Exposure Assessment of methyl mercury from consumption of fish and seafood in Peninsular Malaysia

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Abstract
The concentration of meHg in freshwater fish and seafood was investigated, as well as the consumption patterns of fish and seafood by different demographic groups (age, ethnicity, gender). A potential alarm for human health hazards was also assessed, and the results were compared to the provisional tolerable weekly intakes (PTWIs) and the hazard quotient parameter (HQ). The results showed that meHg levels of 67 species ranged from 0.013 to 0.252 mg/kg of wet weight (WW) with significant differences between different fish and seafood groups ($\chi^2_{KW} = 49.09; p < 0.001$). Median concentrations of meHg in fish and seafood groups in descending orders are as follows: demersal fish (0.1006 mg/kg WW) > pelagic fish (0.0686 mg/kg WW) > freshwater fish 0.045 mg/kg WW) > cephalopods (0.0405 mg/kg WW) crustaceans (0.0356 mg/kg WW). The results revealed that older population (> 40 years old) consumed significantly ($p = 0.000$) more fish compared to younger generations and the elderly consumed the highest amounts of fish (104.0 ± 113.0 g/day). The adolescents (10–17 years old) consumed more than double of amount for both cephalopod and crustacean compared to the older populations ($p < 0.05$). Malay ethnic (96.1 ± 99.6 g/day) consumed significantly ($p = 0.000$) higher amounts of fish and seafood compared to other ethnicities, similar to male subjects (95.2 ± 102 g/day; $p = 0.026$) when compared to the female (86 ± 96.3 g/day). The estimated weekly intake (EWI) values showed results below 1.6 µg/kg BW/week, the tolerable levels recommended by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) for all different demographic factors except for higher consumers at 75th percentile and above. Consumption of marine fish contributed to a higher value of PTWI to all different demographic groups (the estimated weekly intake (EWI) range: 0.2988–0.6893 µg/kg BW/week) but for the adolescents, where from the consumption of crustaceans (0.3488 µg/kg BW/week or 21.8% of PTWI) and cephalopods (0.504 µg/kg BW/week or 31.5% of PTWI). The results from this study also revealed the HQ value for overall consumption of fish and seafood by the adolescents and elderly exceeded one. This was contributed from the consumption of demersal fish and cephalopods, thus indicating the nonacceptable level of noncarcinogenic adverse health effects.

Keywords Methyl mercury · Fish · Seafood · Exposure assessment · Food safety · Malaysia

Introduction
Fish and seafood are a good source of energy and proteins, as well as key nutrients like minerals and vitamins, and they have a lot of health benefits (Mehouel et al 2019; Barone et al 2015). It also contains eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and long-chain omega-3 polyunsaturated fatty acids (n-3 PUFAs), which are vital unsaturated fatty acids linked to excellent health (Barone et al 2015; Larsen et al. 2011; McManus et al. 2011). Medical research has shown that eating meat substitutes, fat fish or lean fish, and fish oil mixed with vegetables can improve fat consumption quality, lower calorie intake, and prevent...
lifestyle diseases, all of which are linked to a variety of health benefits, including maintaining healthy human hearts, brains, joints, and immune systems (Larsen et al. 2011; McManus et al. 2011).

Fish consumption, on the other hand, is the most prevalent way for humans to be exposed to mercury, which is released into the environment by both natural and human sources (Mehouel et al 2019). Mercury (Hg) exists mainly in different forms, an elemental mercury (HgO), inorganic mercury (Hg²⁺, Hg³⁺), and organic mercury (MeHg⁺, EtHg⁺, PhHg⁺, and so on) (Mehouel et al 2019). In fish and seafood, often found is an organic form of meHg as this compound is predominant (Mehouel et al 2019; Morgano et al. 2011; Burger 2009). It occurs at a high percentage, ranging between 95 and 97% of total mercury (THg) when the compound accumulates in fish tissue. Hg linked to aquatic sediments is transformed into organic form by microbial activities through methylation and enzymatic processing, and it then enters the aquatic food chain, where it reaches its maximum concentration in predatory fish (Mehouel et al 2019; Clarkson et al. 2003). MeHg can be concentrated in fish either directly in the water or through food chain components. The ingestion of fish contaminated with meHg has received considerable critical attention due to the adverse health outcomes of neurologic damage such as mental retardation, seizures, vision and hearing lost, delayed development, language disorder, and memory loss as well as renal damage, reproductive disorders, and damage in the cardiovascular system (Mehouel et al 2019; Andrew et al 2016; Barone et al 2015). MeHg could potentially be one of the risk factors for infertility (Hsi et al 2016).

There are concerns about Malaysians being exposed to excessive levels of mercury as a result of eating fish and shellfish. Our earlier survey of people of various ethnicities in this country, conducted in the years 2008 to 2009, revealed that Malaysians had the second highest daily fish intake behind Japan among Asian nations and placed fifth in the world (Ahmad et al 2016). The maximum permitted proportion of meHg in seafood was set at 0.5 mg/kg in Malaysian Food Regulation 1985 (Food Act 1983, Act 281) and Regulations 2006 (International Law Book Services 2006), which is the same level as the one set by the joint FAO/WHO Expert Committee (FAO/WHO 2006). In view of the above, the FAO/WHO Expert Committee on Food Additives (JECA) has established provisional tolerable weekly intake (PTWI) for meHg at 1.6 µg/Kg/BW/week. This is the safe level of intake or the maximum amount of a contaminant that a person is weekly exposed to over a lifetime without intolerable risk of health effects associated with the consumption of food (Wan Azmi et al 2019; Kuras et al 2017). To estimate the potential of health risk due to exposure to the contaminant, the United State Environmental Protection Agency (USEPA) created the reference dose (RfD), an estimated daily oral exposure of contaminant to the human population that is likely to be without considerable risk of harmful effects during a lifetime which is set at 0.0001 mg/kg/day for Hg (Wan Azmi et al 2019; USEPA 2000).

Many research on metal pollution in fish and seafood have been conducted in Malaysia (Wan Azmi et al 2019; Low et al 2015; Alina et al 2012; Mok et al 2012; Kamaruzaman et al 2011; Agusa et al 2005), and a number of published data on THg or meHg levels in fish and seafood are available (Anual et al 2018; Ahmad et al. 2015a, b; Hajeb et al 2009). Many investigations found varying amounts of THg or meHg in a small number of fish and shellfish species gathered from specific locations around Malaysia. The results demonstrated that THg or meHg concentrations were low when compared to Malaysian Standards or JECFA recommended values. Several investigations found that some species of fish and shellfish seized from Malaysian markets have high THg or meHg contents, potentially putting consumers at risk (Ahmad et al. 2015a, b; Hajeb et al 2009, 2010; Agusa et al. 2005). Among those species are fork-tailed threadfin bream and big eye scads (Agusa et al 2005), longtail tuna, mackerel (Hajeb et al 2009), bluespotted stingray, honeycomb stingray, and John’s snapper (Ahmad et al. 2015a). An earlier study also reported that 48% of marine fish had Hg levels higher than the guideline value especially among carnivorous feeding (Agusa et al 2005). In this country, risk assessments studies on mercury have looked at the sources/locations, at-risk populations, fish species and families/groups, seafood preparation, and risk assessment methodologies (Agusa et al 2005, 2007; Hajeb et al 2009; Hajeb and Jinap 2011; Low et al 2015; Anual et al. 2018; Wan Azmi et al 2019). The quantities of trace elements in fish gathered throughout Southeast Asia varied greatly, and the estimated daily intake (EDI) value was calculated higher due to the high consumption rate of seafood in Malaysia. The EDI for all specimens of fork-tailed threadfin bream and sharp-tooth jobfishes exceeded the guideline values and would indicate hazardous to the populations in this region (Agusa et al 2005, 2007). Anual et al. (2018) reported that 14% of seafood had medium to high mercury concentrations with EWI higher than those with the PTWI for a few species of bream, snapper, croaker, barramundi, and tuna. In addition, their study showed the EWI values ranging from 2.1 to 4.0 µg/kg bw in listed fish (Anual et al 2018). The average Malaysian population was exposed to 1182 g per week or 73.95% of the PTWI (Hajeb et al 2009), whereas the exposures for the fisherman families were as high as 2,332 g per week or 145.8% of the PTWI (Hajeb and Jinap 2011). Instead, the probabilistic estimation of reasonable exposure and noncarcinogenic risks associated with consumption of freshwater fish (red tilapia) at 95th percentile exposure revealed hazard quotient (HQ) and hazard index (HI) values below 0.2 and 1.
respectively, indicating that long-term consumption of this fish is likely to have negative consequences for Malaysians (Low et al. 2015).

When assessing the risk of Hg or meHg from fish and shellfish diet, data from various other nations included more complete characteristics. There have been studies conducted to support regulatory analysis that rely on quantitative fish consumption estimates based on representative populations survey (von Stackelberg et al. 2017) or involved a specific or broad range of seafood species consumed by population (Mehouel et al. 2019; Budiyanto et al. 2019; Barone et al. 2015; Al-Mughairi et al. 2013), collected from specific or different locations (Bhupander and Mukherjee 2011; Uratno et al. 2018) or wild and farm species (Chouvelon et al. 2009). There are also studies that involved vulnerable groups of pregnant women, children below 17 years old, women of child-bearing age, and other high-risk consumers (Stuchal et al. 2019; You et al. 2018; Kuras et al. 2017; Juric et al. 2017; Andrew et al. 2016; Whyte et al. 2009). Data from other sources are also reported for common fish eaten or fish parts or organs, for example, fish muscle, liver, gills, kidney, and others (Matos et al. 2018; Zolfaghari 2018). There are also studies that estimate the risk of Hg contamination from seafood eating by analyzing biological materials like blood and hair (You et al. 2018; Ouboter et al. 2018; Kuras et al. 2017; Juric et al. 2017). Current publications revealed results of THQ values for children and adults higher than one (Rakib et al. 2021; Okati et al. 2021) from consumption of selected commercial fish and its products, and the exposure among the indigenous communities are even higher from 3- to 25-folds compared to the USEPA reference dose or up to 11 times of the FAO guideline (Vasconcellos et al. 2021).

