

Assessing and managing the health risk due to ingestion of inorganic arsenic from ...sh and shell...sh farmed in blackfoot disease areas for general Taiwanese

Ching-Ping Liang^a, Chen-Wuing Liu^{b,*}, Cheng-Shin Jang^c, Sheng-Wei Wang^d, Jin-Jing Lee^e

^aDepartment of Environmental Engineering and Science, Fooyin University, Kaohsiung 831, Taiwan, ROC

^bDepartment of Bioenvironmental Systems Engineering, National Taiwan University, Taipei 106, Taiwan, ROC

^cDepartment of Leisure and Recreation Management, Kainan University, Luzhu, Taoyuan 338, Taiwan, ROC

^dAgricultural Engineering Research Center, Jhongli, Taoyuan 320, Taiwan, ROC

^eDepartment of Environmental Sanitation and Toxic Substance Management, Environmental Protection Administration, Executive Yuan 100, Taiwan, ROC

article info

Article history:
Received 29 June 2010
Received in revised form 8 October 2010
Accepted 10 November 2010
Available online 16 November 2010

Keywords:
Risk
Fish and shell...sh
Arsenic
Groundwater
Consumption rate

abstract

This paper assesses health risks due to the ingestion of inorganic arsenic from ...sh and shell...sh farmed in blackfoot disease areas by general public in Taiwan. The provisional tolerable weekly intake of arsenic set by FAO/WHO and the target cancer risk assessment model proposed by USEPA were integrated to evaluate the acceptable consumption rate. Five aquacultural species, tilapia (*Oreochromis mossambicus*), milk...sh (*Chanos chanos*), mullet (*Mugil cephalus*), clam (*Meretrix lusoria*) and oyster (*Crassostrea gigas*) were included. Monte Carlo analysis was used to propagate the parameter uncertainty and to probabilistically assess the health risk associated with the daily intake of inorganic As from farmed ...sh and shell...sh. The integrated risk-based analysis indicates that the associated 50th and 95th percentile health risk are 2.06×10^{-5} and 8.77×10^{-5} , respectively. Moreover, the acceptable intakes of inorganic As are determined and illustrated by a two dimensional graphical model. According to the relationship between C_{inorg} and IR_f derived from this study, two risk-based curves are constructed. An acceptable risk zone is determined (risk ranging from 1×10^{-5} to 6.07×10^{-5}) which is recommended for acceptable consumption rates of ...sh and shell...sh. To manage the health risk due to the ingestion of inorganic As from ...sh and shell...sh in BFD areas, a risk-based management scheme is derived which provides a convenient way for general public to self-determine the acceptable seafood consumption rate.

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1. Introduction

The risk of inorganic arsenic (As) contamination in human food sources has recently received a great public attention because of the potential hazard to human health. Inorganic As compounds are carcinogenic to humans, with evidence for an increased cancer risk of the urinary bladder, lung, and skin [1,2]. People can be exposed to As from a variety of sources (food, water, soil and air), but exposure via ingestion of seafood is by far the most significant one. Martí-Cid et al. [3] indicated that ...sh and shell...sh are the main group showing the highest contribution to the dietary intake of inorganic As. The highest dietary As intake ($217.7 \text{ } \mu\text{g/day}$) came from the consumption of ...sh and seafood, as indicated by Falcó et al. [4]. Farmed ...sh/shrimp bioaccumulates certain amounts of As from aquaculture-used As-contaminated groundwater [5–7]. In recent years, several studies have investigated the amounts of As species contents in seafood to assess the risk of cancer associated

with consuming aquatic products obtained from As-contaminated groundwater areas of local inhabitants, such as the coastal regions of southwestern Taiwan [8–17].

It has also been well documented that As is a major risk factor for blackfoot disease (BFD) [18] and indeed, over the past few decades BFD has become prevalent in the southwestern coastal area of Taiwan (Fig. 1) [19]. Extensive epidemiological evidence has proven that drinking groundwater with a high As content is closely associated with the occurrence of BFD [20]. Nowadays, very few inhabitants in this region drink well water directly, but large amounts of groundwater are utilized for ...sh and shell...sh farming [9]. Since As is accumulated in aquatic organisms [21], the high As content in the groundwater ranging 470–897 $\mu\text{g/l}$ used for aquaculture has resulted in an accumulation of As in the cultured ...sh and shell...sh. Tilapia (*Oreochromis mossambicus*), milk...sh (*Chanos chanos*), mullet (*Mugil cephalus*), clams (*Meretrix lusoria*) and oysters (*Crassostrea gigas*) are the ...ve major aquaculture species farmed in the BFD areas which are frequently consumed by the general population of Taiwan [22].

