



# Distribution and risk assessments of $^{210}\text{Po}$ in the body organs of common carp (*Cyprinus carpio*) and Barbel Chub (*Squaliobarbus curriculus*) within Red River, Vietnam

Trung-Tien Chu<sup>1</sup> · Van-Hao Duong<sup>1</sup> · Thanh-Xuan Pham-Thi<sup>1</sup> · Munawar Suhail Ahmed<sup>2</sup> · Mohamed Saiyad Musthafa<sup>2</sup> · Thanh-Duong Van<sup>3</sup> · Xuan-Huan Nguyen<sup>4</sup> · Trung-Thanh Tran<sup>4</sup> · Thuy-Anh Tran-Thi<sup>4</sup> · Van-Luc Nguyen<sup>4</sup> · Hong Nguyen-Thi<sup>5,6</sup> · Nga Phung-Thi<sup>7</sup> · Thanh-Nam Nguyen<sup>4</sup>

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## Abstract

Toxic polonium-210 ( $^{210}\text{Po}$ ) in freshwater fish poses significant health risks to humans when consumed, as well as fish populations and other aquatic organisms. Alpha spectrometry was employed to determine  $^{210}\text{Po}$  activity concentrations in the organs from two omnivorous fish species, *Cyprinus carpio* and *Squaliobarbus curriculus*, collected from the Red River system across Lao Cai, Phu Tho, and Thai Binh provinces in northern Vietnam. Results revealed an uneven  $^{210}\text{Po}$  distribution between organs, with the lowest levels in muscle and the highest in the intestines and stomach, suggesting that digestion is a primary pathway for  $^{210}\text{Po}$  accumulation. The *C. carpio* exhibited higher  $^{210}\text{Po}$  activity concentrations across most organs compared to *S. curriculus*. Spatially,  $^{210}\text{Po}$  activity varied by location, with the predominance of  $^{210}\text{Po}$  activity in most organs of *C. carpio* in Thai Binh and *S. curriculus* in Phu Tho. These differences underscore the influence of behavior, physiology, and environmental conditions on  $^{210}\text{Po}$  distribution between the two target species. The annual committed effective dose (ED) due to consuming these fish was within the allowable limits for muscle tissue. However, the ED exceeds the safe limited value when consuming digestive organs such as the stomach and intestine, suggesting that eating these parts should be avoided to mitigate health risk. Estimated radiation dose rates from  $^{210}\text{Po}$  to these two freshwater species showed minimal expected radiation impact in the study area based on freshwater.

**Keywords**  $^{210}\text{Po}$  · Erica tool · *Cyprinus carpio* · *Squaliobarbus curriculus* · Annual effective dose

## Introduction

Aquatic organisms can accumulate significant concentrations of pollutants such as metals and radionuclides (e.g., Fowler 2011; Jordanova et al. 2018; Ghajarbeygi et al. 2022). Fish are one of the fundamental sources of protein for humans and their exposure to radionuclides raises global concerns regarding radionuclide accumulation and their associated risks (Ghajarbeygi et al. 2022). This accumulation in fish is often linked to environmental contamination through water, sediments, and the food web (Wada et al. 2019; Manav et al. 2016; Wang et al. 2016).  $^{210}\text{Po}$  is a naturally occurring member of the  $^{238}\text{U}$  decay chain with a half-life of 138.4 days.  $^{210}\text{Po}$  is naturally present in aquatic

systems through atmospheric deposition, fluvial inputs, and in situ decay, with additional contributions from industrial activities such as mining (Carvalho et al. 2017; Ram et al. 2019; Jia et al. 2001; Matthews et al. 2007). The elevated toxicity of  $^{210}\text{Po}$  combined with its widespread occurrence in fish species represents a considerable public health concern. Research indicates that  $^{210}\text{Po}$  constitutes the predominant natural radioactive contaminant in fish-based food products, with typical activity concentrations averaging 2 Bq/kg in aquatic species (Chen et al. 2016; UNSCEAR, 2000). Estimates indicate that  $^{210}\text{Po}$  and  $^{210}\text{Pb}$  account for about 83% of the annual effective dose to humans via ingestion (UNSCEAR, 2000; Chen et al. 2001). Consequently, determining  $^{210}\text{Po}$  activity and assessing its radiological risk

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from fish consumption are crucial for assuring public health protection.

Most previous studies on radionuclides in fish have focused on marine environments, with limited research on freshwater systems (López Castillo 2011). The Red River, the second-largest river in Vietnam and vital to the socio-economic development of the northern region (Dang et al. 2010; Luu et al. 2010; Minh et al. 2014), has experienced increased radionuclide pollution due to mining and other anthropogenic activities (Minh et al. 2014; Tham et al. 2022). Previous studies detected elevated radionuclides in water and sediment in this basin, but few have examined their bioaccumulation in freshwater fish (Van Vuong et al. 2024; Duong et al. 2023; Minh et al. 2014; Chau et al. 2022). A study by Duong (2024) conducted in the Ca Lo River, a tributary of the Red River, revealed elevated concentrations of  $^{210}\text{Po}$  in the intestines and stomach contents of tilapia (Duong, 2024). This finding indicates the bioaccumulation potential of  $^{210}\text{Po}$  in fish and suggests the presence of potential  $^{210}\text{Po}$  sources in this area. Considering the contamination potential and consequent threats to both human populations and ecological systems, comprehensive evaluation of radioactive contamination levels and their health implications from industrial activities becomes essential.

