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广西刁江野生鱼类重金属积累特征及其健康风险评价

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摘要: 为评估广西刁江野生鱼类重金属积累特征及其健康风险, 分析了广西刁江水系8种野生鱼类肌肉中铅(Pb)、镉(Cd)、铬(Cr)、砷(As)和汞(Hg)5种重金属的含量水平. 利用污染指数法和目标危害系数法对其污染程度、食用安全性及健康风险进行了评价. 结果表明, 所有鱼类肌肉样品中Pb、Cd、Cr、As和Hg的含量范围分别为0.041~1.160、0.0001~0.066、0.173~0.789、0.010~2.420和0.0007~0.077 mg·kg⁻¹. Pb和As的含量水平超出《食品中污染物限量》(GB 2762-2012)的限值, 超标率分别为5.06%和64.56%; 而Cd、Cr和Hg的含量水平未出现超标现象. 污染指数结果表明: 越南鲮和须鲮受到重金属严重污染; 罗非鱼处于中污染水平; 餐鲮、南方拟鲮、鲫鱼、大眼鲮和草鱼处于轻污染水平. 刁江水系8种野生鱼类对Pb、Cr和Hg的富集程度较大; 肉食性和杂食性鱼类重金属含量水平高于草食性鱼类. 越南鲮和须鲮复合重金属目标危害系数均大于1, 这表明当地居民长期摄食越南鲮和须鲮暴露重金属存在潜在健康风险. 在所有野生鱼类(南方拟鲮和餐鲮除外)的复合重金属目标危害系数中, As的贡献比例最高, 平均贡献率达到76.63%, 说明As是主要风险元素.

关键词: 刁江; 野生鱼类; 重金属; 积累; 健康风险评估

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Accumulation Characteristics and Health Risk Assessment of Heavy Metals in Wild Fish Species from Diaojiang River, Guangxi

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Abstract: To explore the accumulation characteristics and health risk assessment of heavy metals in wild fish species, the concentrations of heavy metals (Pb, Cd, Cr, As and Hg) in the muscle samples of eight wild fish species collected from Diaojiang River, Guangxi were analyzed. The degree of pollution, food safety and health risk of heavy metals in wild fish species were evaluated using the average pollution index and the target hazard quotient methods. The results showed that the concentrations of Pb, Cd, Cr, As and Hg in wild fish species ranged from 0.041 to 1.160, 0.0001 to 0.066, 0.173 to 0.789, 0.010 to 2.420 and 0.0007 to 0.077 mg·kg⁻¹, respectively. The concentrations of Pb and As in wild fish species exceeded the limit values of the Maximum Levels of Contaminants in Foods (GB 2762-2012), and the over-standard rates were 5.06% and 64.56% respectively. The concentrations of Cd, Cr and Hg did not exceed the standard. The average pollution index results showed that *Acheilognathus tonkinensis* and *Acheilognathus barbatus* were seriously polluted by heavy metals. The *Oreochromis niloticus* were moderately polluted. The *Siniperca kneri* Garman, *Carassius auratus*, *Pseudohemiculter dispar*, *Ctenopharyngodon idellus*, *Hemiculter leucisculus* were slightly polluted. Higher bioaccumulation factors of Pb, Cr and Hg were found in wild fish species from Diaojiang River. The concentrations of heavy metals in carnivorous fish and omnivorous fish were higher than those in herbivorous fish. Potential health risk assessment showed that the total target hazard quotients (TTHQ) of *Acheilognathus tonkinensis* and *Acheilognathus barbatus* were higher than 1. It indicated that the local residents posed higher human health risk due to the long-term consumption of *Acheilognathus tonkinensis* and *Acheilognathus barbatus*. Among all the TTHQ in wild fish species (except *Pseudohemiculter dispar* and *Hemiculter leucisculus*), the contribution rate of As was the highest, and the average contribution rate reached 76.63%, which indicated that As was the main risk factor.