The WHO and the Food and Agriculture Organization (FAO) recommended a regular ...sh consumption of 1–2 servings per week in

* Corresponding author. Tel.: +886 2 2362 6480; fax: +886 2 2363 9557.
E-mail addresses: cw@water.agec.ntu.edu.tw, twpcwliu@ntu.edu.tw (C.-W. Liu).

Fig. 1. BFD areas in southwestern Taiwan. The colored areas are the ...sh ponds where tilapia (TP), milk...sh (MF), mullet (MU), and clams (CL) are cultivated. Oysters are farmed in the inner sea of Putai. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

order to provide an equivalent of 200–500 mg of the ...3 polyunsaturated fatty acids (...3-PUFA) eicosapentaenoic and docosahexaenoic acids [23]. The health benefits of a diet rich in ...sh have been extensively recognized specially in the last decade. Namely, ...3-PUFA

is associated with decreased morbidity and mortality from various diseases. Fish and shell...sh are healthy sources of protein, but the risks accrued from consuming contaminated ...sh and shell...sh have become national concerns [24–27]. Most of previous studies

Table 1
Aquatic species, sample size, location, total As concentration in farmed water, inorganic arsenic (As(V), As(III)), total arsenic concentrations and fitted inorganic As concentration distributions of ...sh and shell...sh in the BFD areas.

| Species | Sample size | Location | Arsenic species analyzed | Total As concentration in farmed water (...g/l) | As species concentration (mean ± SD (...g/g)) | | | Inorganic As distributions (...g/g) |
|------------------------|-------------|---------------------|---|---|---|---------------|-------------|-------------------------------------|
| | | | | | As(III) | As(V) | Total As | |
| Tilapia ^b | 68 | BFD areas | As(III), As(V), MMA, DMA, AsB, Total As | 4.4–302.8 in pond water | 0.026 ± 0.043 | 0.027 ± 0.042 | 0.85 ± 0.83 | LN(0.03, 2.94) ^c |
| Milk...sh ^d | 36 | BFD areas | Inorganic arsenic, Total As | 27 in pond water | 0.33 ± 0.45 | | 0.75 ± 0.92 | LN(0.21, 2.43) |
| Mullet ^e | 24 | Southwestern Taiwan | As(III), As(V), MMA, DMA, AsB, Total As | 49 in pond water | 0.008 ± 0.005 | 0.036 ± 0.023 | 3.28 ± 1.32 | LN(0.03, 1.81) |
| Oyster ^f | 252 | Southwestern Taiwan | As(III), As(V), MMA, DMA, AsB, Total As | 0.15–5 in surface water | 0.091 ± 0.104 | 0.033 ± 0.038 | 9.90 ± 3.68 | LN(0.12, 2.11) |
| Clam ^g | 47 | Southwestern Taiwan | As(III), As(V), MMA, DMA, AsB, Total As | 40–97 in pond water | 0.96 ± 0.65 | 0.17 ± 0.21 | 8.48 ± 4.87 | LN(0.83, 2.33) |

^a Inorganic As is the summation of As(III) and As(V).

^b LN (...g/g) denotes a log-normal distribution identified by a Kolmogorov–Smirnov (K–S) test with a geometric average of ...g and a geometric standard deviation of ...g.

^c Value was taken from Huang et al. [29].

^d Value was taken from Lin and Liao [16].

^e Value was taken from Liu et al. [13–15].

^f Value was taken from Liu et al. [13–15].

^g Value was taken from Liu et al. [13–15].

were focused on the health risk assessment of inhabitants in the BFD areas based on the consumption of single As-contaminated ...sh or shell...sh [9,10,12–14,16]. High target cancer risks ($TR \sim 10^{-4}$) were reported [9,16]. However, the health risk associated with the ingestion of these aquatic species produced from BFD areas by the general population of Taiwan is lacking. Moreover, the method used to assess the health effect is limited to the target cancer risk proposed by USEPA, the provisional tolerable weekly intake set by FAO/WHO is not considered [9,12–14,16]. Thus, the study aims to assess the health risk due to ingestion of inorganic As from ...sh and shell...sh farmed in the BFD areas for general Taiwanese. The probabilistic risk assessment method supported by USEPA and the provisional tolerable weekly intake (PTWI) of As set by FAO/WHO are integrated to assess acceptable consumption rates of ...sh and shell...sh farmed in As-contaminated BFD areas. Moreover, Monte Carlo (MC) simulation is adopted to propagate the uncertainty of parameters concerning inorganic As exposure. The results provide a convenient guideline for self-management of acceptable consumption rates while ingesting popular ...sh and shell...sh from As-contaminated BFD areas.