This study updates information on the concentration of meHg in freshwater fish and seafood, including marine fish, cephalopods, and crustaceans, obtained at random from both fish landing ports and wholesale wet markets across Peninsular Malaysia. The study also looked at the consumption patterns of fish and seafood among Peninsular Malaysians of various age groups, ethnicities, and genders. Fish and seafood consumption for higher consumers was calculated at the 75th percentile and above, and data were compared to the median consumption at the 50th percentile. A potential alarm for human health hazards was evaluated, and results were compared to the PTWIs and through the parameter of HQ.

Methodology

Fish consumption survey

Between February 2008 and May 2009, a household-based cross-sectional study was undertaken in Peninsular Malaysia, with data collected through face-to-face interviews using predesigned questionnaires. Based on the National Household Sampling Frame (NHSF), Department of Statistics, Malaysia, a sampling frame made up of enumeration blocks (EBs) constructed for the 2000 Population and Housing Census was used to pick study subjects’ household addresses (Department of Statistics Malaysia 2000). The sample size was calculated using data from a Selangor population consumption survey, which revealed that 16.2% of the adult population consumed fish (153 g/person/day vs 944 g/person/day total food) (Ahmad 2007). Factors from two separate places (urban and rural), three different ethnic groups (Malay, Chinese, and Indian), and two different age groups were used. A number of 2,496 subjects were required in order to obtain a 95% confidence interval and 5% margin of error. Taking into account a 20% dropped-off rate, 2,996 subjects were identified from 1,500 household addresses received from the NHSF. In this study, a minimum of two adults and all adolescence ages 10 to 17 years were chosen from each family. The final count of 2,675 adults had completed the questionnaire. A number of 890 children/adolescents participated in the survey, but only 484 completed the questionnaires.

The questionnaires were divided into two sections. The first portion was a self-administered questionnaire that included sections on sociodemographic information, fish consumption patterns, frequency of fish intake, and knowledge, perceptions, and practices related to fish eating. The three copies of 24-h dietary diary forms made up the second half. In this portion, participants were instructed to keep track of what they ate and drank at each meal of the day. The interviewers were instructed how to read and understand the questionnaires and how to give instructions to the subjects. They were given a series of questionnaire tools which included pictures of serving dishes, fish commonly found in Malaysia, and common household measures like standard measuring cups, bowls, ladles, and spoons. The questionnaire was provided between the hours of 9:00 a.m. and 6:00 p.m.; however, interviewers were sometimes required to come at night if individuals were not at home during the day. Parents were asked to assist their children in filling out the 24-h dietary diary forms and answering questions on the surveys. Interviewers also rechecked all food recorded in dietary diary forms to verify the types and amount of food consumed by subjects.

The portion weight of food was determined using the “Atlas Makanan: Saiz pertukaran dan Porsi” (Suzana et al. 2002, 2009) and “Nutrient and composition of Malaysian foods” (Tee et al. 1997). If the food consumed was not listed in all of these references, the mean values were determined as the weight of that particular food from at least five different sources. The collections of the 3-day dietary diary were conducted during weekdays and weekends.
calculation of sample size, questionnaires, and interviews involved adults from Peninsular Malaysia for the whole study entitled “Seafood consumption survey in Peninsular Malaysia, 2008–2009” were as described elsewhere (Ahmad et al. 2016), while similar information for a survey that involved adolescence was reported recently (Ahmad et al. 2019). Information on the demographic background of study subjects from both groups were presented in both published articles, accordingly (Ahmad et al. 2016, 2019). The Medical Research and Ethics Committee (MREC) of the Ministry of Health Malaysia (MOH) approved the project, which was funded by the MOH. Informed consent and confidentiality were obtained from the subjects beforehand.

**Seafood collection and preparation**

Sampling was conducted from June to December 2009. Samples were obtained from six major Fisheries Development Authority of Malaysia (LKIM) fish landing complexes and five wholesale wet marketplaces across Peninsular Malaysia. During three trips to each location, a total of 394 seafood samples were gathered. Details on how to collect, prepare, process, and store fish can be found elsewhere (Ahmad et al. 2015a, b).

**Determination of total mercury concentrations in seafood**

In a microwave digestion device, a dried sample was digested (Multiwave 3000—Anton Paar). Total mercury was measured using a Perkin Elmer Flow Injection Mercury System (FIMS) apparatus with a programmable sample dispenser and a cold vapor atomic absorption spectrometry (AAS) methodology, as described by MohdFairulinizal et al. (1998). Analytical control was accompanied by the analysis of reagent blanks and standard reference samples. Details on the analysis were described elsewhere (Ahmad et al. 2015a, b). It was essential to convert mercury contents in fish samples to wet basis values, and the quantity of moisture content was determined using Tee et al. (1997) and other sources (Nurnadia et al. 2011). The results were compared to the recommended guideline levels by the joint FAO/WHO Expert Committee on Food Additives (FAO/WHO 2006) and the Malaysian Food Regulation 1985 (Food Act 1983, Act 281), and Regulations 2006, under the Fourteenth Schedule of Regulation 38, the level at 0.5 mg/kg meHg in fish and seafood.

**Health risk assessment of mercury from seafood consumption**

**Estimated weekly intake (EWI) and maximum safe weekly consumption (MSWC)**

The EWI of total Hg and/or meHg from consumption of seafood can be calculated by multiplying the total Hg and/or meHg contamination levels in seafood with the consumption levels per week dividing by the average body weight of the population by age group. The equation is as shown below:

\[
EWI = \frac{\text{Concentration of meHg}(\text{mg/KgWW}) \times \text{weekly consumption(g)}}{\text{Bodyweight(kg)}}
\]

The typical adult body weight varies between 55 and 62 kg depending on demographic factors, while the average adolescent body weight is 45 kg (Ahmad et al. 2016, 2019). The JECFA has defined a PTWI of 1.6 g/kg body weight/week for inorganic MeHg (WHO 2011).

MSWC to reach the PTWI for the Malaysian population at different sociodemographic characteristics was also estimated. The MSWC was calculated using the PTWI (g/kg body weight/week) value of 1.6 g/kg body weight/week multiplied by body weight for each population group and divided by total Hg and/or meHg concentrations:

\[
\text{PTWI at 1.6mg/kgbodyweight/week} = \frac{\text{Concentration of meHg}(\text{mg/KgWW}) \times \text{MSWC(g/weekly consumption, kgbodyweight/week)}}{\text{Bodyweight(kg)}}
\]

**Hazard quotient (HQ)**

The risk assessment is a tool to estimate the probability of health effects due to exposure to the hazard, in which this study is the exposure through consumption of fish. The oral reference dosage (RfDs) for mercury was set at \(1 \times 10^{-4}\) (mg/kg-day) by the USEPA (Risk Information System (IRIS) (USEPA 2000). The HQ meHg was estimated using the equation below (Wan Azmi et al 2019):

\[
HQ = \frac{EF \times ED \times FIR \times C}{RfD \times BW \times AT} \times 10^{-3}
\]

where HQ is chemical-specific hazard quotient; EF is the exposure frequency (350 days/year); ED is the duration of human exposure for children and adults is 6 and 30 years, respectively; FIR is the seafood ingestion rate (based on total intake per day in gram by different groups of population); C is the metal concentration in the muscle of fishes (mg/kg wet weight); RfD is the oral reference dose (IRIS, USEPA); BW is the average body weight of population group (55 to 62 kg for adult, 45 kg for adolescent, and 60 kg for total population); and AT is the average time of human exposure to non-carcinogenic (ED \(\times 365\) days).

Target hazard is a ratio of the determined dose of a contaminant to an oral reference dose considered detrimental. HQ values were more than or equal to 1; it is assumed that the intake of meHg through the consumption of fish and seafood poses a potential noncancerous health risk to the exposed population.
Statistical analysis

IBM SPSS Statistics 26 was used to analyze the data. Before analyzing the THg data, it was cleaned and examined for discrepancies. The demographic features of different categories and groups were keyed in using data from a dietary survey. After completing the data entry, it was checked for any discrepancies, such as coding numbers, typo errors, and so on. At first, descriptive statistics were used to assess data normality using the one-sample Kolmogorov–Smirnov test, and/or the skewness of descriptive statistics was regulated between −1 and +1, whichever was true. Because of the outliers, the descriptive statistical analysis revealed that both groups of data were not regularly distributed. As a result, nonparametric statistics were employed. The medians and interquartile range were calculated. The Mann–Whitney U and Kruskall–Wallis tests were used to analyze differences across groups. A level of significance at 0.05 is set to determine the result is statistically significant. Significance values have been adjusted by the Bonferroni correction for multiple tests. Higher consumers were chosen among participants who consumed fish and seafood at the 75th, 90th, and 95th percentiles, and their consumption was compared to the median consumption at the 50th percentile.

Results

MeHg in fish and seafood

THg and meHg (median ± IQR) concentrations in marine and freshwater fish from fish landing ports and the wholesale markets in Peninsular Malaysia are summarized in Table 1. MeHg levels of 67 fish and seafood species ranged from 0.013 to 0.252 mg/kg of wet weight. Fish and seafood groups were comprised of 8 species of cephalopods, 12 species of crustaceans, 23 species of demersal fish, 1 species of freshwater fish, and 23 species of pelagic fish. Significant variations of meHg levels exist in different fish and seafood groups (\(\chi^2_{KW} = 137.486; p < 0.001\)). Among marine fish, the median for meHg levels was higher (>0.1 mg/kg WW) in two species of pelagic fish (Selar boops and Sarda orientalis) and eight species of demersal fish (Lutjanus argentimaculatus, Lutjanus russelli, Lates calcarifer, Psammodoperca waigiensis, Dasyatis zugei, Nemipterus japonicus, Nemipterus furcatus, and Nemipterus nematophorus). While for cephalopods and crustaceans as well as the freshwater catfish, meHg levels were nearly half compared to the marine fish at 0.045, 0.046, and 0.066 mg/kg WW, respectively. Pairwise comparisons using Bonferroni correction of meHg levels in fish and seafood groups showed significant differences between pelagic fish and the other three groups of demersal fish (\(p = 0.000\)); crustacean (\(p = 0.000\)), and cephalopod (\(p = 0.000\)). There were also significant differences between demersal fish and crustaceans (\(p = 0.000\)), cephalopod (\(p = 0.000\)), and freshwater fish (\(p = 0.048\)). Median concentrations of meHg in fish and seafood groups in descending order are as follows: demersal fish (0.1006 mg/kg WW) > pelagic fish (0.0686 mg/kg WW) > freshwater fish 0.045 mg/kg WW) > cephalopods (0.0405 mg/kg WW) crustaceans (0.0356 mg/kg WW). The calculation of median concentrations of meHg per species by means of the percentage to THg at 93%, 81%, and 50% for fish, cephalopods, and crustaceans, respectively (Anual et al. 2018). These results showed that none of the meHg levels in fish and seafood groups exceeded both the national and international guidelines.