Key words: Diaojiang River; wild fish; heavy metals; accumulation; health risk assessment

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重金属污染对生物地球化学循环的可持续性和生态风险影响问题日益受到全球关注^[1,2]。重金属因其高毒性、持久性及生物富集与放大性而具有特殊的生态毒理效应^[3]。鱼类富含对人体健康有益的高蛋白、低饱和脂肪酸和奥米伽脂肪酸,是人体蛋白质补充的重要来源^[4,5]。然而,鱼类可能受到多种来源的重金属污染,包括工业废水、市政污水及其河川径流^[6-8]。鱼类能从水体和沉积物中积累富集重金属^[9,10]。鱼体内重金属长期积累会对生物圈的生物地球化学循环产生影响。重金属沿着食物链的生物放大作用导致生态系统破坏与人体健康风险^[2,3,11,12],尤其是摄入的重金属污染的鱼类超过允许每日推荐摄入量时,存在显著的人体健康风险^[12,13]。因此,有必要开展食物链最顶层消费者的人类食用鱼类的重金属健康风险评价^[14]。

关于不同水域中鱼类重金属的研究资料较多,且多数研究都集中在鱼类肌肉组织。例如徐青^[15]研究发现,湘江 Cd 污染较为严重,与广东北江^[16]和大亚湾地区^[17]及山东地区^[18]水平相当,高于珠江^[19]鱼类的污染水平,也相对高于美国、澳大利亚以及西班牙^[20-22]等国的检测结果。Leung 等^[2]研究了珠江三角洲地区鱼类重金属的污染情况,罗非鱼体内 Pb 的含量水平明显高于所测的其他鱼类。

刁江位于广西西北部,流域面积 3 585 km²,干流长 229 km,为红水河最大的一级支流。刁江流域的锡、铅、锌、锑等重要矿产资源丰富、储量大、分布集中,是我国重要的有色金属工业基地之一^[23]。20 世纪 80 年代以来,广西刁江上游有色金属矿山开发活动产生的采矿废水和尾矿渣的排放已对刁江水体和周边的土壤造成了严重污染^[24-30]。但是目前对于刁江野生鱼类重金属累积特征及其健康风险的研究鲜有报道。为此,本文将以广西刁江水系野生鱼类为研究对象,分析野生鱼类体内 5 种重金属(Pb、Cd、Cr、As、Hg)的含量水平,探讨重金属在不同野生鱼类体内的积累特征,评估当地居民通过摄食鱼类的重金属健康风险,以期为广西刁江水系重金属污染防治、生态环境保护提供基础数据及科学依据。

1 材料与方法

1.1 样品采集

2013 年 11 月,在广西河池金城江区沿着刁江水系采集 8 种鱼类,79 个样品。鱼类种类包括大眼鳊、罗非鱼、鲫鱼、南方拟餐、越南鲮、须鲮、草鱼、餐鲙。样品采集后立即冷藏运回实验室,测定鱼类体长、体重等形态学参数,如表 1 所示。解剖后取肌肉组织并于 -20℃ 保存备用。

表 1 广西刁江水系野生鱼类样品信息

Table 1 Information on wild fish species from Diaojiang River, Guangxi

中文名	拉丁学名	样品数量/尾	体长/mm	体重/g
大眼鳊	<i>Siniperca kneri</i> Garman	10	136.7(83.0 ~ 171.0)	68.5(14.0 ~ 119.0)
罗非鱼	<i>Oreochromis niloticus</i>	14	108.7(71.0 ~ 160.0)	65.4(16.0 ~ 205.0)
鲫鱼	<i>Carassius auratus</i>	15	131.0(96.0 ~ 193.0)	87.4(31.0 ~ 222.0)
南方拟餐	<i>Pseudohemiculter dispar</i>	11	141.0(109.0 ~ 173.0)	33.7(16.0 ~ 66.0)
越南鲮	<i>Acheilognathus tonkinensis</i>	12	77.3(74.0 ~ 87.0)	11.8(9.0 ~ 17.0)
须鲮	<i>Acheilognathus barbatus</i>	7	71.1(64.0 ~ 79.0)	9.4(7.0 ~ 12.0)
草鱼	<i>Ctenopharyngodon idellus</i>	5	227.4(189.0 ~ 260.0)	310.2(180.0 ~ 489.0)
餐鲙	<i>Hemiculter leucisculus</i>	5	147.8(130.0 ~ 170.0)	39.6(23.0 ~ 60.0)