2. Material and methods

2.1. Study region

The study region, the BFD areas, includes the Putai, Yichu, Hsuehchia and Peimen townships located in the plain region of Chiayi and Tainan counties, all of which are As-contaminated groundwater areas in southwestern Taiwan (Fig. 1). Aquaculture is the primary source of revenue for the local inhabitants in these coastal plains. Tilapia, milk...sh, mullet, and clams are mainly cultured in inland ...sh ponds, while oysters are farmed in the shallow inner sea of the Putai township. According to the geographical information system (GIS) database obtained from the Taiwan Fishery Agency, approximately 30% of the land in these townships is used for aquaculture ponds [28]. For the inland aquaculture, 37.8%, 18.4%, 2.5% and 7.6% of the ...sh ponds are farmed milk...sh, tilapia, mullet and clams, respectively. The ratio of aquaculture area in the study region to the total aquaculture area in Taiwan (for the aforementioned species) is 22.8% for oysters, 17.9% for milk...sh, 14.4% for tilapia, 13.2% for clams and 2.0% for mullet [22]. Moreover, the amount of oysters produced in the Putai township constitutes 35.6% of the total amount produced in Taiwan. Tilapia, milk...sh, mullet, clams and oyster are popular farmed species consumed by general population in Taiwan. Large amount of high As content groundwater is withdrawn for aquaculture need. Use of high As contents groundwater for aquaculture has resulted in an accumulation of As in cultured ...sh and shell...sh in BFD areas [15].

2.2. Inorganic arsenic contents in ...sh and shell...sh

Huang et al. [29], Lin and Liao [16], and Liu et al. [13–15] have sampled farmed tilapia, milk...sh, mullet, oysters and clams and reported the measurements for inorganic As contents, respectively (Table 1). Table 1 presents the aquatic species, sample size, location, As concentration of farmed water, measured inorganic As (As(V), As(III)) and total As concentrations of ...sh and shell...sh in As-contaminated groundwater areas. Detailed description of analysis of As species in ...sh and shell...sh can be found in previously published literatures [13–16,29]. The inorganic As contents of ...ve ...sh and shell...sh were ...tted by various probability density functions and followed log-normal distributions as determined by the 2 and Kolmogorov–Smirnov (K–S) statistics which optimized the goodness of ...t of distribution.

Table 2
Used parameters for cancer risk estimation for ingestion of ...sh and shell...sh farmed in the BFD areas.

| Species | Parameters | IR _w a(g/day) | ..b | ..c | ..d | C _{inorg} (...g/g) | |
|------------------------|------------|--------------------------|------|-------|-------|-----------------------------|------------------|
| | | | | | | 50% _o | 95% _o |
| Tilapia ^e | | 12.7 | 0.32 | 0.073 | 0.773 | 0.03 | 0.17 |
| Milk...sh ^f | | 10.9 | 0.32 | 0.441 | 0.773 | 0.21 | 0.92 |
| Mullet ^g | | 0.6 | 0.32 | 0.016 | 0.76 | 0.04 | 0.10 |
| Oyster ^h | | 12.4 | 0.2 | 0.015 | 0.85 | 0.12 | 0.44 |
| Clam ⁱ | | 6.1 | 0.2 | 0.135 | 0.83 | 0.83 | 3.44 |

- a Council of Agriculture, Taiwan (2007).
- b .. is the ratio of edible weight to total weight of ...sh and shell...sh.
- c .. is the ratio of inorganic As content to total As content in ...sh and shell...sh.
- d .. is the water content in ...sh and shell...sh.
- e Value was taken from Huang et al. [29].
- f Value was taken from Lin and Liao [16].
- g Value was taken from Liu et al. [13–15].
- h Value was taken from Liu et al. [13–15].
- i Value was taken from Liu et al. [13–15].