Fish and seafood consumption at different demographic backgrounds

Fish and seafood consumption (g/day/person) (median ± IQR) by population in Peninsular Malaysia at different demographic categories were shown in Tables 2, 3, and 4. There are significant differences (\(p < 0.05\)) between the consumption of seafood among different age groups for all fish and seafood categories except for freshwater fish (Table 2). Overall, the results revealed that the older population (> 40 years old) consumed significantly (\(p = 0.000\)) more fish compared to younger generations (< 40 years old). The elderly consumed the highest amounts of fish (104.0 ± 113.0 g/day), but the difference is not significant when compared to the next age group of 41 to 60 years old (95.8 ± 99.8 g/day). Nevertheless, the differences are significant (\(p < 0.05\)) when compared to the other two age groups, the adolescents (10 to 17 years old) (84.9 ± 104.1 g/day), and the young adults (18 to 40 years old) (82.0 ± 89.1 g/day). In addition, the adolescents (10–17 years old) consumed about half amounts of marine fish (26.0 ± 30.6 g/day) compared to the older population, and the differences are significant at \(p = 0.000\). Conversely, the amount they consumed were more than double for both cephalopod (80.0 ± 90.0 g/day) and crustacean (63.0 ± 65.0 g/day) compared to the consumption by the older populations (\(p < 0.05\)).

Fish and seafood consumption by three different major ethnicities in Peninsular Malaysia were shown in Table 3. The overall fish and seafood consumption was led by the Malay ethnic (96.1 ± 99.6 g/day) when compared to the Chinese (66.0 ± 88.0 g/day) and Indians (60.0 ± 64.5 g/day). The differences are significant at \(p = 0.000\). The Chinese significantly (\(p = 0.046\)) consumed lesser marine fish compared to the other two ethnic groups. In the contrary, the Indians consumed significantly (\(p = 0.009\)) the least pelagic fish compared to the Malay ethnic and the Chinese. No significant differences (\(p > 0.05\)) were shown by different ethnicity towards consumption of demersal fish and
Table 1: Total Hg and meHg (mg/kg WW) levels in fish/seafood from the LKIM Complexes and wholesale market in Peninsular Malaysia

| Common name         | Species                          | n  | total Hg (DW) | IQR   | 95%MC (%) | Total Hg (WW) | meHg (WW) |
|---------------------|----------------------------------|----|---------------|-------|------------|---------------|-----------|
| Pelagic fish        |                                  |    |               |       |            |               |           |
| Yellowstripe scad   | Selaroides leptolepis            | 10 | 0.252         | 0.125 | 79.5       | 0.0517        | 0.0480    |
| Oxeye scad          | Selar boops                      | 3  | 0.555         | -     | 78.2       | 0.1210        | 0.1125    |
| Bigeye scad         | Selar crumenopalimus             | 1  | 0.298         | -     | 78.8       | 0.0632        | 0.0588    |
| Yellowtail scad     | Atule mate                       | 4  | 0.458         | 0.304 | 76.8       | 0.1063        | 0.0988    |
| Bigeye trevally     | Caranx sexfasciatus              | 1  | 0.293         | -     | 76.8       | 0.0680        | 0.0632    |
| Greater amberjack   | Seriola dumerili                 | 1  | 0.203         | -     | 84.7       | 0.0311        | 0.0289    |
| Redtail scad        | Decapterus kurroides             | 2  | 0.272         | 0.263 | 74.7       | 0.0896        | 0.0833    |
| Round scad          | Decapterus muraudsi              | 7  | 0.317         | 0.171 | 77.4       | 0.0716        | 0.0666    |
| Slender scad        | Decapterus russelli              | 4  | 0.195         | 0.108 | 74.7       | 0.0493        | 0.0459    |
| Shortfin scad       | Decapterus macrosoma             | 1  | 0.354         | -     | 74.7       | 0.0896        | 0.0833    |
| Torpedo scad        | Megalaspis cordyla               | 17 | 0.319         | 0.198 | 74.8       | 0.0804        | 0.0748    |
| Black pomfret       | Parastromateus niger             | 8  | 0.242         | 0.121 | 76.5       | 0.0569        | 0.0529    |
| Indian mackerel     | Rastrelliger kanagurta           | 9  | 0.18          | 0.066 | 73.1       | 0.0484        | 0.0450    |
| Faughn’s mackerel   | Rastrelliger faughni             | 3  | 0.357         | 0.246 | 77.9       | 0.0789        | 0.0734    |
| Indo-Pacific mackerel| Rastrelliger brachysoma         | 3  | 0.261         | -     | 78.9       | 0.0551        | 0.0512    |
| Slimmy mackerel     | Scomber australasicus            | 10 | 0.269         | 0.065 | 77.7       | 0.0600        | 0.0558    |
| Indo-Pacific king mackerel| Scomberomorus guttatus | 9  | 0.262         | 0.355 | 75.9       | 0.0631        | 0.0587    |
| Narrowbarred Spanish mackerel | Scomberomorus commerson | 9  | 0.368         | 0.953 | 75.5       | 0.0902        | 0.0838    |
| Dogtooth tuna       | Gymnosarda unicolor              | 9  | 0.342         | 0.456 | 74.5       | 0.0872        | 0.0811    |
| Striped bonito      | Sarda orientalis                 | 6  | 0.543         | 1.048 | 76.9       | 0.1254        | 0.1167    |
| Longtail tuna       | Thunnus tonggol                  | 7  | 0.358         | 0.173 | 71         | 0.1038        | 0.0966    |
| Frigate tuna        | Auxis thazard thazard           | 2  | 0.237         | -     | 76.8       | 0.0550        | 0.0511    |
| Kawakawa            | Euthymus affinis                 | 2  | 0.289         | -     | 75.2       | 0.0717        | 0.0667    |
| Demersal fish       |                                  |    |               |       |            |               |           |
| Mangrove red snagge | Lutjanus argentimaculatus        | 3  | 0.856         | -     | 75.8       | 0.2072        | 0.1927    |
| Humpback red snapper| Lutjanus gibbus                  | 1  | 0.436         | -     | 82.1       | 0.0780        | 0.0726    |
| Emperor red snapper | Lutjanus sebae                   | 10 | 0.334         | 0.516 | 80.7       | 0.0645        | 0.0599    |
| Malabar blood snapper| Lutjanus malabaricus            | 3  | 0.413         | 0.366 | 80.9       | 0.0789        | 0.0734    |
| John's snapper      | Lutjanus russellii               | 4  | 1.366         | -     | 80.2       | 0.2705        | 0.2515    |
| Giant sea perch     | Lates calcarifer                 | 7  | 0.537         | 0.436 | 78.1       | 0.1176        | 0.1094    |
| Waigui sea perch    | Psammodopera waiginiensis        | 4  | 0.532         | 0.165 | 79.1       | 0.1112        | 0.1034    |
| Sharpnose stingray  | Himantura gerrardi               | 8  | 0.384         | 0.741 | 79.1       | 0.0803        | 0.0746    |
| Bluespotted stingray| Neotrygon kahlii                 | 6  | 0.492         | 1.251 | 82         | 0.0886        | 0.0824    |
| Pale-edged stingray | Dasyatis zuegi                   | 4  | 0.548         | 0.509 | 76.1       | 0.1310        | 0.1218    |
| Honeycomb stingray  | Himantura uarnak                 | 2  | 0.425         | -     | 79.2       | 0.0884        | 0.0822    |
| Reeve’s croaker     | Chrysochir aureus                | 3  | 0.498         | -     | 80.6       | 0.0966        | 0.0898    |
| Tigertooth croaker  | Otolithoides ruber               | 5  | 0.421         | 0.423 | 79.9       | 0.0846        | 0.0787    |
| Soldier croaker     | Nibeia soldado                   | 11 | 0.424         | 0.132 | 76.8       | 0.0984        | 0.0915    |
| Bronze croaker      | Otolithoides biauritus           | 1  | 0.069         | -     | 79.9       | 0.0139        | 0.0129    |
| Yellowbelly threadfin bream | Nemipterus bathybius | 5  | 0.383         | 0.328 | 76.9       | 0.0885        | 0.0823    |
| Japanese threadfin bream | Nemipterus japonicus          | 9  | 0.464         | 0.724 | 76.9       | 0.1072        | 0.0997    |
| Forktail threadfin bream | Nemipterus furcatus           | 3  | 0.642         | -     | 79.2       | 0.1335        | 0.1242    |
| Threadfin bream     | Nemipterus thosaporni           | 2  | 0.57          | 0.659 | 82.4       | 0.1003        | 0.0933    |
| Fivelined threadfin bream | Nemipterus tambuloides       | 2  | 0.426         | -     | 78.1       | 0.0933        | 0.0868    |
| Doublwhip threadfin bream | Nemipterus nematophorus      | 2  | 1.211         | -     | 80.4       | 0.2374        | 0.2207    |
| Red filament threadfin bream | Nemipterus marginatus       | 2  | 0.244         | -     | 76.2       | 0.0581        | 0.0540    |
| Redspine threadfin bream | Nemipterus nemurus         | 1  | 0.298         | -     | 79.5       | 0.0611        | 0.0568    |
| Total               |                                  | 128| 0.31          | 0.17  | 76.6       | 0.0738        | 0.0686    |
freshwater fish, as well as cephalopods and crustaceans. Table 4 showed the consumption of different categories of fish and seafood by different genders. The overall results showed that fish and seafood consumption by male subjects (95.2 ± 102 g/day) were significantly (p = 0.026) higher when compared to the female (86 ± 96.3 g/day) and female at reproductive age (81 ± 87.9 g/day). But no significant differences (p > 0.05) were shown for the other food categories between different genders except for total marine fish. Female at reproductive age consumed the least (44 ± 76.85 g/day) of this fish categories compared to the other two groups. Table 5 showed consumption of fish and seafood by higher consumers. The consumption rates by the third quartile (75th percentile) consumers were 2.1 to 3.6 times greater than that of the median consumers (50th percentile). The rates were even higher for the 90th and 95th percentile consumer groups at 2.9 to 4.4 times and 3.7 to 5.3 times, respectively.