1.2 重金属含量测定

准确称取鱼类肌肉样品 1.000 0 g 到聚四氟乙烯试管中,加入 20 mL 硝酸加盖过夜后,将聚四氟乙烯试管放入石墨消解炉(PE50-48)中,逐步升温至 120℃,加热 120 min,取出聚四氟乙烯试管充分冷却后加入 3 ~ 5 mL 高氯酸直至样品完全溶解,然后加入 5 mL 硝酸继续加热至溶液剩余 1 ~ 2 mL,转移至 25 mL 比色管中,定容后摇匀,用一次性针筒抽取 10 ~ 12 mL 溶液通过聚醚砜过滤至 15 mL 塑料离心管中,上机测定重金属含量水平。本实验消解所用试

剂均为优级纯,水为超纯水,所用器皿均用 15% 硝酸浸泡过夜,超纯水冲洗 3 ~ 5 次,晾干备用。

镉、铬和铅采用原子吸收分光光度计(岛津 AA800)进行分析,砷和汞采用原子荧光光度计(北京普析通用仪器有限责任公司,PF6-2 型)进行分析。利用加标回收方法进行质量控制。每隔 10 个样品添加 2 个有证标准物质(GBW-10020)进行质量控制,同时按照 10% 的原则进行平行样品测试。各元素的加标回收率范围为 88.73% ~ 108.41%,符合重金属分析质量控制的相关要求。

1.3 鱼类重金属污染评价

1.3.1 评价标准

鱼体内重金属污染程度评价标准按照国家食品安全标准《食品中污染物限量》(GB 2762-2012)执行^[31]。

1.3.2 评价方法

本研究利用均值型污染指数法评价不同野生鱼类的重金属污染状况。计算公式如下:

$$PI = \frac{1}{n} \sum_{i=1}^n \frac{\overline{C}_i}{S_i}$$

式中,PI 为鱼体内重金属污染指数; n 为重金属污染物的种类数; \overline{C}_i 为鱼体内重金属实测值平均含量; S_i 为某种重金属污染物的评价标准;PI 值越大,说明鱼类受污染程度越严重^[32]。根据鱼类体内重金属含量水平,按照表 2 的分级标准进行评价。

表 2 鱼类重金属污染指数分级

序号	污染指数	级别	分级依据
1	<0.1	未污染	多数项目为检出,个别项目检出也在标准内
2	0.1~0.2	微污染	检出值均在标准内,个别项目接近标准值
3	0.2~0.5	轻污染	个别项目超过标准值
4	0.5~0.7	中污染	2项超过标准值
5	0.7~1.0	重污染	相当一部分值超过标准值
6	>1.0	严重污染	相当一部分检出值超过标准数倍或几十倍

1.4 重金属健康风险评价

本研究利用目标危害系数法 (THQ) 评估重金属暴露的健康风险^[33]。THQ 是美国环保署 (USEPA) 提出的一种用于评估人体通过食物摄取重金属风险的方法。该方法假定人体摄入量等于吸收剂量,以测定的摄入量与参考剂量的比值作为评价标准,具体计算公式如下:

单一重金属风险计算公式:

$$THQ = \frac{E_F \times E_D \times F_{IR} \times c}{R_{FD} \times W_{AB} \times T_A} \times 10^{-3}$$

多种重金属复合风险计算公式:

$$TTHQ = \sum THQ$$

式中, E_F 为接触频率 ($d \cdot a^{-1}$); E_D 为平均寿命 (70 a); F_{IR} 为消化食物的比率 [$g \cdot (人 \cdot d)^{-1}$]; c 为食物中重金属的含量水平 ($mg \cdot kg^{-1}$); R_{FD} 为参比剂量 [$mg \cdot (kg \cdot 人)^{-1}$]; W_{AB} 为人体平均体重 (kg); T_A 为平均接触时间 ($E_D \times 365 d \cdot a^{-1}$)。