2.3. Dietary exposure via the ingestion of ...sh and shell...sh

We assessed the human health risk of intake of inorganic As via the ingestion of the ...sh and shell...sh farmed in As-contaminated BFD areas. The potential carcinogenic risk due to the uptake of inorganic As from various seafood species was assessed using the method suggested by the US EPA [30,31]. Table 2 shows used parameters for cancer risk estimation. The 50th and 95th percentiles were also tabulated for the analyses of the daily consumer intake of inorganic As from seafood. This work probabilistically treats inorganic As contents in various ...sh and shell...sh species. Data on daily consumption of aquaculture species by the general population of Taiwan were obtained from the Taiwanese Food Supply and Demand Annual Report of 2008 [22]. The daily intake of inorganic As from each type of ...sh and shell...sh was calculated by multiplying the individual As concentration in each species with the average amount of ...sh and shell...sh consumed by the public. The total intake of inorganic As was obtained by summing the products for all ...ve aquaculture species. Thus, the total daily intake of inorganic As (DI) can be calculated as follows:

$$DI = \sum_{i=1}^5 IR_i \cdot C_{inorg,i} = \sum_{i=1}^5 (IR_{w,i} \cdot \dots_i) [C_{f,i} \cdot \dots_i (1 - w_{w,i})] \quad (1)$$

where DI is the total daily intake of inorganic As (...g/day); IR_i is the estimated individual ingestion rate of ...sh and shell...sh (g/day); the subscript $i = 1-5$ corresponding to tilapia, milk...sh, mullet, oysters and clams, respectively; $C_{inorg,i}$ is the concentration of inorganic As in i ...sh or shell...sh (...g/g wet wt). $IR_{w,i}$ is the estimated individual ingestion amount of i ...sh or shell...sh (g/day); \dots_i is the ratio of the edible weight to total weight of i ...sh or shell...sh; $C_{f,i}$ is the As concentration in the i ...sh or shell...sh (...g/g wet wt); \dots_i is the ratio of the inorganic As content to the total As content in the i ...sh or shell...sh; and \dots_i is the water content in the i ...sh and shell...sh. The average water content in the ...sh or shell...sh sample is utilized to convert the dry weight. The total consumption amount of ...sh and shell...sh was obtained from the Taiwanese Food Supply and Demand Annual Report of 2008 [22]. The Taiwanese population over the age of four years old was 21.55 million in 2008 [32]. IR_w was obtained by dividing the total amount consumed by the total Taiwanese population.

The distributions of $C_{inorg,i}$ follow log-normal distributions as identified by a Kolmogorov–Smirnov (K–S) test. Owing to sparsely measured data in the organism experiments of the aquatic species, the MC technique was then employed to characterize uncertainty

based on the log-normal distribution of inorganic As content in ...sh and shell...sh. Probabilistic analyses of the daily consumer intake corresponding to the 50th and 95th percentiles were conducted. The Risk (version 4.5, Professional Edition, Palisade Corp.) software was used to analyze statistically the measured data and to carry out MC simulation.

2.4. Provisional tolerable daily intake (PTDI) of ...sh and shell...sh

The FAO/WHO Joint Expert Committee on Food Additives (JECFA) set the provisional tolerable weekly intake (PTWI) for inorganic As at 15 ...g/kg of body weight per week [33]. The PTWI can be translated to the value of 127.3 ...g/day for an average 59.4 kg Taiwanese adult.

WHO reported that food is generally the principal contributor to the daily intake of total As in non-occupationally exposed individuals and ...sh is the main source of As in the diet [34]. Schoof et al. [35,36] and Ysart et al. [37] also pointed out that the intake of As from ...sh and shell...sh contributes over 90% of the total dietary As intake. Background information about community public health was provided by the Nutrition and Health Surveys in Taiwan (NAHSIT) conducted by the Bureau of Food Hygiene, Department of Health (DOH) from 1993 to 1996. The ...ve aquatic species are in the list of 100 types of seafood surveys by the NAHSIT [38]. For general Taiwanese, the consumption behavior is diversi...ed and the ...ve ...sh and shell...sh comprise a small portion of seafood sources. Therefore, we used a weight ratio of 1/20 (the ...ve ...sh and shell...sh to the 100 surveyed seafood) to estimate the daily intake of inorganic As from the ...ve ...sh and shell...sh produced in the BFD areas. Multiplying the weight ratio of 1/20 with the provisional tolerable daily intake of inorganic As (127.3 ...g/day) set by the FAO/WHO [33] yields approximately 6.37 ...g/day. The value of 6.37 ...g/day was adopted as the provisional tolerable daily intake (PTDI) of ...ve ...sh and shell...sh produced from the BFD areas for general public in Taiwan. The PTDI is expressed as follows.

