet weight. The mean T-Hg were significantly different among species in the following order; *N. nemurus* > *N. tambuloides* > *N. japonicus* > *N. hexodon* > *N. nematophorus* > *N. furcosus* > *N. marginatus* > *N. peronii*. Fish size, feeding habit and habitat, and trophic position of each threadfin bream species were significantly determined its T-Hg variation. By location in the GoT, lower content of T-Hg was found in samples from the upper GoT than those from the middle GoT and lower GoT and might be influenced by locally sources e.g., gas/petroleum operation and river run off. Though, all threadfin breams caught contained T-Hg level less than the maximum concentration allowed in fish and fishery products. Consumption risk was calculated and the maximum safe daily consumption (MSDC) recommended for threadfin bream caught in the GoT was 95.3 g person day^{-1}.

CRediT authorship contribution statement

Irwan Ramadhan Ritonga: Conceptualization, Formal analysis, Investigation, Methodology, Data collection, Visualization, Writing the original draft, Writing - review & editing writing. **Sujaree Bureekul:** Data collection, Conceptualization, Project administration, Supervision, Writing - review & editing Writing, Funding acquisition. **Tanakorn Ubonyaem:** Data collection, Formal analysis, Investigation, Methodology. **Isara Chanrachkij:** Data collection, Methodology, Investigation, Funding acquisition. **Penjai Sompongchaiyakul:** Methodology, Conceptualization, Project administration, Supervision, Writing - review & editing Writing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful for the assistance from crew members on-board of M.V. SEAFDEC-2 during the collaborative research survey on marine fisheries resources and marine environment in the Gulf of Thailand, technical staffs in the laboratory of the Department of Marine Science, and Coax Group Corporation Ltd. The first author would like to thank you for the Ph.D. scholarships from BKC/BKT East Kalimantan and Mulawarman University and the Graduate School Thesis Grant, Graduate School, Chulalongkorn University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113363.

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