当 THQ 比值小于 1 时,暴露人群无明显健康风

险;当 THQ 比值大于 1 时,暴露人群存在健康风险。由于多种重金属可以共同作用对人体健康产生危害,重金属的总危害系数 (TTHQ) 等于各种重金属的危害系数之和。

根据 USEPA 的数据资料,Pb、Cd、Cr、As 和 Hg 的 RfD 分别为 $0.004 mg \cdot kg^{-1}$ 、 $0.001 mg \cdot kg^{-1}$ 、 $1.5 mg \cdot kg^{-1}$ 、 $300 mg \cdot kg^{-1}$ 和 $0.0001 mg \cdot kg^{-1}$ 。基于广西居民膳食营养状况调查资料,平均每人每天摄入水产品 24 g,标准体重以 55.9 kg 计算。

1.5 数据处理与分析

鱼类重金属含量水平采用 Excel 2007 进行整理;实验结果采用 SPSS 17.0 软件进行统计分析 ($P < 0.05$);图形采用 Origin 8.0 软件制作。

2 结果与讨论

2.1 鱼类重金属含量水平

在所有鱼类样品中,Pb、Cr 和 As 均能检出;Cd 和 Hg 的检出率分别为 88.61% 和 79.75%。不同鱼类体内重金属含量水平差异较大 ($P < 0.05$),如表 3 所示,在所有鱼类样品中,Pb、Cd、Cr、As 和 Hg 的含量范围分别为 $0.041 \sim 1.160 mg \cdot kg^{-1}$ (平均值为 $0.317 mg \cdot kg^{-1}$)、 $0.0001 \sim 0.066 mg \cdot kg^{-1}$ (平均值为 $0.018 mg \cdot kg^{-1}$)、 $0.173 \sim 0.789 mg \cdot kg^{-1}$ (平均值为 $0.522 mg \cdot kg^{-1}$)、 $0.010 \sim 2.420 mg \cdot kg^{-1}$ (平均值为 $0.397 mg \cdot kg^{-1}$)、和 $0.0007 \sim 0.077 mg \cdot kg^{-1}$ (平均值为 $0.016 mg \cdot kg^{-1}$)。对于 Pb 而言,须鲮、南方拟餐和餐鲮中 Pb 的含量水平较高,分别为 1.026 、 0.452 和 $0.439 mg \cdot kg^{-1}$ 。对于 Cd 而言,须鲮、越南鲮和南方拟餐中 Cd 的含量水平较高,分别为 0.053 、 0.026 和 $0.025 mg \cdot kg^{-1}$ 。对于 Cr 而言,大眼鳊、罗非鱼、鲫鱼和越南鲮的含量水平较高,分别为 0.641 、 0.571 、 0.581 和 $0.559 mg \cdot kg^{-1}$ 。对于 As 而言,越南鲮和须鲮中 As 的含量水平较高,分别为 $1.574 mg \cdot kg^{-1}$ 和 $0.661 mg \cdot kg^{-1}$ 。对于 Hg 而言,南方拟餐和餐鲮中 Hg 的含量较高,分别为 $0.034 mg \cdot kg^{-1}$ 和 $0.028 mg \cdot kg^{-1}$ 。广西刁江水系鱼类体内 Pb、Cd、Cr、As 和 Hg 的平均含量水平均低于珠江及松花江水系鱼类的含量水平^[34,35];Cd 和 Cr 的含量与安徽蚌埠食用鱼类的含量处于同一水平,Pb 和 As 的含量却高于安徽蚌埠食用鱼类的含量,而 Hg 的含量低于该区域鱼类含量^[36]。此外,本研究区鱼类重金属含量水平明显低于孟加拉邦仕河鱼类样品中的重金属含量^[37],这可能与孟加拉邦仕河接纳未经处理工业废水有关。