This study focuses on two common omnivorous freshwater species in the Red River: *Cyprinus carpio* (Common carp) and *Squaliobarbus curriculus* (Barbel chub). Both are widely distributed, highly adaptable to different environmental conditions, and important protein source in many countries, including Vietnam (Vilizzi and Tarkan 2016; Froese & Pauly, 2024). Both species are omnivorous, with *C. carpio* primarily consuming plankton, benthic invertebrates, plant material, and detritus, while *S. curriculus* feeds more on zoobenthos, zooplankton, plants/detritus, and small animals. Omnivorous fish are known to accumulate higher levels of  $^{210}\text{Po}$  (Khan and Wesley 2011; Aközcan 2013; Steiner et al. 2016; Alam and Mohamed 2011; Shuryak 2018; Ababneh et al. 2018) and plankton, in particular, shows increased uptake of  $^{210}\text{Po}$  (Fowler 2011; Carvalho et al. 2017), which may contribute to biomagnification of  $^{210}\text{Po}$  through the aquatic food chain. Despite similar diets, *C. carpio* and *S. curriculus* live in different habitats. Their living behavior *C. carpio* being benthic and *S. curriculus* more pelagic—may influence radionuclide uptake (Çatal et al. 2012; Iç et al., 2018; Deiaa et al. 2020). Comparing the  $^{210}\text{Po}$  accumulation levels of these two species offers insight into the fish's living behaviour and feeding habits regarding  $^{210}\text{Po}$  accumulation in freshwater environments. Moreover, prior studies have demonstrated that  $^{210}\text{Po}$  is not uniformly distributed among fish organs, with this distribution strongly

influenced by dietary habits (Fowler 2011; Carvalho et al. 2017; Bustamante et al. 2002; Uddin et al. 2012). Understanding the distribution of  $^{210}\text{Po}$  activity in specific fish organs can provide baseline data for radionuclide behavior and biogeochemical processes. In Many countries, including those in Southeast Asia, Japan, Canada, China, Russia, and Sri Lanka, etc. consume various fish organs (stomach, intestine, liver, heart, eyes) (Huffpost.com 2024; bclivespotprawns.com 2024). Thus, research on radionuclides on specific fish organs provides additional information for further refining dose calculated models both for humans and other organisms.

Recently, the risks to aquatic organisms from radionuclide exposure have garnered significant international attention, as evidenced by earlier foundational works (Andersson et al. 2008; ICRP, 2003, 2007; Larsson 2008; Vetikko and Saxén 2010) and more recent assessments and ecological studies (ICRP 2020, 2021; Aryanti et al. 2022; Ni et al. 2024). Due to biological reconcentration, the radioactivity levels in edible parts of aquatic organisms can be much higher than in water (Musthafa and Krishnamoorthy 2012), making these organisms vulnerable to external and internal radiation (Suseno and Prihatiningsih 2014). Estimating the risks to organisms and establishing reference values are crucial for assessing and making decisions about current operations, facilities, locations, and potentially contaminated areas (Larsson 2008). Several models have been developed to assess the effects of ionizing radiation on various organisms, with the ERICA (Environmental Risk from Ionising Contaminants: Assessment and Management) tool being one of the most effective and widely used (Brown et al. 2004, 2008; Gjelsvik et al. 2012; ERICA 2021; Aryanti et al. 2022). The ERICA tool estimates dose rates for biological populations in terrestrial, freshwater, and marine ecosystems for both default reference organisms and user-defined organisms (Vetikko and Saxén 2010).

The objectives of this study were to: (1) examine the distribution of  $^{210}\text{Po}$  across a wide range of fish organs of two common freshwater fish species, *Cyprinus carpio* and *Squaliobarbus curriculus*, at three different locations (Lao Cai, Phu Tho, and Thai Binh) along the Red River, Vietnam; (2) assess radiological risk to humans due to the consumption of these two fish species; and (3) estimate radiation doses to the two fish species using the ERICA tool. This study provides baseline data on the distribution of  $^{210}\text{Po}$  in eleven organs from two common freshwater fish species from the largest river in North Vietnam.

## Materials and methods

### Sample collection

The Red River basin supports a wide variety of human activities and natural environments. The locations for this study were selected based on representing the most probable representation of radioactive contamination risk of each area (Fig. 1), including Lao Cai ( $22^{\circ}35'10''\text{N}$ ,  $103^{\circ}51'39''\text{E}$ ), Phu Tho ( $21^{\circ}19'38''\text{N}$ ,  $105^{\circ}11'55''\text{E}$ ) and Thai Binh ( $20^{\circ}23'19''\text{N}$ ,  $106^{\circ}17'16''\text{E}$ ). In the study areas, the physico-chemical parameters of water, including pH ( $6.97 \pm 0.50$  to  $7.96 \pm 0.23$ ) and  $\text{BOD}_5$  ( $1.10 \pm 0.36$  to  $1.50 \pm 0.64$  mg/l) were within the allowable limits of QCVN 08: MT 2023/BTNMT at level A (MOST, 2023; Ha et al. 2024). During the rainy season, dissolved oxygen (DO) met the level B criteria ( $6.36 \pm 0.83$  mg/l), while in the dry season, DO levels were in the level C range ( $4.24 \pm 0.49$  mg/l) according to QCVN 08: 2023/BTNMT life (Ha et al. 2024). Additionally, temperatures ranged from  $21.18 \pm 0.87$  °C to  $29.58 \pm 1.58$  °C. Overall, the water quality of the Red River was suitable for supporting aquatic life (Ha et al. 2024).

In the Lao Cai Province, there are numerous mineral exploitation and processing industries, along with many intrusive magmatic rock formations. Phu Tho has a high population density and several chemical industries, while Thai Binh is known for its light industries and agricultural products. At each sampling location, *C. carpio* and *S. curriculus* specimens were captured using gill nets with 3 cm mesh size. Three individuals from each species were selected

based on commercially representative size criteria for subsequent laboratory processing (Table 1). All specimens were immediately preserved in ice containers and transported to the laboratory for bioprocessing, sample preparation, and radioactivity analysis. Concurrent water sampling was conducted at each site for  $^{210}\text{Po}$  activity determination. Water samples underwent pre-filtration through 0.5  $\mu\text{m}$  mesh filters to eliminate particulate matter and ensure analytical consistency across sampling locations.