**Health risk assessment (EWI, MSCW, and HQ)**

Health risk assessment (EWI, MSCW, and HQ) of meHg from consumption of fish and seafood by populations in Peninsular Malaysia at different demographic factors were shown in Table 6, and the EWI were expressed in microgram per unit body weight per week (µg/kg BW/week).

### Table 1 (continued)

| Common name       | Species               | n  | total Hg (DW) | IQR | 8MC (%) | Total Hg (WW) | 8meHg (WW) |
|-------------------|-----------------------|----|---------------|-----|---------|---------------|------------|
| **Total marine fish** |                       | 226| 0.42          | 0.40| 77.9    | 0.0910        | 0.0846     |
| **Freshwater fish** |                       |    |               |     |         |               |            |
| Catfish           | *Clarias batrachus*   | 9  | 0.334         | 0.325| 77.1 | 0.0490        | 0.0450     |
| **Cephalopods**   |                       |    |               |     |         |               |            |
| Golden cuttlefish | *Sepia esculenta*     | 6  | 0.257         | 0.11| 81.4 | 0.0478        | 0.0387     |
| Indian squid      | *Sepia pharaonis*     | 10 | 0.199         | 0.16| 81.4 | 0.0614        | 0.0497     |
| Little squid      | *Loligo duvaucelli*   | 4  | 0.249         | -   | 81.4 | 0.0370        | 0.0300     |
| Mitre squid       | *Loligo uyii*         | 7  | 0.275         | 0.12| 81.4 | 0.0463        | 0.0375     |
| Old women octopus | *Loligo chinensis*    | 1  | 0.208         | -   | 81.4 | 0.0512        | 0.0414     |
| Pharaoh cuttlefish| *Loligo sibogae*      | 2  | 0.33          | -   | 81.4 | 0.0677        | 0.0548     |
| Sibogae squid     | *Loligo edulis*       | 6  | 0.364         | 0.51| 81.4 | 0.0497        | 0.0402     |
| Sword tip squid   | *Cistopus indicus*    | 9  | 0.267         | 0.28| 81.4 | 0.0387        | 0.0313     |
| **Total**         |                       | 45 | 0.25          | 0.13| 81.4 | 0.0500        | 0.0405     |
| **Crustaceans**   |                       |    |               |     |         |               |            |
| Banana prawn      | *Penaeus merguiensis* | 7  | 0.277         | 0.10| 80.5 | 0.0540        | 0.0270     |
| Giant tiger prawn | *Penaeus monodon*     | 2  | 0.399         | -   | 80.5 | 0.0778        | 0.0389     |
| Greasyback shrimp | *Penaeus semissulcatus* | 3 | 0.251         | -   | 80.5 | 0.0532        | 0.0266     |
| Green tiger prawn | *Penaeus indicus*     | 2  | 0.273         | -   | 80.5 | 0.0538        | 0.0269     |
| Indian white prawn| *Penaeus japonicus*   | 8  | 0.276         | 0.13| 80.5 | 0.0260        | 0.1325     |
| Kuruma prawn      | *Penaeus latissulcatus* | 1 | 1.359         | -   | 80.5 | 0.0710        | 0.0355     |
| Pink shrimp       | *Metapenaeus ensis*   | 4  | 0.28          | 0.50| 80.5 | 0.0489        | 0.0245     |
| Rainbow shrimp    | *Metapenaeus affinis* | 4  | 0.242         | 0.25| 80.5 | 0.0546        | 0.0273     |
| Sand velvet shrimp| *Parapenaeopsis sculpitilis* | 9 | 0.269         | 0.08| 80.5 | 0.0472        | 0.0236     |
| Spear shrimp      | *Metapenaeopsis barbata* | 3 | 0.176         | -   | 80.5 | 0.0525        | 0.0262     |
| Western king prawn| *Parapenaeopsis hardwickii* | 5 | 0.364         | 0.17| 80.5 | 0.0343        | 0.0172     |
| Yellow shrimp     | *Metapenaeus brevicornis* | 4 | 0.215         | 0.05| 80.5 | 0.0419        | 0.0210     |
| **Total**         |                       | 52 | 0.272         | 0.15| 80.5 | 0.0712        | 0.0356     |
| **Overall**       |                       | 405| 0.06          | 0.05| 78.74| 0.0610        | 0.0305     |

Total Hg in median ± IQR; DW, dry weight; IQR, interquartile range; MC, moisture content

8MC content was based on the works by Tee et al. (1997) and Nurnadia et al. (2011)

 WW, wet weight; conversion of DW mercury concentrations in fish samples to WW were by means formula: DW = WW × (100/100-MC).

Details on total mercury concentrations in seafood are referred to Ahmad et al. (2015a, b)

Calculation of meHg concentrations were based on mean percentage of methylmercury to total mercury at 93% for fish, 81% for cephalopods and 50% for crustaceans (Anual et al 2018)

Comparison of meHg levels between different fish/seafood groups: χ²KW = 49.090, p = 0.000, N = 405, Median = 0.061 ± 0.050 mg/kg WW
Table 2  Freshwater fish and seafood consumption (g/day/person) (median ± IQR) by population in Peninsular Malaysia at different age categories

| Food category         | Age by category | p-value |
|-----------------------|-----------------|---------|
|                       | 10–17 years (n = 653) | 18–40 years (n = 1,209) | 41–60 years (n = 1,073) | ≥ 61 years (n = 422) |
| Pelagic fish          | 22.0 ± 32.7a    | 44.0 ± 60.7b   | 48.7 ± 66.4bc  | 48.3 ± 66.8bc | 0.000 |
| Demersal fish         | 30.5 ± 26.0a    | 46.0 ± 57.7a   | 35.0 ± 46.5b   | 52.0 ± 71.8b   | 0.017 |
| Total marine fish     | 26.0 ± 30.6a    | 50.0 ± 77.0b   | 60.0 ± 77.8bc  | 66.0 ± 100.7c  | 0.000 |
| Total freshwater fish | 38.3 ± 39.3     | 35.3 ± 45.4    | 36.7 ± 47.0    | 36.7 ± 77.3    | 0.790 |
| Cephalopods           | 80.0 ± 90.0a    | 30.0 ± 37.0b   | 40.0 ± 31.9bc  | 29.8 ± 31.9bc  | 0.000 |
| Crustaceans           | 63.0 ± 65.0a    | 13.3 ± 26.7b   | 21.0 ± 28.9bc  | 13.3 ± 22.9bc  | 0.000 |
| Overall consumption   | 84.9 ± 104.1a   | 82.0 ± 89.1a   | 95.8 ± 99.8b   | 104.0 ± 113.0c | 0.000 |

Age categories: 10–17 years, adolescents; 18–40 years, young adults; 41–60 years, older adults; ≥ 61 years, elderly; IQR, interquartile range

* Kruskal–Wallis test were applied

Different alphabet within the different columns indicated significant differences (p < 0.05)

Table 3  Freshwater fish and seafood consumption (g/day/person) (median ± IQR) by different ethnicities in Peninsular Malaysia

| Food category         | Ethnicity | p-value |
|-----------------------|-----------|---------|
|                       | Malays (n = 2,592) | Chinese (n = 457) | Indians (n = 270) |
| Pelagic fish          | 58.7 ± 64.0a    | 55.3 ± 46.5a   | 20.0 ± 79.0a    | 0.009 |
| Demersal fish         | 46.0 ± 49.0    | 37.3 ± 53.2    | 42.3 ± 37.6    | 0.763 |
| Total marine fish     | 69.5 ± 73.3a   | 45.0 ± 82.7ab  | 73.3bc         | 0.046 |
| Total freshwater fish | 36.7 ± 45.7    | 42.7 ± 30.8    | 44.0          | 0.532 |
| Cephalopods           | 47.8 ± 42.0    | 53.3 ± 0.0     | 26.7 ± 28.3    | 0.741 |
| Crustaceans           | 21.3 ± 20.7    | 3.8 ± 0.0      | 70.0 ± 36.5    | 0.908 |
| Overall consumption   | 96.1 ± 99.6a   | 66.0 ± 88.0b   | 60.0 ± 64.5bc  | 0.000 |

IQR, interquartile range

* Kruskal–Wallis test was applied

Different alphabet within the different columns indicated significant differences (p < 0.05)

Table 4  Freshwater fish and seafood consumption (g/day/person) (median ± IQR) by different gender in Peninsular Malaysia

| Food category         | Gender | p-value1 | p-value2 |
|-----------------------|--------|----------|----------|
|                       | Female (n = 1,859) | 4Female (reproductive age) (n = 1,091) | Male (n = 1,495) |
| Pelagic fish          | 70.7 ± 73.3 | 40.0 ± 60.7 | 58.7 ± 49.7 | 0.234 | 0.057 |
| Demersal fish         | 50.0 ± 58.0 | 41.2 ± 50.2 | 47.5 ± 54.5 | 0.876 | 0.980 |
| Total marine fish     | 58.7 ± 91.0 | 44.0 ± 76.8a | 53.7 ± 75.7b | 0.215 | 0.034 |
| Total freshwater fish | 35.3 ± 43.9 | 35.0 ± 35.7 | 46.0 ± 44.1 | 0.231 | 0.116 |
| Cephalopods           | 43.3 ± 31.7 | 31.9 ± 34.1 | 64.5 ± 40.3 | 0.231 | 0.329 |
| Crustaceans           | 26.7 ± 33.3 | 15.0 ± 33.2 | 29.3 ± 34.2 | 0.631 | 0.223 |
| Overall consumption   | 86.0 ± 96.3a | 81.0 ± 87.9b | 95.2 ± 102ab | 0.026 | 0.002 |

IQR, interquartile range

* Age between 15 and 49 years old

* Kruskal–Wallis test was applied

p value1, differences between female and male

p value2, differences between female at selected reproductive age and male

Different alphabet within the different columns indicated significant differences (p < 0.05)
The EWI estimated values showed results below 1.6 µg/kg BW/week, the acceptable or tolerable levels recommended by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) for all different demographic factors except for higher consumers at 75th percentile and above. The EWI for overall consumption of fish and seafood for higher consumers exceeded more than two times compared to the PTWI values, and major sources of meHg intake were from the consumption of both the pelagic and demersal fish. The EWI value for overall consumption of fish and seafood consumed by the 50th percentile consumers was 0.6443 µg/kg BW/week (Table 6), and this value is corresponding to 40% of the PTWI. Major sources of meHg were from the consumption of demersal (0.5149 µg/kg BW/week) and pelagic (0.4693 µg/kg BW/week) fish at 32% and 29% of the PTWI value, respectively. Consumption of marine fish contributed to a higher value of PTWI to all different demographic groups (the EWI range: 0.2988–0.6092 µg/kg BW/week) (Table 6) except for the adolescents, where the major sources for this group are from the consumption of crustaceans (0.3488 µg/kg BW/week or 22% of PTWI) and cephalopods (0.504 µg/kg BW/week or 32% of PTWI). These contributed to the EWI values of 0.8196 µg/kg BW/week or 51% of the PTWI for the overall consumption of fish and seafood among the adolescents. The value is at the highest rank when compared to the EWI values from the consumption of fish and seafood of the other groups.