$$PTDI = \sum_{i=1}^5 PTIR_i \times C_{inorg,i} = 6.37, \quad (2)$$

where $PTIR_i$ is the provisional tolerable ingestion rate of i ...sh or shell...sh (g/day) and 6.37 ...g/day denotes provisional tolerable daily intake of inorganic As from ...sh and shell...sh (PTDI) for general public in Taiwan.

2.5. Potential health risks

The US EPA Region III Risk-Based Concentration Table [31] supports a method for estimating the target cancer risk (TR). The risk of the carcinogenic effects of inorganic As is expressed as exceeding the probability of contracting the cancer over a lifetime of 70 years. A model for estimating the target cancer risks (lifetime cancer risks) is,

$$TR = \frac{EFr \times ED_{tot} \times IR \times C_{inorg} \times CPSo}{BWa \times ATc} \times 10^{-3} \quad (3)$$

where TR represents the target cancer risk or the risk of cancer over a lifetime; EFr is the exposure frequency (350 days/year) [31]; ED_{tot} is the exposure duration (30 years) [31]; IR is the estimated individual ingestion rate of ...sh and shell...sh (g/day wet wt); C_{inorg} is the concentration of inorganic As in ...sh and shell...sh (...g/g wet wt); CPSois the oral carcinogenic potency slope of inorganic As (risk per mg/kg/day) ($1.5(\text{mg/kg/day})^{-1}$) [31]; BWa is the body weight of a Taiwanese adult (59.4 kg) [32]. An averaging time of 365 days/year for 76 years ($ATc = 76 \times 365$ days) is used to characterize the lifetime exposure of a Taiwanese in calculation of the cancer risk [39].

2.6. Evaluation of the risk-based ingestion rate (RBIR)

Risk assessment is the process that evaluates the potential health effects from doses to humans of one contaminant received through one or more exposure pathways. The dose of one contaminant is estimated by assuming daily ingestion rates. We evaluate the risk-based ingestion rate (RBIR, g/day) of inorganic As contained ...sh and shell...sh, based on the inorganic As level in ...sh and shell...sh and the acceptable values for TR, using Eq. (4),

$$RBIR = \frac{TR \times BWa \times ATc}{EFr \times ED_{tot} \times C_{inorg} \times CPSo} \times 10^3 \quad (4)$$

where RBIR represents the risk-based ingestion rate in ...sh and shell...sh (g/day). Values of TR, BWa, ATc, EFr, ED_{tot} , C_{inorg} and CPSo in Eq. (4) are the same as those used in Eq. (3).

The acceptable consumption rate of ...sh and shell...sh was evaluated from the BFD areas on the basis of acceptable lifetime risk and the estimation of the actual dietary intake of inorganic As which compared with their corresponding toxicological reference intakes, such as PTWI. The goal of most health actions is to ensure excess lifetime cancer risks do not exceed levels deemed "acceptable," typically 10^{-5} to 10^{-6} (although in some contexts, risks from individual sources as high as 1×10^{-4} may be permitted by regulatory agencies) [40]. By substituting all the parametric values as denoted in Section 2.5 of BWa, ATc, EFr, ED_{tot} , C_{inorg} and CPSo, Eq. (4) was further simplified to

$$RBIR = \frac{TR}{C_{inorg}} \times 1.05 \times 10^5 \quad (5)$$

For a given TR, Eq. (5) provides a quantitative relationship between RBIR and C_{inorg} . If the inorganic As in the ...sh and shell...sh (C_{inorg}) is high, the ingestion rate (RBIR) should decrease accordingly to comply with the acceptable health risk (TR) and vice versa. By applying Eq. (5) we can manage the health risk associated with ingestion of seafood from BFD areas.