### Determination of $^{210}\text{Po}$ activity concentrations

In the laboratory, 11 organs (muscle, stomach, skin, liver, gill, eye, intestine, stomach content, heart, fin, and bone) from all specimens of both species at each site were combined and then analyzed to determine the distribution of  $^{210}\text{Po}$  among the fish organs. The fish samples were dried at 80 °C in the laboratory and then reweighed to determine the dry/wet ratio. Before digestion with  $\text{H}_2\text{SO}_4$  acid (98%, Merk™), a  $^{209}\text{Po}$  standard solution (Eckert & Ziegler™) was added to the samples. Complete digestion of the samples was achieved using  $\text{H}_2\text{O}_2$  (30%, Merk™) before precipitation with  $\text{MnO}_2$  (Merk™). The analytical procedures for both species after being completely digested and dissolved, and the field-collected water samples, followed the methodology described by Duong et al. (2022, 2024) (Duong et al. 2022, 2024). Both  $^{210}\text{Po}$  and  $^{209}\text{Po}$  were absorbed onto a silver plate with a diameter of 1 cm and a thickness of 0.2 mm. The  $^{210}\text{Po}$  activity concentration in the samples was determined using the ORTEC Alpha-Ensemble-4 alpha

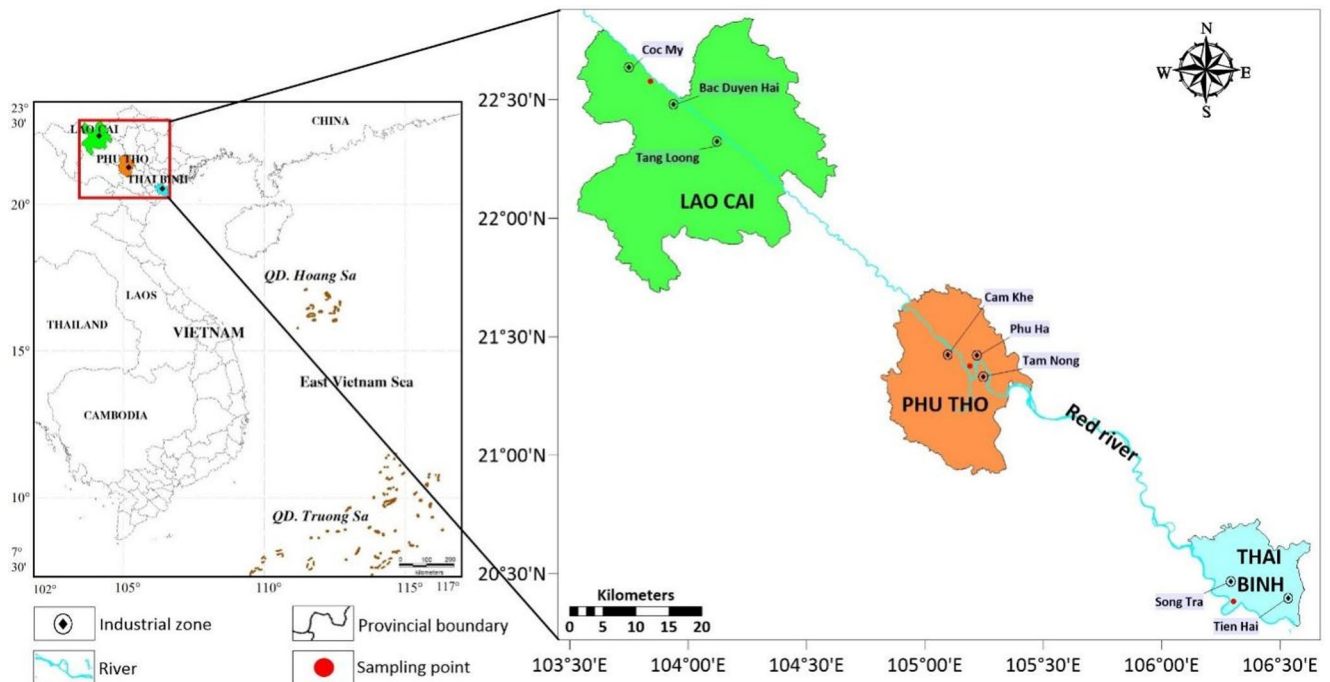


Fig. 1 Study area

**Table 1** Specimens of *Cyprinus Carpio* and *squaliobarbus curriculus* in 03 sites

| No of Specimens | Scientific name      | Lt (mm) | LF (mm) | Ls (mm) | W (g) | W <sub>0</sub> (g) | Sites                                     |
|-----------------|----------------------|---------|---------|---------|-------|--------------------|---|
| 1               | <i>C. carpio</i>     | 400     | 358     | 311     | 1390  | 1098               | Lao Cai<br>(22°35'10"N,<br>103°51'39"E)   |
| 2               | <i>C. carpio</i>     | 207     | 185     | 164     | 170   | 147                |   |
| 3               | <i>C. carpio</i>     | 171     | 152     | 132     | 82    | 73                 |   |
| Average (1–3)   |                      | 259     | 232     | 202     | 547   | 439                |   |
| 4               | <i>S. curriculus</i> | 303     | 269     | 250     | 290   | 219                |   |
| 5               | <i>S. curriculus</i> | 291     | 267     | 251     | 230   | 190                |   |
| 6               | <i>S. curriculus</i> | 220     | 201     | 186     | 123   | 96                 | Phu Tho<br>(21°19'38"N,<br>105°11'55"E)   |
| Average (4–6)   |                      | 271     | 246     | 229     | 214   | 168                |   |
| 7               | <i>C. carpio</i>     | 330     | 300     | 240     | 1000  | 940                |   |
| 8               | <i>C. carpio</i>     | 195     | 173     | 151     | 146   | 106                |   |
| 9               | <i>C. carpio</i>     | 179     | 162     | 145     | 90    | 76                 |   |
| Average (7–9)   |                      | 235     | 212     | 179     | 412   | 374                |   |
| 10              | <i>S. curriculus</i> | 320     | 274     | 262     | 350   | 253                | Thai Binh<br>(20°23'19"N,<br>106°17'16"E) |
| 11              | <i>S. curriculus</i> | 251     | 224     | 196     | 180   | 155                |   |
| 12              | <i>S. curriculus</i> | 250     | 220     | 190     | 164   | 145                |   |
| Average (10–12) |                      | 274     | 239     | 216     | 231   | 184                |   |
| 13              | <i>C. carpio</i>     | 301     | 270     | 239     | 650   | 550                |   |
| 14              | <i>C. carpio</i>     | 252     | 224     | 203     | 266   | 221                |   |
| 15              | <i>C. carpio</i>     | 189     | 175     | 151     | 114   | 99                 | Average (13–15)                           |
| Average (13–15) |                      | 247     | 223     | 198     | 343   | 290                |   |
| 16              | <i>S. curriculus</i> | 282     | 259     | 235     | 234   | 185                |   |
| 17              | <i>S. curriculus</i> | 271     | 245     | 227     | 201   | 168                |   |
| 18              | <i>S. curriculus</i> | 240     | 215     | 202     | 166   | 140                | Average (16–18)                           |
| Average (16–18) |                      | 264     | 240     | 221     | 200   | 164                |   |