MSWC values in kg are given on fish and seafood by group basis (Table 6). The amounts of demersal fish from Peninsular Malaysia which should be consumed by all population groups to reach the PTWI for meHg would be below 1 kg/week and very much lower (< 713 g/week) for the adolescents. The adolescents were allowed to consume < 2 kg per week (range: 1.04–2.02 kg/week) for all types of fish and seafood: to be more specific, about a kilogram for pelagic fish, one and a half kilogram to two kilograms of freshwater fish, the cephalopods, and crustaceans. While for the adults, they were allowed to consume a greater amount (< 2.5 kg/week) of marine and freshwater fish per week.

Table 6 also showed a summary of the HQ values for meHg from the consumption of fish and seafood by population in Peninsular Malaysia at different demographic backgrounds. The HQ is an integrated risk index that compares the ingested amount of meHg with the standard reference dose. The results from this study revealed that the overall consumption of fish and seafood by the adolescents and the elderly exceeded one. This is indicating the nonacceptable level of noncarcinogenic adverse health effects. Still, the HQ < 1 for the other groups of population at different types of fish and seafood categories assumes that daily exposure is not likely to cause negative health effects during the lifetime of the Malaysian population. High HQ values were contributed from the consumption of the demersal fish which exceeded a range between 0.5 and 0.8 or nearly 90% of the HQ values. For the adolescents, high HQ values were also contributed from the consumption of demersal fish, but the highest is from consumption of cephalopods. The high consumer at 75th percentile and above, the HQ values reached of up to 4.3 which indicated the presence of adverse effects due to meHg intoxication.

### Discussion

This study was carried out to assess the potential health risk of meHg exposure to population of Peninsular Malaysia from consumption of freshwater fish and seafood. We used two approaches for the estimation of human health risks to meHg in fish and seafood; the widely applied is the comparison with the PTWIs which representing the amount of meHg that can be ingested over a lifetime without appreciable risks (WHO 2011). Another approach is to determine risk through the value of HQ (USEPA 2000). This HQ value is an integrated index that compares the ingested amount of meHg with the standard reference dose where HQ < 1 signifies that the level of exposure is lower than the reference dose. It is assumed that a daily exposure at this level is not likely to cause any negative health effects during a lifetime in a human population.
Table 6  Health risk assessment (EWI, MSCW and HQ) of meHg from consumption of fish/seafood by populations in Peninsular Malaysia at different demographic factors

| Demographic factors | $n$ | BW (kg) | meHg (mg/kg WW) | Fish intake (g/day) | *EWI % | PTWI # | *MSWC (kg) | HQ |
|---------------------|-----|---------|-----------------|---------------------|--------|-------|-----------|-----|
| **Different age groups** |     |         |                 |                     |        |       |           |     |
| **Age 10–17 years old** | 653 |         |                 |                     |        |       |           |     |
| Pelagic fish        | 135 | 45      | 0.069           | 22.0                | 0.2361 | 15    | 1.0435    | 0.3235 |
| Demersal fish       | 28  | 45      | 0.101           | 30.5                | 0.4792 | 30    | 0.7129    | 0.6564 |
| Total marine fish   | 156 | 45      | 0.074           | 26.0                | 0.2988 | 19    | 0.9745    | 0.4093 |
| Total freshwater fish| 33 | 45      | 0.045           | 38.3                | 0.2681 | 17    | 1.6000    | 0.3673 |
| Cephalopods         | 43  | 45      | 0.041           | 80.0                | 0.5040 | 32    | 1.7778    | 0.6904 |
| Crustaceans         | 46  | 45      | 0.036           | 63.0                | 0.3488 | 22    | 2.0227    | 0.4779 |
| Overall consumption | 505 | 45      | 0.062           | 84.9                | 0.8196 | 51    | 1.1602    | 1.1227 |
| **Age 18–40 years old** | 1,209 |         |                 |                     |        |       |           |     |
| Pelagic fish        | 546 | 60      | 0.069           | 44.0                | 0.3542 | 22    | 1.3913    | 0.4852 |
| Demersal fish       | 95  | 60      | 0.101           | 46.0                | 0.5420 | 34    | 0.9505    | 0.7425 |
| Total marine fish   | 581 | 60      | 0.074           | 50.0                | 0.4310 | 27    | 1.2993    | 0.5904 |
| Total freshwater fish| 53 | 60      | 0.045           | 35.3                | 0.1853 | 12    | 2.1333    | 0.2539 |
| Cephalopods         | 71  | 60      | 0.041           | 30.0                | 0.1418 | 9     | 2.3704    | 0.1942 |
| Crustaceans         | 104 | 60      | 0.036           | 13.3                | 0.0552 | 3     | 2.6970    | 0.0757 |
| Overall consumption | 894 | 60      | 0.062           | 82.0                | 0.5937 | 37    | 1.5470    | 0.8132 |
| **Age 41–60 years old** | 1,073 |         |                 |                     |        |       |           |     |
| Pelagic fish        | 562 | 65      | 0.069           | 48.7                | 0.3619 | 23    | 1.5072    | 0.4957 |
| Demersal fish       | 118 | 65      | 0.101           | 35.0                | 0.3807 | 24    | 1.0297    | 0.5215 |
| Total marine fish   | 602 | 65      | 0.074           | 60.0                | 0.4774 | 30    | 1.4076    | 0.6540 |
| Total freshwater fish| 61 | 65      | 0.045           | 36.7                | 0.1779 | 11    | 2.3111    | 0.2436 |
| Cephalopods         | 80  | 65      | 0.041           | 40.0                | 0.1745 | 11    | 2.5679    | 0.2390 |
| Crustaceans         | 93  | 65      | 0.036           | 21.0                | 0.0805 | 5     | 2.9217    | 0.1103 |
| Overall consumption | 193 | 65      | 0.062           | 95.8                | 0.6402 | 40    | 1.6759    | 0.8770 |
| **Age ≥ 60 years old** | 422 |         |                 |                     |        |       |           |     |
| Pelagic fish        | 209 | 59      | 0.069           | 48.3                | 0.3954 | 25    | 1.3681    | 0.5417 |
| Demersal fish       | 60  | 59      | 0.101           | 52.0                | 0.6321 | 39    | 0.9347    | 0.8536 |
| Total marine fish   | 223 | 59      | 0.074           | 66.0                | 0.5786 | 36    | 1.2777    | 0.7925 |
| Total freshwater fish| 15 | 59      | 0.045           | 36.7                | 0.1959 | 12    | 2.0978    | 0.2684 |
| Cephalopods         | 18  | 59      | 0.041           | 29.8                | 0.1432 | 9     | 2.3309    | 0.1962 |
| Crustaceans         | 27  | 59      | 0.036           | 13.3                | 0.0562 | 4     | 2.6520    | 0.0769 |
| Overall consumption | 340 | 59      | 0.062           | 104.0               | 0.7657 | 48    | 1.5212    | 1.0489 |
| **Different ethnicity** |     |         |                 |                     |        |       |           |     |
| **Malays**          | 1,495 |         |                 |                     |        |       |           |     |
| Pelagic fish        | 1,219 | 59      | 0.069           | 58.7                | 0.4805 | 30    | 1.3681    | 0.6583 |
| Demersal fish       | 264 | 59      | 0.101           | 46.0                | 0.5512 | 34    | 0.9347    | 0.7551 |
| Total marine fish   | 1,314 | 59      | 0.074           | 69.5                | 0.6092 | 38    | 1.2777    | 0.8346 |
| Total freshwater fish| 150 | 59      | 0.045           | 36.7                | 0.1959 | 12    | 2.0978    | 0.2684 |
| Cephalopods         | 196 | 59      | 0.041           | 47.8                | 0.2297 | 14    | 2.3309    | 0.3146 |
| Crustaceans         | 219 | 59      | 0.036           | 21.3                | 0.0900 | 6     | 2.6520    | 0.1232 |
| Overall consumption | 2,116 | 59  | 0.062           | 96.1                | 0.7075 | 44    | 1.5212    | 0.9692 |
| **Chinese**         | 457 |         |                 |                     |        |       |           |     |
| Pelagic fish        | 125 | 60      | 0.069           | 55.3                | 0.4452 | 28    | 1.3913    | 0.6098 |
| Demersal fish       | 21  | 60      | 0.101           | 37.3                | 0.4395 | 27    | 0.9505    | 0.6021 |
| Total marine fish   | 131 | 60      | 0.074           | 45.0                | 0.3879 | 24    | 1.2993    | 0.5314 |
| Total freshwater fish| 5  | 60      | 0.045           | 42.7                | 0.2242 | 14    | 2.1333    | 0.3071 |
| Cephalopods         | 10  | 60      | 0.041           | 53.3                | 0.2518 | 16    | 2.3704    | 0.3450 |
Table 6 (continued)