3. Results and discussion

3.1. As contents in ...sh and shell...sh

The inorganic As contents for the ...ve aquaculture species follow a log-normal distribution as determined by performing a K-S test. Geometric averages and geometric standard deviations of inorganic As in tilapia, milk...sh, mullet, oysters and clams are obtained from the log-normal distributions (Table 1). Based on the observed data, ten thousand sets of inorganic As concentration were generated by MC simulation to quantify the uncertainty of the evaluated parameters. The simulation results show that the inorganic As contents in ...ve aquaculture species are generally predicted to fall within the range from the 5th to 95th percentiles. The distribution of inorganic As concentration in clams is more skewed with a long tail at higher concentrations. In the 50th percentile, the highest and lowest inorganic As contents are in clam (0.83 ...g/g wet wt) and in tilapia (0.03 ...g/g wet wt), while in the 95th percentile, the highest and lowest inorganic As contents are in clam (3.44 ...g/g wet wt) and in mullet (0.1 ...g/g wet wt), respectively (Table 1).

The mean ratios for inorganic As content to total As content in tilapia, milk...sh, mullet, oysters and clams range from 1.51% to 44.1%, with As content in milk...sh being especially high (44.1%) (Table 2). It has been assumed in several previous studies that inorganic As comprises about 5–10% of the total As in seafood [41–45]. Other studies suggest that the proportion of inorganic As in ...sh and marine animals is generally low, less than 1–4% of the total As [41,46]. Munoz et al. reported the ratio ranging from 0.02% to 11% [47]. The widely varied ratios of inorganic As content to total As content in seafood reported in this study exceed data reported

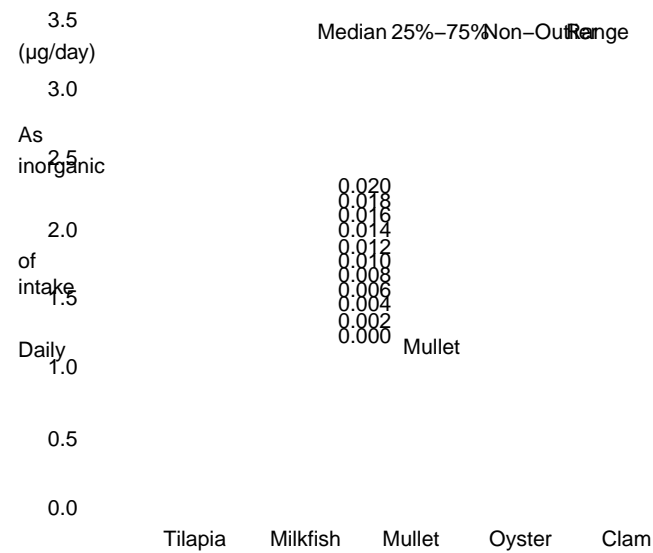


Fig. 2. Distributions of daily intake of inorganic As of ...sh and shell...sh by a box and whiskers plot in the BFD areas.

in previous studies. Arbitrarily assume some ratio of inorganic As to total As may lead to significant error and further invalidate the health risk assessment.

3.2. Daily inorganic As intakes via ...sh and shell...sh

On the basis of the ...sh and seafood consumption, the total daily intake (DI) associated with inorganic As is expressed using Eq. (1) as probability distribution to account the uncertainty. Fig. 2 illustrates the distributions of daily intake of inorganic As from the ...ve major aquaculture species by a box-and-whiskers plot. In the 95th and 50th percentiles of daily intake, clams contribute the highest percentages to the total intake of inorganic As: 46% and 47%, respectively. The second highest contribution is from milk...sh (33–35%) and the lowest one is from mullet (<1%). The total daily intakes of inorganic As from the ...ve aquaculture species are 2.17 and 9.22 ...g/day for the 50th and 95th percentiles, respectively. Notably, the distributions of daily inorganic As intake varied widely in both clams and milk...sh (Fig. 2). These total daily intakes of inorganic As (DI) of the ...ve aquaculture species were used to compare with the value of 6.37 ...g/day, the provisional tolerable daily intake for ...sh and shell...sh (PTDI). The 50th percentile (2.17 ...g/day) of the total DI is lower than the PTDI. Nevertheless, the 95th percentile (9.22 ...g/day) of the total DI is higher than the PTDI, and is also higher than the 95th percentile of 6.2 ...g/day reported by Yost et al. [48]. Related to the importance of the contribution of ...sh and shell...sh to inorganic As intake, our results show large variation in the inorganic As content among the ...ve investigated aquaculture species. A single value used for all seafood may lead to significant errors in estimating potential health risks. The NAHSIT recently investigated the contribution of various food groups, including ...sh and shell...sh to the total food in the Taiwanese diet, but it did not consider the inorganic As uptake. This study estimated the PTDI to illustrate the potential impact of the variation of intake level of inorganic As on human health.