Note: Lt=Total length; LF=At fork length; Ls=Standard length; W=Weight; W<sub>0</sub>=Weight without internal organs

spectroscopy (ALPHA-DUOM1–450 mm<sup>2</sup> area detector) with a high-resolution PIPS detector. The recovery rate of the <sup>209</sup>Po tracer was up to 90% when quality control was performed using 0.5 g of reference material IAEA-414 per sample. The MDL of the measurement method was 0.5mBq.

### Estimation of annual committed effective dose

The annual committed effective dose (ED) due to fish consumption of <sup>210</sup>Po is calculated using the formula:

$$ED_{210Po} = A_{210Po} \times C \times D_f$$

Where,

- -  $A_{210Po}$  is the <sup>210</sup>Po activity in the muscles of two fish species.
- -  $C$  is the average annual fish consumption volume of Vietnamese people (18.8 Kg/year) (Van 2020).
- -  $D_f$  is dose conversion factor of <sup>210</sup>Po observed for adults ( $1.2 \times 10^6$  Sv/Bq) (WHO 2017).

### Estimation of radiation dose using the ERICA tool

The ERICA Assessment Tool, version 2.0 (June 2023) was used to estimate dose rates for *C. carpio* and *S. curriculus*

in our study. ERICA offers a three-level approach for entering measured activity into biota and site-specific environments (Brown et al. 2008). Following recommendations, the assessment was performed using Tier 2, which provides results in terms of total dose rate, including both external and internal dose rates (Brown et al. 2008). External dose rates refer to radiation exposure from unabsorbed environmental radionuclide concentrations, while internal dose rates pertain to absorbed concentrations (Aryanti et al. 2022). The total dose rate was directly compared with the screening dose rate provided by the ERICA tool to assess the risk to organisms from ionizing radiation (Brown et al. 2008; Vetikko and Saxén 2010).

Input data include activity concentrations measured in fish, water and/or sediment (Table 2). In this study, due to the lack of data on <sup>210</sup>Po activity concentrations in sediments, <sup>210</sup>Po activity in sediments was estimated based on data on <sup>210</sup>Po activity concentrations in water and the distribution coefficient provided by the ERICA tool ( $K_d = 416.260$  L/kg for <sup>210</sup>Po).

**Table 2** Input parameters in tier 2

| Area      | Freshwater Organism  | Reference organism <sup>a</sup> | Activity concentration of $^{210}\text{Po}$ |               | Occupancy factor <sup>c</sup> |
|-----------|----------------------|---------------------------------|---|---------------|-------------------------------|
|           |                      |                                 | Fish <sup>b</sup> (Bq/kg)                   | Water (mBq/L) |                               |
| Lao Cai   | <i>C. carpio</i>     | Benthic fish                    | 2.02  | 0.5           | Sediment-surface=1            |
|           | <i>S. curriculus</i> | Benthopelagic fish              | 3.19  |               | Water-surface=0.2, Water=0.8  |
| Phu Tho   | <i>C. carpio</i>     | Benthic fish                    | 3.59  | 0.47          | Sediment-surface=1            |
|           | <i>S. curriculus</i> | Benthopelagic fish              | 2.07  |               | Water-surface=0.2, Water=0.8  |
| Thai Binh | <i>C. carpio</i>     | Benthic fish                    | 7.03  | 0.56          | Sediment-surface=1            |
|           | <i>S. curriculus</i> | Benthopelagic fish              | 1.54  |               | Water-surface=0.2, Water=0.8  |

<sup>a</sup>Reference organism selected in Erica. <sup>b</sup>Whole fish body (fresh weight) was estimated using a mass balance approach (Yankovich et al., 2010). <sup>c</sup>Fraction of time spent in a given habitat