| Demographic factors | $n$ | BW (kg) | meHg (mg/kg) WW | Fish intake (g/day) | *EWI | % PTWI | $^a$MSWC (kg) | HQ |
|---------------------|-----|---------|-----------------|---------------------|------|--------|---------------|----|
| Crustaceans         | 15  | 60      | 0.036           | 3.8                 | 0.0158 | 1      | 2.6970        | 0.0216 |
| Overall consumption | 274 | 60      | 0.062           | 66.0                | 0.4778 | 30     | 1.5470        | 0.6546 |
| **Indians**         |     |         |                 |                     |       |        |               |     |
| Pelagic fish        | 89  | 55      | 0.069           | 20.0                | 0.1756 | 11     | 1.2754        | 0.2406 |
| Demersal fish       | 10  | 55      | 0.101           | 42.3                | 0.5437 | 34     | 0.8713        | 0.7449 |
| Total marine fish   | 95  | 55      | 0.074           | 73.3                | 0.6893 | 43     | 1.1911        | 0.9442 |
| Total freshwater fish | 1  | 55      | 0.045           | 44.0                | 0.2520 | 16     | 1.9556        | 0.3452 |
| Cephalopods         | 6   | 55      | 0.041           | 26.7                | 0.1376 | 9      | 2.1728        | 0.1885 |
| Crustaceans         | 36  | 55      | 0.036           | 70.0                | 0.3171 | 20     | 2.4722        | 0.4344 |
| Overall consumption | 196 | 55      | 0.062           | 60.0                | 0.4739 | 30     | 1.4181        | 0.6492 |
| **Different gender**|     |         |                 |                     |       |        |               |     |
| Male                |     |         |                 |                     |       |        |               |     |
| Pelagic fish        | 645 | 62      | 0.069           | 58.7                | 0.4573 | 29     | 1.4377        | 0.6264 |
| Demersal fish       | 130 | 62      | 0.101           | 47.5                | 0.5417 | 34     | 0.9822        | 0.7420 |
| Total marine fish   | 690 | 62      | 0.074           | 53.7                | 0.4840 | 28     | 1.3426        | 0.6136 |
| Total freshwater fish | 83  | 62      | 0.045           | 46.0                | 0.2337 | 15     | 2.0444        | 0.3202 |
| Cephalopods         | 97  | 62      | 0.041           | 53.3                | 0.2437 | 15     | 2.4494        | 0.3339 |
| Crustaceans         | 112 | 62      | 0.036           | 28.0                | 0.1125 | 7      | 2.7869        | 0.1541 |
| Overall consumption | 1,142 | 62  | 0.062           | 95.2                | 0.6670 | 42     | 1.5986        | 0.9137 |
| Female              | 1,859 |       |                 |                     |       |        |               |     |
| Pelagic fish        | 806 | 57      | 0.069           | 70.7                | 0.5991 | 37     | 1.3217        | 0.8207 |
| Demersal fish       | 171 | 57      | 0.101           | 50.0                | 0.6202 | 39     | 0.9030        | 0.8496 |
| Total marine fish   | 871 | 57      | 0.074           | 58.7                | 0.5326 | 33     | 1.2344        | 0.7296 |
| Total freshwater fish | 79  | 57      | 0.045           | 35.3                | 0.1951 | 12     | 2.0267        | 0.2672 |
| Cephalopods         | 115 | 57      | 0.041           | 43.3                | 0.2154 | 13     | 2.2519        | 0.2950 |
| Crustaceans         | 158 | 57      | 0.036           | 26.7                | 0.1167 | 7      | 2.5621        | 0.1599 |
| Overall consumption | 1,474 | 57  | 0.062           | 86.0                | 0.6554 | 41     | 1.4969        | 0.8978 |
| Female **(reproductive age)** | 1,091 | | | | | | |
| Pelagic fish        | 477 | 59      | 0.069           | 40.0                | 0.3275 | 20     | 1.3681        | 0.4486 |
| Demersal fish       | 86  | 59      | 0.101           | 41.2                | 0.4937 | 31     | 0.9347        | 0.6763 |
| Total marine fish   | 514 | 59      | 0.074           | 44.0                | 0.3857 | 24     | 1.2777        | 0.5284 |
| Total freshwater fish | 49  | 59      | 0.045           | 35.0                | 0.1869 | 12     | 2.0978        | 0.2560 |
| Cephalopods         | 74  | 59      | 0.041           | 31.9                | 0.1533 | 10     | 2.3309        | 0.2100 |
| Crustaceans         | 96  | 59      | 0.036           | 15.0                | 0.0633 | 4      | 2.6520        | 0.0868 |
| Overall consumption | 841 | 59      | 0.062           | 81.0                | 0.5964 | 37     | 1.5212        | 0.8169 |
| **Consumption rate by percentile** | | | | | | | |
| Median (50 percentile) | 3,357 | | | | | | |
| Pelagic fish        | 1452 | 60 | 0.069           | 58.3                | 0.4693 | 29     | 1.3913        | 0.6429 |
| Demersal fish       | 301  | 60   | 0.101           | 43.7                | 0.5149 | 32     | 0.9505        | 0.7054 |
| Total marine fish   | 1562 | 60 | 0.074           | 51.1                | 0.4405 | 28     | 1.2993        | 0.6034 |
| Total freshwater fish | 162 | 60 | 0.045           | 36.7                | 0.1927 | 12     | 2.1333        | 0.2639 |
| Cephalopods         | 212 | 60     | 0.041           | 45.0                | 0.2126 | 13     | 2.3704        | 0.2913 |
| Crustaceans         | 270 | 60     | 0.036           | 22.9                | 0.0951 | 6      | 2.6970        | 0.1303 |
| Overall consumption | 2,619 | 60  | 0.062           | 89.0                | 0.6443 | 40     | 1.5470        | 0.8827 |
| **High consumer**   |     |         |                 |                     |       |        |               |     |
| Median (75th percentile) | 657 | | | | | | |
| Pelagic fish        | 323 | 60     | 0.069           | 124.3               | 1.0006 | 63     | NC            | 1.3707 |
| Demersal fish       | 72  | 60     | 0.101           | 105.0               | 1.2373 | 77     | NC            | 1.6949 |
| Total marine fish   | 368 | 60     | 0.074           | 149.5               | 1.2887 | 81     | NC            | 1.7653 |

**Environmental Science and Pollution Research (2022) 29:24816–24832**
It is well documented that meHg occurs at a high percentage in fish muscle and is the most toxic form of Hg. We analyzed THg in freshwater fish and seafood; these data were used to estimate meHg intakes for risk assessment data. In our earlier published data (Ahmad et al. 2015a, b), we presented and discussed in detail on THg levels in 46 species of commonly consumed marine fish samples and other seafood as well (cephalopods; 8 species and crustaceans; 12 species). The relationship between THg levels and size of samples (length and weight) was also discussed, and THg burden sampled from fish and seafood at different habitats, family group, and areas was compared. Previous results revealed only 1%, or three samples of demersal fish (bluespotted singray (Neotrygon kuhlii), honeycomb stingray (Himantura uarnak), and John’s snapper (Lutjanus ruselli)) had very high levels of THg (Ahmad et al 2015a). However, only one sample exceeded the Malaysian and international guidelines (FAO/WHO 2006; Malaysian Food Regulation 1985) when considering 95% or more of THg in the edible portion of seafood in the form of meHg (Khaniki et al 2005). The previous results for THg levels in crustaceans and cephalopods were either similar or reasonably low when compared to values published in various locations throughout the world (Ahmad et al 2015b), and none of these samples surpassed the guidelines. As data for meHg analysis in seafood for this country is scanty, we used levels recently reported by Anual and co-workers (Anual et al. 2018) for the nearest estimation, yet, only one sample each was analyzed for crustacean (Metapenaeus affinis) and cephalopod (Loligo duvauceli).

The recalculated levels of meHg in fish and seafood were shown in Table 1. The results showed significant differences ($p < 0.05$) between pelagic fish and the other three groups of demersal fish, crustacean, and cephalopod ($\chi^2_{KW} = 49.090, p = 0.000, N = 405, median = 0.061 \pm 0.050$ mg/kg WW). Concentrations of meHg in fish and seafood groups showed the highest in demersal fish (0.1006 mg/kg WW) followed by in pelagic fish (0.0686 mg/kg WW), freshwater fish (0.045 mg/kg WW), cephalopods (0.0405 mg/kg WW), and crustaceans (0.0356 mg/kg WW). The level of meHg reported in Algerian small pelagic fish (sardine, Sardina...
**pilchardus)** (0.04 mg/kg WW) is similar to levels from this study. However, in bigger pelagic (swordfish (**Xiphias gladius**); 0.57 mg/kg ww), its level is higher by nearly ten times (Mehouel et al. 2019). Similarly, in Taiwan meHg level in swordfish was reported to be five times higher (0.28 mg/kg of meHg) (Hsi et al. 2016). MeHg concentration in other most popular fish consumed by women of childbearing age in Taiwan also showed higher levels compared to this study, except for species like mackerel, milkfish, and anchovy. This group of researchers also reported that meHg levels in tilapia (Hsi et al. 2016) is similar when compared to its level in freshwater catfish captured from this study. Tang et al. (2009, 2014), respectively, reported on relatively low meHg levels in local small-size farmed freshwater or marine whole fish from Hong Kong (0.0045–0.16 µg/g).

In this study, we also calculated fish and seafood consumption pattern by the Malaysian population based on different background which included four different age groups, three major ethnicities, and gender. Data on consumption of higher fish and seafood consumers were also calculated at three centiles of 75th, 90th, and 95th. The main results illustrated the most relevant aspect of fish and seafood consumption patterns for the adolescent and adult population. In our previous fish consumption published data (Ahmad et al. 2016), the results were only presented for adults, and discussion has emphasized fish consumption frequencies or most consumed fish and seafood, most preferred cooking style, amounts of fish and seafood consumed by different types and groups, cooking style, and the amount per meal consumed by different ethnics in the country. Published data also described that Malay adolescents in this country consumed seafood most frequently compared to other food groups (Ahmad et al. 2019). The consumption data together with levels of meHg in freshwater fish and seafood enables us to calculate and evaluate its contamination status and possible health risk in fish and seafood in Peninsular Malaysia. Table 6 indicated that the risk index (percentage of the PTWI) of meHg is not likely to cause health effects at the estimated mean of fish and seafood consumption at 89 g/day or 623 g/week (median data for overall fish and seafood consumption) using the JECFA PTWI value guideline. The risk index by different demographic factors ranges between 30 and 51% of the PTWI. There were few studies that attempt to compare fish and seafood consumption with dietary intakes estimates of meHg, and the results were similar to this study where the risk index value was lower than the PTWI established by EFSA and JECFA (Mehouel et al. 2017; Tang et al. 2009; Tsuchiya et al. 2008). Mehouel and co-workers (Mehouel et al. 2019) assessed the risk of meHg intake through consumption of sardine and swordfish fished in three Algerian coasts; the EWI were at 2.8% and 40%, respectively. They highlighted the relationship between trophic levels and biomagnification factors where higher meHg concentration in large predatory fish is due to age, diet, and time of exposure. Intervention research on intake of fish meals based in the Polish subpopulation also revealed the risk index level of up to 38.8% with a range between 22.7 and 59.8%. These researchers also reported the hazard index at 0.39 and revealed that 32.8% of the volunteers exceeded the intake limit by the US-NRC (0.7 µg/kg bw) at 800 g/week of fish consumption (Kuras et al. 2017). Another related study is a dietary exposure of Hong Kong secondary school students which showed the estimated exposure to meHg at 25–31% for average fish consumers while the estimation for high consumer was between 75 and 88% of PTWI (Tang et al. 2009). Tsuchiya and co-workers (Tsuchiya et al. 2008) conducted a longitudinally study among women of child-bearing age within the Japanese and Korean populations in the state of Washington and reported the differences between levels of total mercury intake by these two populations: the Japanese at 0.09 µg/kg/d or 39% of PTWI and the Korean at 0.05 µg/kg/d or 22% of PTWI.