表 3 广西刁江水系野生鱼类样品重金属含量水平¹⁾/mg·kg⁻¹Table 3 Concentrations of heavy metals in wild fish species from Diaojiang River, Guangxi/mg·kg⁻¹

鱼类种类	样本量	Pb	Cd	Cr	As	Hg
大眼鳊	10	0.146 ± 0.055	0.003 ± 0.003	0.641 ± 0.116	0.119 ± 0.04	0.020 ± 0.011
罗非鱼	14	0.180 ± 0.227	0.004 ± 0.003	0.571 ± 0.167	0.214 ± 0.09	0.007 ± 0.005
鲫鱼	15	0.138 ± 0.091	0.007 ± 0.004	0.581 ± 0.129	0.139 ± 0.06	0.008 ± 0.007
南方拟餐	11	0.452 ± 0.150	0.025 ± 0.009	0.486 ± 0.118	0.083 ± 0.04	0.034 ± 0.026
越南鱮	12	0.265 ± 0.055	0.026 ± 0.004	0.559 ± 0.028	1.574 ± 0.44	0.010 ± 0.011
须鱮	7	1.026 ± 0.091	0.053 ± 0.014	0.253 ± 0.044	0.661 ± 0.20	0.013 ± 0.004
草鱼	5	0.287 ± 0.054	0.008 ± 0.009	0.438 ± 0.235	0.028 ± 0.02	—
餐鲦	5	0.439 ± 0.075	0.018 ± 0.009	0.425 ± 0.209	0.100 ± 0.03	0.028 ± 0.018
P 值		0	0	0.001	0	0.002
检出限		0.005	0.000 1	0.005	0.01	0.000 15

1) “—”表示未检出

2.2 鱼类重金属污染评价

利用食品安全国家标准《食品中污染物限量》(GB 2762-2012)标准对不同种类鱼体重金属含量进行了评价,结果表明:在所有鱼类样品中,Pb 和 As 的含量水平出现超标现象,超标率分别为 5.06% 和 64.56%。在所有鱼类样品中 5 种重金属平均含量水平从高到低为 Cr > As > Pb > Cd > Hg。须鱮 Pb 的平均含量水平超标,最大超标倍数为 1.16 倍;大眼鳊、罗非鱼、鲫鱼、餐鲦、南方拟餐、越南鱮、须鱮中 As 的含量水平超出标准;而 Cd、Cr 和 Hg 均未出现超标现象。

广西刁江水系野生鱼类重金属污染指数如图 1 所示。8 种野生鱼类中重金属的污染指数具有种属差异。越南鱮和须鱮的重金属污染指数均大于 1,说明这 2 种鱼类受到重金属严重污染;罗非鱼重金属污染指数大于 0.5,小于 0.7,处于中污染水平。其他鱼类重金属污染指数大小顺序依次为餐鲦 > 南方拟餐 > 鲫鱼 > 大眼鳊 > 草鱼,均大于 0.2,处于轻污染水平。

2.3 鱼类重金属积累特征

生物体内某种重金属含量水平除以水体中某种重金属的含量水平即得到生物体对该种重金属的富集系数。刁江不同监测断面水体中 Pb、Cd、Cr、As 和 Hg 的平均含量水平分别为 0.29、0.43、0.41、29.90 和 0.02 μg·L⁻¹。根据鱼体和水中不同重金属含量水平计算富集系数,如表 4 所示,在所有鱼类样品中 Pb、Cd、Cr、As 和 Hg 的富集系数变化范围分别为:478 ~ 3 563、8 ~ 122、621 ~ 1 573、1 ~ 53 和 315 ~ 1 549。刁江水系野生鱼类对 Pb、Cr 和 Hg 的富集程度较大;而对 Cd 和 As 的富集程度较小。须鱮对 Pb 和 Cd 的富集能力较强;大眼鳊、罗非鱼、鲫鱼和须鱮对 Cr 的富集能力较强;越南鱮对 As 的