## Results and discussion

### $^{210}\text{Po}$ activity concentrations in different organs of two species and locations

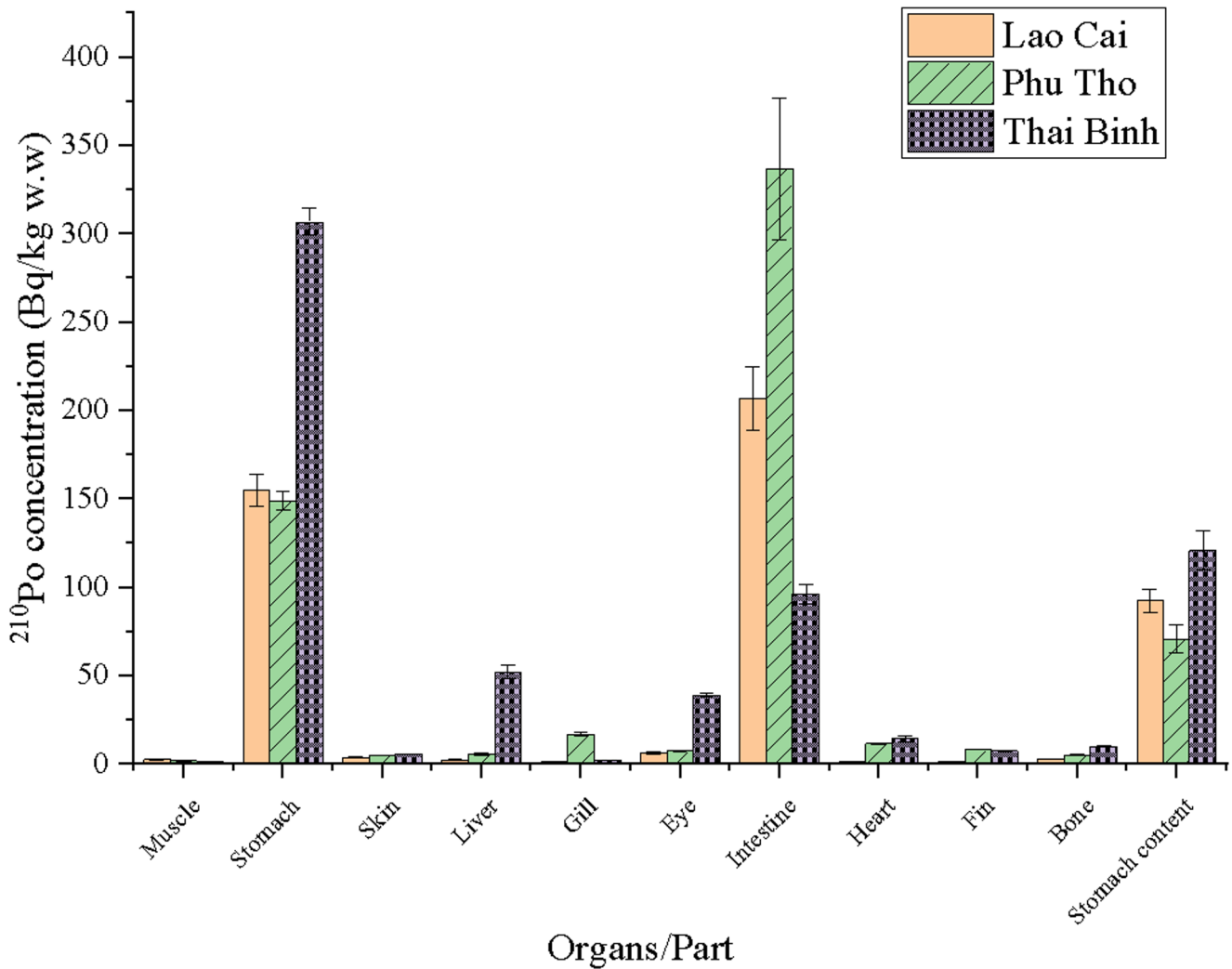
The  $^{210}\text{Po}$  activity in different organs of *C. carpio* and *S. curriculus* across the three sites (Lao Cai, Phu Tho, and Thai Binh) revealed significant differences in activity levels ( $p < 0.05$ ). In *C. carpio*, the lowest  $^{210}\text{Po}$  activity was consistently found in the muscle ( $2.6 \pm 0.3$ ,  $1.94 \pm 0.14$ , and  $1.2 \pm 0.13$  Bq/kg for Lao Cai, Phu Tho, and Thai Binh, respectively), while the highest activity was observed in the intestine for Lao Cai ( $207 \pm 17.8$  Bq/kg) and Phu Tho ( $337 \pm 40$  Bq/kg), and in the stomach for Thai Binh ( $307 \pm 7.7$  Bq/kg). The highest average  $^{210}\text{Po}$  activity was in Thai Binh ( $59.7 \pm 3$  Bq/kg) and the lowest in Lao Cai ( $43.4$  Bq/kg). For *S. curriculus*, muscle also showed the lowest  $^{210}\text{Po}$  activity ( $0.63 \pm 0.07$ ,  $0.56 \pm 0.09$ , and  $0.36 \pm 0.028$  Bq/kg for Lao Cai, Phu Tho, and Thai Binh, respectively), with the highest activity in the stomach for Lao Cai ( $15.4 \pm 1.15$  Bq/kg) and in the intestine for Phu Tho ( $64.4 \pm 5.5$  Bq/kg) and Thai Binh ( $4.01 \pm 0.29$  Bq/kg). Phu Tho exhibited the highest average  $^{210}\text{Po}$  activity ( $13.7 \pm 1.2$  Bq/kg) and Thai Binh the lowest ( $2.9 \pm 0.2$  Bq/kg). Although the gills of both species can directly absorb and accumulate heavy metals, including  $^{210}\text{Po}$  from water, their activity levels were low. Overall, the lowest  $^{210}\text{Po}$  activity was in muscle tissue and the highest in digestive organs for both species, suggesting that the food digestion is the primary mechanism and pathway for  $^{210}\text{Po}$  accumulation, as corroborated by similar findings in marine and

freshwater organisms (Heyraud and Cherry 1979; Carvalho 2011; Strady et al. 2015; Duong et al. 2022; Carvalho, 2018; López Castillo 2011; Skipperud et al. 2013).

Differences in  $^{210}\text{Po}$  levels in the organs of the *C. carpio* and *S. curriculus* were also found between regions (Figs. 2 and 3). For *C. carpio*, there was a predominance of  $^{210}\text{Po}$  accumulation in almost all fish organs in Thai Binh, whereas for *S. curriculus*, higher levels were recorded in Lao Cai and Phu Tho. In Thai Binh, where light industrial and agricultural activities are strongly developed, *C. carpio* organs generally showed higher  $^{210}\text{Po}$  activity. Conversely, in Lao Cai and Phu Tho, which was known for mining, mineral processing, and chemical industries, *S. curriculus* showed higher  $^{210}\text{Po}$  levels. Overall,  $^{210}\text{Po}$  shows variations across the three locations along the Red River, indicating potential hotspots of  $^{210}\text{Po}$  contamination. We found that levels of  $^{210}\text{Po}$  are mainly influenced by local sources such as mining and industrial, and agricultural activities, while the influence of runoff transporting  $^{210}\text{Po}$  from upstream to downstream remains unclear.