Our results also revealed that a higher risk index for all demographic groups was contributed from the consumption of marine fish, specifically the demersal group. Despite these results, the highest risk index was shown from the overall consumption of seafood by the adolescent and contributed from the consumption of cephalopod (EWI = 0.8196 µg/kg BW/week). For higher consumers, the EWI values were exceeded the PTWI (risk index > 100%) which also contributed mainly to the consumption of marine fish. The minimum intake of meHg (0.0158 to 0.3488 µg/kg BW/week) was found from the consumption of crustacean in all demographic groups (risk index < 10%) except at a higher rate for the adolescent and Indian ethnicity, which is at 22 and 20%, respectively. We also proved that meHg intake per kilogram body weight depended on species of fish and seafood being consumed. Exposure in some cases was close to the safety margin and observed in top predators and benthic carnivorous fish. Current study reported for this country showed that 14% of seafood had medium to high mercury concentrations with EWI higher than the PTWI. The results appeared for a few species of bream, snapper, croaker, barramundi, and tuna where the EWI values range from 2.1 to 4.0 µg/kg bw (Anual et al. 2018). Barone and co-workers (Barone et al. 2015) also reported on this matter where the highest risk index values were calculated from the consumption of such group of fish; the example was from the consumption of European conger eel (1.26 µg/kg bw/week), black belly rosefish (1.22 µg/kg bw/week), long-nose skate (1.12 µg/kg bw/week), swordfish (1.44 µg/kg bw/week), and Atlantic bluefin tuna (1.33 µg/kg bw/week). Although the toxicological evaluation seems to be no important hazard, the levels of meHg in these fishes should be under frequent surveillance. A suggestion has to be made for caution on their consumption by either regular fish consumers or the vulnerable
groups of pregnant and lactating women and also young children (Barone et al 2015).

In this current study, we pooled fish and seafood species into a larger group, and the risk index was calculated per group, not for specific species. The present estimations were also consistent with recommended PTWI for the general population, and the emphasis is placed on the toxicity of meHg which essentially accounts from the average data reported by Anual and co-workers (Anual et al. 2018). If we considered the worst-case situation on data for THg in fish and seafood samples, population with all demographic backgrounds would exceed the PTWI defined in the WHO/JECFA guidelines. As it is apparent from these results, a person from a different demographic background can consume 1 to 2 kg of fish and seafood groups weekly, and still the PTWI established by the FAO/WHO will not be exceeded. However, for demersal fish, the same person can only consume <1 kg (720 g) weekly before exceeding the PTWI value limit of 1.6 μg/kg body weight/week. The health risk exposure associated with the consumption of crustacean analyzed was minor with MSCW of 2 kg and above for all population groups. The exposure diet intake is linked to the HQ which signifies the relationship between the exposure obtained in the diet and the oral reference dose for meHg. The results of this study revealed health risk when HQs were computed for the vulnerable population in the community, while the HQ for adolescents and the elderly reached 1.1227 and 1.0489, respectively. The HQ values close to 1 were associated with the consumption of fish and seafood for adults age > 41 years old, Malay ethnic, both male and female group. Even, HQ for median fish and seafood consumption for the overall population reached 0.8827. The exposure to meHg in this study is likely to exceed the recommended value of PTWI in the case of consumption of high amount of fish and seafood with higher Hg content. The results showed that high consumers consumed fish and seafood at 322 to 406 g/day or 2.3 to 2.8 kg/week. The EWI would be 2.3 to 2.9 μg/kg BW/week or risk index of 146 to 184% compared to the PTWI. These factors caused HQ values to rise above one, ranging from 3.1 to 4.0 for more affluent consumers (fish/seafood intake in the 75th percentile). These results showed that average consumers are doubtful to encounter unnecessary health effects from meHg due to fish and seafood consumption, but the risk is higher for adolescents, the elderly, and high consumers. This study also found that adolescents consumed different types of seafood compared to adults at different demographic factors. They preferred cephalopods and crustaceans, and these groups contributed to the highest mean estimated meHg weekly intakes (EWI) other than from demersal fish. Although the level of meHg in cephalopod and crustacean is lower compared to other marine fish, a high amount of consumption caused these groups of seafood to be significant contributors to meHg accumulation in adolescents in Peninsular Malaysia. Similar patterns of results were reported elsewhere, for example, Andrew et al. (2016) demonstrated the disability-adjusted life years (DALYs) for eating different parts of fish using a risk model (iRISK) and reported the frequency of consumption had exposed the children (< 17 years old) to noncarcinogenic risk, even the amount of Hg in fish part was minute. Their finding also showed that frequent access to tilapia fish in the community and district market attributed to more DALYs. Other findings conducted among secondary school students in Hong Kong revealed that there were no undesirable health effects from consumption of median level of meHg of seafood for both average and high consumers but other sources of meHg, namely shellfish and other seafood products, might add significantly to dietary exposure (Tang et al 2009). Studies on the association between seafood consumption and meHg accumulation revealed a higher average daily dose (ADD) level among the higher seafood consumers who resided in the coastal areas compared to the inland residents (Lee et al. 2012; Jeewanaranj et al 2018).

Conclusions

The median concentrations of meHg in fish and seafood from Peninsular Malaysia were within the permissible limits by both national and international guidelines. MeHg evaluation seems to be an important hazard associated with average seafood consumers. However, the risk is significantly higher for high consumers when the value of EWI estimated for this group had approached the PTWI. Exposure in some cases was close to the safety margins, thus the meHg level in a certain group of seafood; the demersal fish is recommended to be under frequent surveillance. Regular fish consumers are suggested to be cautious in their consumption of seafood with higher levels of meHg, particularly in young children and the elderly. There is a need for community compassion about risks associated with mercury especially for the vulnerable group. A potential exposure source from consumption of shellfish should be further monitored. There is also a need to investigate the amount of meHg in blood and hair for the total population in the country as human biomonitoring programs are important tools in assessing current population exposure and in discovering trends and patterns related to policies, lifestyle, and food consumption. Information from this study is essential for assessing the effectiveness of policies and advisory authorities in developing relevant consumer recommendations with respect to consumption of seafood and health risk. There is a need to update and refine food consumption databases and levels of meHg in seafood for the purpose of constructing safe-eating guidelines for the public. The limitation of this study is that meHg data in seafood were generated from an earlier study that reported...
from a limited number of samples. However, this is the nearest estimated which is possible to calculate meHg data for risk assessment estimation to the population in the country.

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Author contribution Nurul Izzah Ahmad: conceptualization, methodology, sampling, sample and data analysis, visualization, preparation of the original draft, writing—review and editing. Wan Rozita Wan Mahiyuddin: methodology and data analysis. Wan Nurul Farah Wan Azmi: methodology, sample and data analysis. Ruzanaz Syafira Ruzman Azlee: data analysis. Rafiza Shaharudin: writing—review. Lokman Hakim Sulaiman: conceptualization and methodology.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The project was funded by the National Institutes of Health Malaysia, and the proposal was priority reviewed and approved by the Medical Research and Ethics Committee, Ministry of Health Malaysia.

Consent of participate The informed consent and confidentiality were obtained from the subjects included in the study beforehand.

Competing interests The authors declare no competing interests.