According to the 1997 UK Total Diet Study, the greatest portion of As due to dietary exposure (94% of the total As) comes from the ...sh group. The ...sh group also had the highest mean As concentration (4.4 mg/kg) [37]. Delgado-Andrade et al. reported total As mean concentrations in ...sh and seafood of 2.72, 1.06, and 61.0 ...g/g per fresh weight of ...sh, mollusks, and cephalopods, respectively [49]. Falcó et al. reported mean As concentrations ranging from 1.13 ...g/g to 16.6 ...g/g of fresh weight for 14 species of ...sh and

Table 3
Statistical results of different percentiles TR for ingestion of ...sh and shell...sh farmed in the BFD areas.

| Species | Percentiles of risks ($\times 10^{-6}$) | | | | |
|------------------|---|-------|-------|-------|------|
| | 95th | 75th | 50th | 25th | 5th |
| Tilapia | 6.55 | 2.28 | 1.08 | 0.50 | 0.18 |
| Milk...sh | 30.57 | 12.79 | 6.87 | 3.68 | 1.56 |
| Mullet | 0.19 | 0.10 | 0.07 | 0.05 | 0.03 |
| Oyster | 10.3 | 4.94 | 2.93 | 1.75 | 0.85 |
| Clam | 40.09 | 17.49 | 9.67 | 5.35 | 2.35 |
| Cumulative risks | 87.70 | 37.60 | 20.62 | 11.33 | 4.97 |

shell...sh, giving an intake of As in the range of 0.12–65 ...g/day [4]. The probabilistic risk approach of this study for the estimation of dietary intake of inorganic As provides a wider range corresponding to various dietary intake of inorganic As, which is more robust.

3.3. Carcinogenic risks assessment

The TRs for various levels of percentile are estimated for the different aquaculture species to facilitate the assessment of the potential health risks due to the above intake (Table 3). The TRs for clams and milk...sh all exceed 10^{-6} . The TR values are significantly higher for clams than for the other aquaculture species in all percentiles. Milk...sh has the second highest TRs for all percentiles while mullet has the lowest TR in all percentiles (all less than one millionth). The cumulative risks from ...ve aquaculture species show cancer risks in the range of 10^{-6} to 10^{-4} . Toxicologically, this indicates that ingesting some aquaculture species every day for a lifetime at higher ingestion rates might be harmful to human health.

3.4. Risk-based management of scheme

The 50th percentile RBIR calculated by Eq. (4) based on $TR = 10^{-5}$ of tilapia, milk...sh, mullet, oyster and clam are 37.5, 5.1, 27.7, 8.5 and 1.3 g/day, respectively. The RBIR of tilapia and mullet are higher than the average Taiwanese ingestion rates, while the RBIR of milk...sh and clam are far lower than the average Taiwanese ingestion rates (see Table 2). The RBIR of oyster is close to the average Taiwanese ingestion rate. Based on the current Taiwanese seafood consumption behavior, the ingestion of tilapia and mullet pose less threat to human health than the ingestion of milk...sh and clam. We herein adopt the revised value of 6.37 ...g/day for provisional tolerable daily intake (PTDI) of inorganic As from ...ve aquaculture species and incorporate with the target cancer risk method to determine the acceptable consumption rate of ...sh and shell...sh for general public in Taiwan. We used Eq. (3) to evaluate the maximum acceptable risk of 6.07×10^{-5} . We then calculated the cumulative risk based on the estimated daily ingestion rate. The 5th, 25th, 50th, 75th and 95th percentiles of risks are 4.97×10^{-6} , 1.13×10^{-5} , 2.06×10^{-5} , 3.76×10^{-5} and 8.77×10^{-5} , respectively. The 5th to 75th percentile risks of daily ingestion rate of ...sh and shell...sh are within the risk of PTDI. However, the 95th percentile risk of 8.77×10^{-5} is higher than the maximum acceptable risk of 6.07×10^{-5} . The risk level is closely related to the inorganic As content in ...sh and shell...sh and the IR. We can construct a risk diagram using C_{inorg} as the abscissa and IR as the ordinate (Fig. 3). The risk diagram graphically illustrates the relationship of C_{inorg} versus IR. The two curves of $PTIR \times C_{inorg} = 6.37 \text{ ...g/day}$ and $PTIR \times C_{inorg} = 1.05 \text{ ...g/day}$, corresponding to risks of 6.07×10^{-5} and 1×10^{-5} , respectively, were plotted in Fig. 3. A range of 10^{-4} to 10^{-6} is typically considered as an acceptable risk to consumers via seafood ingestion [50,51]. Because this study combines ...ve different seafood species, the cancer risk of 1×10^{-4} to 1×10^{-5}