The  $^{210}\text{Po}$  activity in organs of the *C. carpio* and *S. curriculus* in this study was much lower than that observed in *Cyprinus carpio*, *Carassius auratus*, and *Chelon labrosus* in Peníscola swamp, Spain (López Castillo 2011), or in *Carrasius auratus* and *Cyprinus carpio* in wastewater reservoirs in Tajikistan (Appendix). Although the two reference areas are polluted and rich in natural radiation, the  $^{210}\text{Po}$  content in the muscles of species such as *Leuciscus cephalus*, *Oncorhynchus mykiss*, *Salmo trutta*, *Barbus barbus* (Štrok and Smodiš 2011), were observed with similar values to those in *S. curriculus*, and lower than those in *C. carpio*. The differences in  $^{210}\text{Po}$  activity between organs and fish species have been reported to be related to local environmental pollution, climate, food content, habitat, feeding type, metabolism, and nutrition demand (Ababneh et al. 2018; Van 2020).

Although both are omnivorous,  $^{210}\text{Po}$  activity in *C. carpio* was consistently higher than in *S. curriculus* across all organs, ranging from 1.2 times higher in the fins to about 300 times higher in the stomach in Thai Binh. As mentioned above, the presence of  $^{210}\text{Po}$  in fish is primarily due to the absorption of contaminated food (Heyraud and Cherry 1979; Carvalho 2018). The heterogeneous  $^{210}\text{Po}$  distribution patterns observed between species can be attributed to variations in metabolic processes, dietary preferences, and species-specific biological characteristics (Al-Masri et al. 2000). Additionally,  $^{210}\text{Po}$  concentrations may be influenced by the living behavior of fish in the water column. The *C. carpio* (benthic) showed significantly higher  $^{210}\text{Po}$  in stomach content (about 37 times higher in Thai Binh) compared to *S. curriculus* (benthopelagic). This supports a habitat preference accumulation pattern, as  $^{210}\text{Po}$  activity



**Fig. 2** Distribution of  $^{210}\text{Po}$  in the organs of *C. carpio* by study area

is generally higher in fish species that live near the water surface compared to those living on the bottom (Stewart et al. 2005; Çatal et al. 2012; Çatal et al., 2018; Deiaa et al. 2020). These combined factors, habitat preferences, species-specific biological characteristics and varying environmental conditions that influence  $^{210}\text{Po}$  distribution patterns across the study locations.

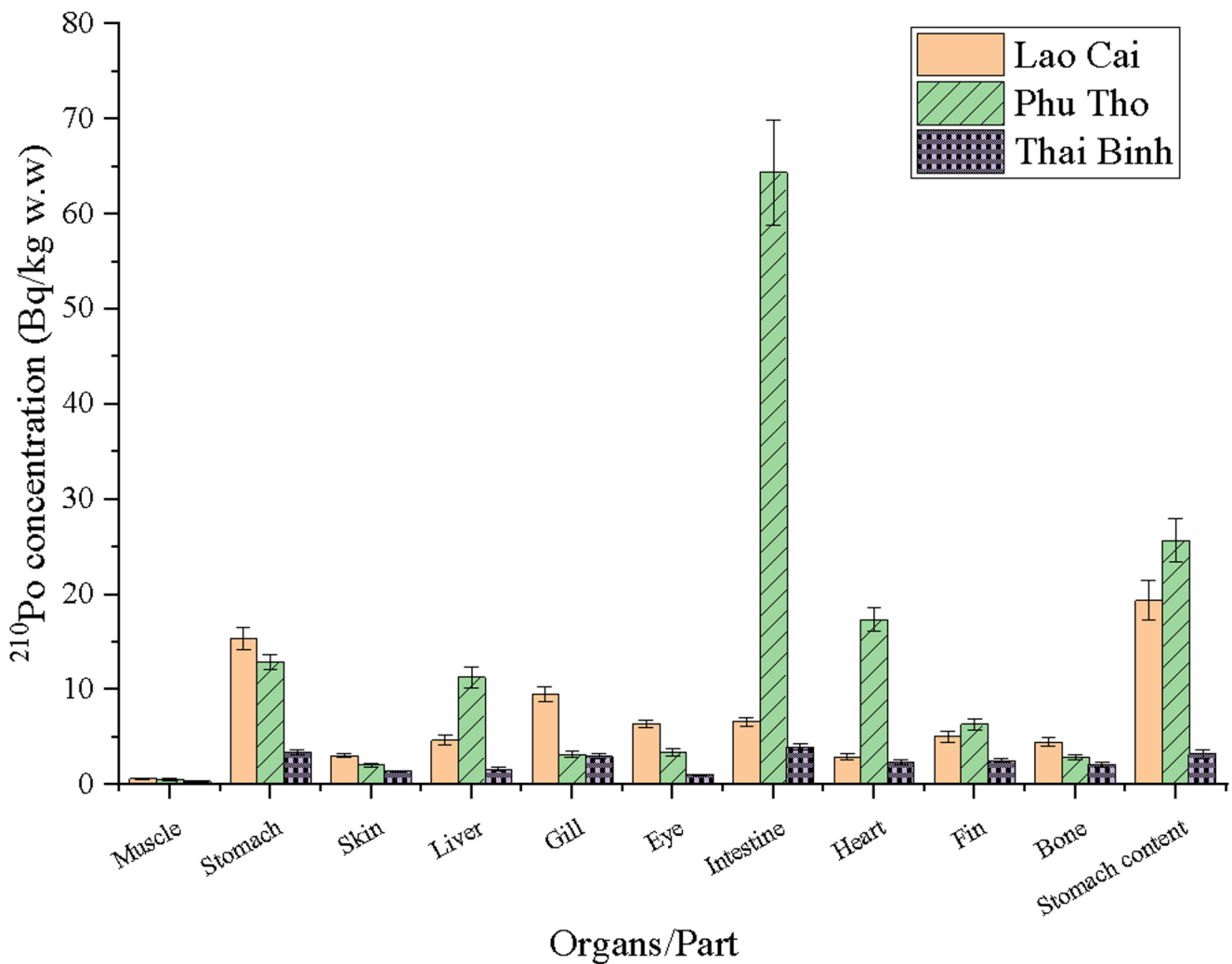
### Annual committed effective dose

The ED due to consuming fish containing  $^{210}\text{Po}$  was calculated and presented in Table 3. For *C. carpio*, the minimum, maximum, and average  $^{210}\text{Po}$  activity resulted in ED values of 0.87, 0.03, and 4.67 mSv/year, respectively, for Lao Cai; 1.24, 0.04, and 7.60 mSv/year for Phu Tho; and 1.21, 0.03, and 6.93 mSv/year for Thai Binh. In contrast, for *S. curriculus*, the corresponding ED values were 0.13, 0.01, and 0.35 mSv/year for Lao Cai; 0.28, 0.01, and 1.45 mSv/