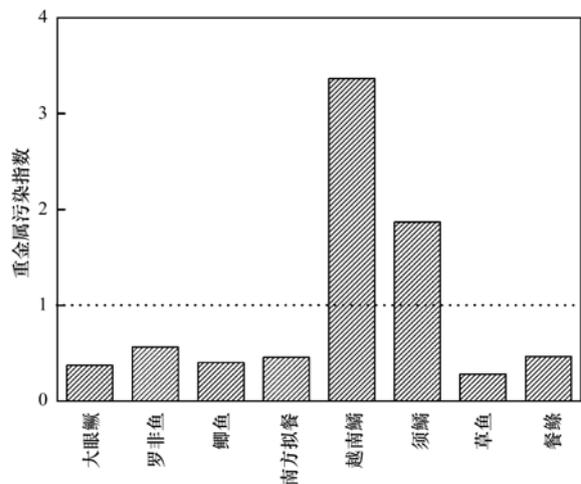


图 1 广西刁江水系野生鱼类重金属污染指数

Fig. 1 Pollution index of heavy metals in wild fish species from Diaojiang River, Guangxi

富集能力明显高于其他鱼类;南方拟餐和餐鲦对 Hg 的富集能力明显高于其他鱼类。

表 4 广西刁江水系野生鱼类重金属的富集系数

Table 4 Bioaccumulation factors of heavy metals in wild fish species from Diaojiang River, Guangxi

鱼类种类	Pb	Cd	Cr	As	Hg
大眼鳊	508	8	1 573	4	935
罗非鱼	625	10	1 402	7	315
鲫鱼	478	15	1 425	5	354
南方拟餐	1 571	57	1 194	3	1 549
越南鱮	919	60	1 372	53	452
须鱮	3 563	122	621	22	605
草鱼	995	20	1 074	1	—
餐鲦	1 523	43	1 043	3	1 310

广西刁江水系不同种野生鱼类的重金属富集系数差异较大,可能是由于不同鱼类的生活习性不同导致。草鱼为草食性鱼类;大眼鳊属于肉食性鱼类;罗非鱼、鲫鱼、须鱮、越南鱮、餐鲦、南方拟餐属于

杂食性鱼类. 肉食性、草食性及杂食性鱼类重金属平均含量水平从高到底顺序分别为: $Cr > Pb > As > Hg > Cd$, $Cr > Pb > As > Cd > Hg$, $Cr > As > Pb > Hg > Cd$ (图2). 对于 Pb 和 Cd 而言, 杂食性 > 草食性 > 肉食性; 对于 Cr 和 Hg 而言, 肉食性 > 杂食性 > 草食性; 对于 As 而言, 杂食性 > 肉食性 > 草食性. 上述分析表明: 肉食性和杂食性鱼类重金属含量水平比较高, 而草食性鱼类重金属含量水平较低. 可能原因有两种: 一是食物链中处于高营养级的生物富集程度要高于低营养级的生物, 肉食性鱼类在其食物链中处于较高的营养级, 因此其体内富集重金属的程度要高于杂食性和草食性鱼类^[11,12]; 二是肉食性鱼类和杂食性鱼类多栖息于水体中下层, 而草食性鱼类多在水体中上层活动, 大量的重金属可能通过迁移转换作用沉于水体底泥. 肉食性和杂食性鱼类摄食过程中可能吸收大量被污染的沉积物, 从而导致体内重金属富集的程度较高^[3,38,39].

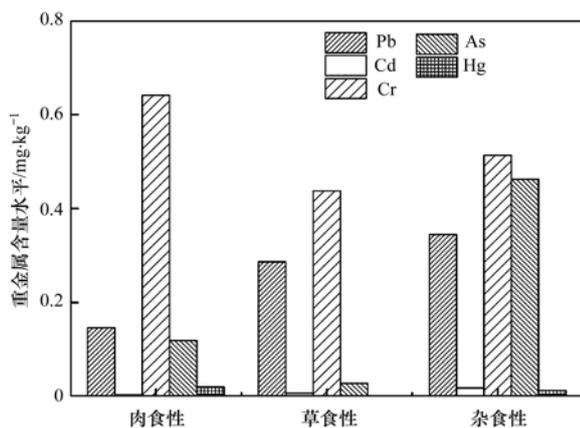


图2 广西刁江不同食性鱼体内重金属含量比较

Fig. 2 Comparison of concentrations of heavy metals in different wild fish species from Diaojiang River, Guangxi