Fig. 3. Two dimensional risk diagram for the determination of acceptable consumption rates. The two curves of $PTIR \times C_{inorg} = 6.37 \dots g/day$ and $PTIR \times C_{inorg} = 1.05 \dots g/day$, corresponding to risks of 6.07×10^{-5} and 1×10^{-5} , respectively. Low risk, acceptable risk, hazardous zones are delineated by two curves where the dotted line denotes $TR = 6.07 \times 10^{-5}$ and the solid line denotes $TR = 1 \times 10^{-5}$, respectively.

is adopted to determine the acceptable consumption rate of ...sh and shell...sh. The plotted two curves were used to delineate three zones – the low risk zone, the acceptable risk zone and the hazardous zone. The low risk zone (i.e. risk below 1×10^{-5}) denotes that the intake of inorganic As is less than $1.05 \dots g/day$, indicating no threat to human health. Moreover, nutritional and inorganic As intakes should be balanced when evaluate the acceptable consumption rate of ...sh and shell...sh. If the low risk zone is used to determine the acceptable consumption rate of ...sh and shell...sh, the corresponding recommended daily ingestion rate of ...sh and shell...sh is too strict to consumers. To rationally manage the nutrition benefits and health risk of seafood consumption, this study suggests that the consumption rate of ...sh and shell...sh can be loosely moved to the acceptable risk zone. The acceptable risk zone, bounded by two curves, $PTIR \times C_{inorg} = 6.37 \dots g/day$ and $PTIR \times C_{inorg} = 1.05 \dots g/day$, denotes a risk range from 1×10^{-5} to 6.07×10^{-5} , and the intake of inorganic As from ...sh and shell...sh honors the PTDI ($6.37 \dots g/day$). The total DI ($2.17 \dots g/day$) in the 50th percentile is within the acceptable risk zone, while the total DI ($9.22 \dots g/day$) of the 95th percentile falls to the hazardous zone. The hazardous zone implies that the health risk exceeds 6.07×10^{-5} corresponding to an intake of inorganic As higher than the PTDI ($6.37 \dots g/day$). To protect general public health, seafood consumption rates fall to the hazardous zone should be avoided.

The acceptable risk zone (with risk ranging from 1×10^{-5} to 6.07×10^{-5}) is recommended as the seafood ingestion rate for protecting general public health in Taiwan. Moreover, the two dimensional consumption risk diagram offers a convenient way to determine rational levels of consumption rate of seafood produced from As-contaminated BFD areas.

4. Conclusions

Ingesting ...sh and shell...sh produced in As-contaminated farm regions is a major source of background exposure to inorganic As. To balance the health benefits of ...sh consumption and the risk of over-

ingesting ...sh and shell...sh produced from As-contaminated BFD areas, we use a probabilistic-risk method supported by USEPA and the provision tolerable weekly intake of arsenic set by FAO/WHO to determine acceptable consumption rates of ...sh and shell...sh based upon the published data for general public. The intakes of inorganic As were determined and illustrated by a two dimensional graphical model. According to the relationship between C_{inorg} and IR derived from this study, two risk-based curves were constructed. An acceptable risk zone is determined (risk ranging from 1×10^{-5} to 6.07×10^{-5}) which is recommended as the acceptable consumption rates of ...sh and shell...sh for general public. Translate to lay language, the general Taiwanese is advised to eat more tilapia and mullet, eat less milk...sh and clam, and maintain the current ingestion habit for oyster. From a human health perspective, this study integrates dietary information related to the ingestion of ...ve ...sh and shell...sh produced from As-contaminated BFD areas and determines the acceptable seafood consumption for the alleviation of general public concerns.

Acknowledgements

The authors would like to thank the National Science Council of Taiwan ROC for financially supporting this work under Contract nos. NSC-95-2313-B-002-050-MY3 and NSC-96-2313-B-242-001.

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