year for Phu Tho; and 0.05, 0.01, and 0.09 mSv/year for Thai Binh. The consumption of muscle from these fish is relatively safe compared to the reference values of 1 mSv/year issued by the WHO (2011) and UNSCEAR (2008). However, higher dose values were observed in the digestive organs of *C. carpio*, such as the stomach (3.50–6.93 mSv/year) and intestine (2.18–7.60 mSv/year), and the intestine of *S. curriculus* (1.45 mSv/year). Therefore, consuming digestive tract organs pose a meaningful risk to human health. A comprehensive study is needed to assess the health impacts of other radioactive isotopes through fish consumption in this region.

### Radiation dose on two study species using the ERICA tool

The results from the ERICA tool for external and internal radiation doses, as well as total dose rates, for *C. carpio* and



**Fig. 3** Distribution of  $^{210}\text{Po}$  in the organs of *S. curriculus* by study area

*S. curriculus* in three study sites (Lao Cai, Phu Tho, and Thai Binh) are presented in Table 4. The total dose rates for *C. carpio* were recorded as  $6.31\text{E-}2$ ,  $1.12\text{E-}1$ , and  $2.19\text{E-}1$   $\mu\text{Gy/h}$ , while for *S. curriculus*, they were  $9.95\text{E-}2$ ,  $6.46\text{E-}2$ , and  $4.8\text{E-}2$   $\mu\text{Gy/h}$  in Lao Cai, Phu Tho, and Thai Binh, respectively. It's important to note that  $^{210}\text{Po}$  emits alpha particles, making the external dose rate negligible in comparison to the internal dose rate. Overall, *C. carpio* showed higher total dose rate values when compared to *S. curriculus* across all three study sites. The total dose rate received by both fish species from  $^{210}\text{Po}$  was found to be lower than the screening level of  $10$   $\mu\text{Gy/h}$  recommended by the ERICA Tool. Based on this assessment, the total  $^{210}\text{Po}$  radiation dose to the *C. carpio* and *S. curriculus* species in the study area suggests insignificant hazardous effects from the mining, chemical, and agricultural industries affecting these freshwater fish species in their aquatic environment. This finding will facilitate comprehensive ecological risk

assessment for fish populations and associated aquatic food web components.

## Conclusions

The  $^{210}\text{Po}$  activity concentrations in eleven organs of *C. carpio* and *S. curriculus* were determined in Lao Cai, Phu Tho, and Thai Binh provinces along the Red River in Vietnam. The results showed that the uneven distribution of  $^{210}\text{Po}$  activity across different organs of *C. carpio* and *S. curriculus* suggests that the digestive pathway is a primary route for radionuclides entering these fish species. Furthermore, differences in biological features between the species likely contribute to the varying  $^{210}\text{Po}$  activity concentrations observed in their organs. Notably,  $^{210}\text{Po}$  concentrations in fish varied among different locations along the Red River, suggesting the influence of local sources,

**Table 3**  $^{210}\text{Po}$  concentration in different organs of two species and the annual effective dose

| Species                              | Organs/Part     | $^{210}\text{Po}$ concentration (Bq/kg w.w) |            |            | Annual effective dose (mSv/year) |         |           |
|--------------------------------------|-----------------|---|------------|------------|----------------------------------|---------|-----------|
|                                      |                 | Lao Cai                                     | Phu Tho    | Thai Binh  | Lao Cai                          | Phu Tho | Thai Binh |
| <i>Cyprinus carpio</i> (dw)          | Muscle          | 2.6±0.3                                     | 1.94±0.14  | 1.2±0.13   | 0.06                             | 0.04    | 0.03      |
|                                      | Stomach         | 155±9.3                                     | 149±5.4    | 307±7.7    | 3.50                             | 3.36    | 6.93      |
|                                      | Skin            | 3.84±0.2                                    | 5.1±0.2    | 5.89±0.1   | 0.09                             | 0.12    | 0.13      |
|                                      | Liver           | 2.48±0.25                                   | 5.74±0.45  | 52.3±3.9   | 0.06                             | 0.13    | 1.18      |
|                                      | Gill            | 1.34±0.2                                    | 17.1±0.8   | 2.12±0.1   | 0.03                             | 0.39    | 0.05      |
|                                      | Eye             | 6.43±0.5                                    | 7.51±0.4   | 39.2±0.9   | 0.15                             | 0.17    | 0.88      |
|                                      | Intestine       | 207±17.8                                    | 337±40     | 96.5±5.6   | 4.67                             | 7.60    | 2.18      |
|                                      | Heart           | 1.51±0.2                                    | 11.6±0.3   | 14.5±1.9   | 0.03                             | 0.26    | 0.33      |
|                                      | Fin             | 1.53±0.1                                    | 8.31±0.1   | 7.52±0.2   | 0.03                             | 0.19    | 0.17      |
|                                      | Bone            | 2.85±0.23                                   | 5.06±0.3   | 9.9±0.4    | 0.06                             | 0.11    | 0.22      |
|                                      | Stomach content | 92.5±6.5                                    | 70.9±8     | 121±11.2   | -                                | -       | -         |
| Average                              |                 | 43.4±3                                      | 56.3±5     | 59.7±3     | 0.87                             | 1.24    | 1.21      |
| Min                                  |                 | 1.34±0.2                                    | 1.94±0     | 1.2±0.13   | 0.03                             | 0.04    | 0.03      |
| Max                                  |                 | 207±17.8                                    | 337±4      | 307±7.7    | 4.67                             | 7.60    | 6.93      |
| <i>Squaliobarbus curriculus</i> (dw) | Muscle          | 0.63±0.07                                   | 0.56±0.09  | 0.36±0.028 | 0.01                             | 0.01    | 0.01      |
|                                      | Stomach         | 15.4±1.15                                   | 12.9±0.8   | 3.42±0.3   | 0.35                             | 0.29    | 0.08      |
|                                      | Skin            | 3.06±0.2                                    | 2.08±0.2   | 1.42±0.1   | 0.07                             | 0.05    | 0.03      |
|                                      | Liver           | 4.68±0.51                                   | 11.3±1.1   | 1.63±0.17  | 0.11                             | 0.25    | 0.04      |
|                                      | Gill            | 9.51±0.8                                    | 3.18±0.31  | 2.98±0.26  | 0.21                             | 0.07    | 0.07      |
|                                      | Eye             | 6.42±0.4                                    | 3.43±0.42  | 1.03±0.1   | 0.14                             | 0.08    | 0.02      |
|                                      | Intestine       | 6.66±0.45                                   | 64.4±5.5   | 4.01±0.29  | 0.15                             | 1.45    | 0.09      |
|                                      | Heart           | 2.93±0.31                                   | 17.4±1.2   | 2.36±0.24  | 0.07                             | 0.39    | 0.05      |
|                                      | Fin             | 5.07±0.56                                   | 6.35±0.65  | 2.55±0.2   | 0.11                             | 0.14    | 0.06      |
|                                      | Bone            | 4.49±0.45                                   | 2.92±0.257 | 2.17±0.26  | 0.10                             | 0.07    | 0.05      |
|                                      | Stomach content | 19.4±2.1                                    | 25.7±2.3   | 3.25±0.46  | -                                | -       | -         |
| Average                              |                 | 7.11±0.5                                    | 13.7±1.2   | 2.9±0.2    | 0.13                             | 0.28    | 0.05      |
| Min                                  |                 | 0.63±0.07                                   | 0.56±0.09  | 0.36±0.028 | 0.01                             | 0.01    | 0.01      |
| Max                                  |                 | 15.4±1.15                                   | 64.4±5.5   | 4.01±0.29  | 0.35                             | 1.45    | 0.09      |