2.4 鱼类重金属健康风险评价

居民通过摄入水产品暴露重金属的健康风险的研究主要集中在与国家标准进行比较分析, 定性判断鱼类受到单一金属元素污染的程度, 而美国 EPA 的目标危害系数 (THQ) 则考虑多种金属复合暴露的健康风险. 本研究中当地居民通过摄入鱼类暴露重金属的 THQ 如表 5 所示. 在所有野生鱼类中, 单一重金属的 THQ 从高到低的顺序依次为: $As > Hg > Pb > Cd > Cr$. 越南鱮中 As 的 THQ 最高, 为 2.099. 不同野生鱼类中复合重金属 TTHQ 的高低顺序依次为越南鱮 > 须鱮 > 罗非鱼 > 南方拟餐 > 餐鲦 > 大眼鳊 > 鲫鱼 > 草鱼. 越南鱮和须鱮复合重金属 TTHQ 均大于 1, 说明当地居民如果长期摄食越

南鱮和须鱮暴露重金属的健康风险较大. 其他野生鱼类复合重金属 TTHQ 均小于 1, 说明长期摄入这些鱼类暴露重金属的健康风险较小. 在所有野生鱼类(南方拟餐和餐鲦除外)的复合重金属 TTHQ 中, As 的贡献比例最高, 平均贡献率为 76.63%, 说明 As 是主要风险元素. 虽然鱼体中 Cr 的含量水平较高, 但是 Cr 的 THQ 最小, 对于 TTHQ 贡献率不到 1%, 不足以对当地居民造成潜在健康风险.

表5 广西刁江水系野生鱼类重金属目标危害系数

Table 5 Target hazard quotients of heavy metals in wild fish species from Diaojiang River, Guangxi

鱼类种类	Pb	Cd	Cr	As	Hg	TTHQ
大眼鳊	0.015	0.001	0.171×10^{-3}	0.159	0.081	0.256
罗非鱼	0.018	0.002	0.152×10^{-3}	0.286	0.027	0.333
鲫鱼	0.014	0.002	0.153×10^{-3}	0.192	0.030	0.239
南方拟餐	0.045	0.010	0.130×10^{-3}	0.110	0.134	0.300
越南鱮	0.026	0.010	0.149×10^{-3}	2.099	0.039	2.175
须鱮	0.103	0.021	0.067×10^{-3}	0.882	0.052	1.058
草鱼	0.029	0.003	0.117×10^{-3}	0.037	0.003	0.072
餐鲦	0.044	0.007	0.113×10^{-3}	0.133	0.114	0.298

3 结论

(1) 广西刁江水系野生鱼类样品中重金属平均含量水平从高到低顺序为 $Cr > As > Pb > Cd > Hg$, 其中 Pb 和 As 的含量水平超出《食品中污染物限量》(GB 2762-2012) 的限值, 而 Cd、Cr 和 Hg 的含量水平未出现超标现象. 广西刁江水系野生鱼类受重金属不同程度污染, 其中越南鱮和须鱮污染严重; 罗非鱼处于中污染水平; 其他鱼类重金属污染处于轻污染水平.

(2) 广西刁江野生鱼类对 Pb、Cr 和 Hg 的富集程度较大, 而对 Cd 和 As 的富集程度较小. 不同食性鱼类积累富集重金属具有种属差异, 肉食性和杂食性鱼类重金属含量水平高于草食性鱼类.

(3) 当地居民长期摄入越南鱮和须鱮暴露重金属的健康风险较大, 而摄入其他鱼类暴露重金属的潜在健康风险较低. As 是主要风险元素, 对复合重金属 TTHQ 的贡献率较高.

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