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References

Agusa T, Kunito T, Yasunaga G, Iwata H, Subramanian A, Ismail A, Tanabe S (2005) Concentration of trace elements in marine fish and its risk assessment in Malaysia. Mar Pollut Bull 51:896–911. https://doi.org/10.1016/j.marpolbul.2005.06.007
Ahmad NI (2007) Penilaian risiko pengambilan sisa racun perosak terpilih melalui pemakanan sayur-sayuran di kalangan penduduk dewasa di negeri Selangor. Malaysia: Universiti Kebangsaan Malaysia:PhD thesis. https://malcat.ukm.edu.my/kip/Record/ukm.b14173888
Ahmad NI, Mohd Fairulnizal MN, Wan Rozita WM, Hamdani J, Ismail I, Wan Nurul Farah WA, Yuvaneswary V, Mohd HH (2015a) Mercury levels of marine fish commonly consumed in Peninsular Malaysia. Environ Sci Pollut Res 22:3672–3686. https://doi.org/10.1007/s11356-014-3538-8
Ahmad NI, MohdFairulnizal MN, Wan Rozita W, Hamdani J, Ismail I, Wan Nurul Farah WA, Yuvaneswary V, Fazlin Anis M (2015b) Determination of total mercury levels in commercial cephalopod and crustacean in Peninsular Malaysia. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-015-4415-9
Ahmad NI, Wan Rozita WM, Tengku Rozaina TM, Cheong YL, Siti Fatimah D, Nasiyah CH, Nor Ainia A, Rafiza S, Lokman Hakim S (2016) Fish consumption pattern among adults of different ethnicities in Peninsular Malaysia. Food Nutr Res 60:32697. https://doi.org/10.3402/nfr.v60.32697
Ahmad NI, Nadia M, Wan Rozita WM, Tengku Rozaina TM, Rafiza S, Lokman Hakim S (2019) The prevalence of overweight and obesity and its association factors among Malays’ adolescents: findings from seafood consumption survey in Peninsular Malaysia. J Child Obes 4:2. http://childhood-obesity.imedpub.com
Alina M, Azrina A, Mohd Yunus AS, Mohd Zakuardi S, Mohd Izuan Effendi H, Muhammad Rizal R (2012) Heavy metal (mercury, arsenic, cadmium, plumbing) in selected marine fish and shellfish along the Straits of Malacca. Int Food Res J 19(1):135–140. https://doi.org/10.1016/j.jmarpolbul.2005.06.007
Al-Mughairi S, Yusudhason P, AL-Busaidi M, AL-Waili A, Al-Rabhi WAK, Al-Mazrooei N, Al-Habsi SH (2013) Concentration and exposure assessment of mercury in commercial fish and other seafood marketed in Oman. J Food Sci 78(7):T1082–T1090. https://doi.org/10.1111/1750-3841.12150
Andrew T, Francis E, Charles M, Irene N, Jesco N, Ocaido M, Drago K, Celcus S, Deborah A, Rumbeilha W (2016) Risk estimates for children and pregnant women exposed to mercury-contaminated Oreochromis niloticus and Lates niloticus in Lakes Albert Uganda. Cogent Food Agric 2:1228732. https://doi.org/10.1080/23319332.2016.1228732
Anual ZF, Maher W, Krikowa K, Sulaiman LH, Ahmad NI, Foster S (2018) Mercury and risk assessment from consumption of crustaceans, cephalopods and fish from West Peninsular Malaysia. Microchem J 140:214–221. https://doi.org/10.1016/j.microc.2018.04.024
Barone G, Storelli R, Busco VP, Quaglia NC, Centrone G, Storelli MM (2015) Assessment of mercury and cadmium via seafood consumption in Italy: estimated dietary intake (EWI) and target hazard quotient (THQ). Food Addit Contam A. https://doi.org/10.1080/19440049.2015.1055594
Bhupander K, Mukherjee DP (2011) Assessment of human health risk for arsenic, copper, nickel and zinc in fish collected from Tropical Wetlands in India. Adv Life Sci Technol. ISSN 2224–7181 (Paper) ISSN 2225–062X Vol 2
Budiyanto F, Arbi UY, Suratno (2019) Risk assessment on mercury concentration in six edible mollusks from Bintan Island, Indonesia. Inter. Conference on Biology and Applied Science (ICOBAS). AIP Conf. 2120, 040009–1–040009–8; https://doi.org/10.1063/1.5115647
Burger J (2009) Risk to consumers from mercury in bluefish (Pomatomus saltatrix) from New Caledonia. Environ Res 109:803–811. https://doi.org/10.1016/j.envres.2009.07.005
Chouvelon T, Warnau M, Churlaud C, Bastumante P (2009) Hg concentrations and related risk assessment in coral reef crustaceans, mollusk and fish from New Caledonia. Environ Pollut 157:331–340. https://doi.org/10.1016/j.envpol.2008.06.027
Clarkson TW, Magos L, Myers GJ (2003) The toxicology of mercury-
aceous forms: Bryconidae) and human health risk by consumption of this fish from the Teles Pires River, Southern Amazonia. Neotrop Ichthyol 16(1):e160106. https://doi.org/10.1592/1982-0224-20160

Hajeb P, Jinap S (2011) Mercury exposure through fish and seafood consumption in the rural and urban coastal communities of Peninsular Malaysia. World J Fish Mar Sci 3(3):217–226

Hajeb P, Jinap S, Ahmad I (2010) Biomagnifications of mercury and methylmercury in tuna and mackerel. Environ Monit Assess 171:205-217. https://doi.org/10.1007/s10661-009-1272-3

Hajeb P, Jinap S, Ismail A, Fatimah AB, Jamilah B, Abdul RM (2009) Assessment of mercury level in commonly consumed marine fishes in Malaysia. Food Control 20:79–84. https://doi.org/10.1016/j.foodcont.2008.02.012

Hsi HC, Hsu YW, Chang TC, Chien LC (2016) Methylmercury exposure via sardine and swordfish consumption in Algeria. J Hellenic Vet Med Soc 70(3):1679–1686. https://doi.org/10.12681/jhvm.s.21792

Mehouel F, Bouyad L, Berber A, Van hautegeh I, Van de Wiele (2019) Risk assessment of mercury and methyl mercury intake via sardine and swordfish consumption in Algeria. J Hellenic Vet Med Soc 70(3):1679–1686. https://doi.org/10.12681/jhvm.s.21792

Mohd Fairunizal MN, Tumijah AH, Zakiah I (1998) Determination of mercury in urine by on-line digestion with a flow injection mercury system. Atomic Spectrosc 19(3):95–99. https://www.reserchgate.net/publication/232804981_Determination_of_Mercury_in_Urine_by_On-Line_Digestion_with_a_Flow_Injection_Mercury_System [Cited 10 July 2019]

Mok WJ, Senoo S, Itoh T, Tsukamasu Y, Kawasaki K, Ando M (2012) Assessment of concentrations toxic elements in aquaculture food products in Malaysia. Food Chem 133:1326–1332. https://doi.org/10.1016/j.foodchem.2012.02.011

Morgano MA, Rabonato LC, Milani RF, Miyaguskia L, Balian SC (2011) Assessment of trace elements in fishes of Japanese foods marketed in Sao Paulo (Brazil). Food Control 22:778–785. https://doi.org/10.1016/j.foodcont.2010.11.016

Nurnadia AA, Azrina A, Amin I (2011) Proximate composition and energetic value of selected marine fish and shellfish from the West Coast of Peninsular Malaysia. Int Food Res J 18:137–148. http://www.irj.upm.edu.my/18%20(01)%202011/14(2)PFJR-2010-059%20Azrina%20UPM[1].pdf

Okati N, Shahriri Moghadam M, Einnollahipheer F (2021) An evaluation of target hazard quotiation of mercury and Arsenic in four commercially fish species of the Oman Sea, Iran. J Wildl Biodivers 5(3):1–20. https://doi.org/10.22212/jwjb.2021.138824.1192

Ouboter PE, Landburg G, Satnarain GU, Starke SY, Nanden I, Simon-Fried B, Hawkins WB, Taylor R, Lichveld MY, Harville E, Wicklilfe JK (2018) Mercury levels in Women and children from interior villages in Suriname, South America. Int J Environ Res Public Health 15:1007. https://doi.org/10.3390/ijerph15051007

Rakib MRJ, Jolly YN, Enyoh CE et al (2021) Level and health risk assessment of heavy metals in dried fish consumed in Bangladesh. Sci Rep 11:14642. https://doi.org/10.1038/s41598-021-93989-w

Statistical Department of Malaysia (2000) Press statement: population distribution and basic demographic characteristics report population and housing census. Available from: http://www.statistics.gov.my/English/pressdemo.htm. [Cited 10 July 2015]

Stuchal LD, Charles-Ayinde MKS, Kane AS, Kozuch M, Roberts SM (2019) Probabilistic risk assessment for high-end consumers of seafood on the Northeastern Gulf Coast. J Expos Sci Environ Epidemiol. Author manuscript; available in PMC. August 07. https://doi.org/10.1093/jesep/ezy064

Tang ASP, Kwong KP, Chung SC, Ho YY, Xiao Y (2009) Dietary exposure of Hong Kong secondary school students to total mercury and methylmercury from fish intake. Food Addit Contam B 2(1):8–14. https://doi.org/10.1080/02652030802642102

Tee ES, Mohd Ismail N, Mohd Nasir A, Khatijah I (1997) Nitrient composition of Malaysian foods. ASEAN Sub-Committee on protein: food habits research and development, Kuala Lumpur: Institute for Medical Research

Tsukamasa Y, Kawasaki K, Ando M (2012) Assessment of concentrations toxic elements in aquaculture food products in Malaysia. Food Chem 133:1326–1332. https://doi.org/10.1016/j.foodchem.2012.02.011

US Environmental Protection Agency (USEPA) (2000) Guidance for assessing chemical contaminant data for use in fish advisory vol. II: risk assessment and fish consumption limits. US Environmental
Protection Agency, Office of Science and Technology, Office of Water, Washington (D.C.), EPA823-B-00-008. Retrieved January 2019 from https://www.epa.gov/sites/default/files/2015-06/documents/volume2.pdf [Cited 10 July 2019]

Vasconcellos ACSd, Hallwass G, Bezerra JG, Aciole ANS, Meneses HNdM, Lima MdO, Jesus IMd, Hacon SdS, Basta PC (2021) Health risk assessment of mercury exposure from fish consumption in Munduruku indigenous communities in the Brazilian amazon. Int J Environ Res Public Health 18(15):7940. https://doi.org/10.3390/ijerph18157940

von Stackelberg K, Miling Li, Sunderland E (2017) Results of a national survey of high-frequency fish consumers in the United States. Environ Res 158:126–136. https://doi.org/10.1016/j.envres.2017.05.042

Wan Azmi WNF, Ahmad NI, and Wan Mahiyuddin WR (2019) Heavy metal levels and risk assessment from consumption of marine fish in Peninsular Malaysia. J Environ Prot 10(11). https://doi.org/10.4236/jep.2019.1011086

WHO/FAO (2011) Safety evaluation of certain contaminants in food. WHO Food Additive. Series 63, India p. 673 Retreived January 2019 from http://www.fao.org/3/ at881e/ at881e.pdf [Cited 10 July 2019]

Whyte ALH, Hook GR, Greening GE, Gibbs-Smith E, Gardner JPA (2009) Human dietary exposure to heavy metals via the consumption of greenshell mussels (Perna canaliculus Gmelin 1791) from the Bay of Islands, Northern New Zealand. Sci Total Environ 407:4348–4355. https://doi.org/10.1016/j.scitotenv.2009.04.011

You SH, Wang SL, Pan WH, Chan WC, Fan AM, Lin P (2018) Risk assessment or methyl mercury based on internal exposure and fish and seafood consumption estimates in Taiwanese children. Int J Hyg Environ Health. https://doi.org/10.1016/j.ijeh.2018.03.220

Zolfaghari G (2018) Risk assessment of mercury and lead in fish species from Iranian international wetlands. Methods x 5:438–447. https://doi.org/10.1016/j.mx.2018.05.002

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