**Table 4** The estimated value of the total radiation dose rate  $^{210}\text{Po}$  on the *C. carpio* và *S. curriculus* (freshwater biota) was calculated using the ERICA tool

| Area      | Freshwater Organism  | Dose rate of $^{210}\text{Po}$ ( $\mu\text{Gy/h}$ ) |          |         |
|-----------|----------------------|---|----------|---------|
|           |                      | External  | Internal | Total   |
| Lao Cai   | <i>C. carpio</i>     | 5.07E-5   | 6.3E-2   | 6.31E-2 |
|           | <i>S. curriculus</i> | 2.22E-9   | 9.95E-2  | 9.95E-2 |
| Phu Tho   | <i>C. carpio</i>     | 4.77E-5   | 1.12E-1  | 1.12E-1 |
|           | <i>S. curriculus</i> | 2.08E-9   | 6.46E-2  | 6.46E-2 |
| Thai Binh | <i>C. carpio</i>     | 5.68E-5   | 2.19E-1  | 2.19E-1 |
|           | <i>S. curriculus</i> | 2.48E-9   | 4.8E-2   | 4.8E-2  |

while upstream-to-downstream transport effects were not observed. These differences underscore the impact of habitat and environmental conditions on  $^{210}\text{Po}$  distribution between the two study species.

Regarding human health implications, the estimated annual effective dose (ED) of consuming muscle tissue of both species containing  $^{210}\text{Po}$  falls within allowable limits when compared with the recommended value. However, the ED exceeds these limits when consuming digestive organs such as the stomach and intestine. Thus, the consumption of

freshwater fish digestive organs should be discontinued to mitigate health risks. Additionally, the total estimated dose rates calculated using the ERICA tool were below the 10  $\mu\text{Gy/h}$  screening level recommended by ERICA. This indicates negligible effects on *C. carpio* and *S. curriculus* from  $^{210}\text{Po}$  associated with mining, chemical industry, or agricultural activities in the study areas, though the assumption of no harm at  $<10 \mu\text{Gy/h}$  requires confirmation in future studies.

These conclusions highlight the complex interactions between environmental factors, habitat preference, and human health risks associated with  $^{210}\text{Po}$  contamination in freshwater fish species along the Red River in Vietnam. This research ultimately contributes to the scientific knowledge base regarding  $^{210}\text{Po}$  bioaccumulation mechanisms in aquatic environments and their implications for both ecosystem integrity and public health protection.

## Appendix 1

**Table Appendix 1** The distribution of  $^{210}\text{Po}$  in organs of different fish species from worldwide

| Country    | Species   | Part           | $^{210}\text{Po}$ (Bq/Kg) | Ref.                         |
|------------|---|----------------|---------------------------|------------------------------|
| Spain      | <i>Cyprinus carpio</i> (dw)   | Spine          | 63–94                     | López Cas-tillo et al., 2011 |
|            |   | Muscle         | 11–54                     |                              |
|            |   | Gills          | 201–343                   |                              |
|            |   | Hepatopancreas | 292–1163                  |                              |
|            |   | Gut            | 293–3773                  |                              |
|            | <i>Carassius auratus</i> (dw)   | Spine          | 57–509                    |                              |
|            |   | Muscle         | 43–555                    |                              |
|            |   | Gills          | 355–937                   |                              |
|            |   | Hepatopancreas | 474–2067                  |                              |
|            |   | Gut            | 1159–5897                 |                              |
|            | <i>Chelon labrosus</i> (dw)   | Spine          | 142–590                   |                              |
|            |   | Muscle         | 25–208                    |                              |
|            |   | Gills          | 376–1303                  |                              |
|            |   | Hepatopancreas | 619–1381                  |                              |
|            |   | Gut            | 1232–5389                 |                              |
| Tajikistan | <i>Sander lucioperca</i> (ww)   | Liver          | 11                        | Skip-perud et al. 2013       |
|            |   | Muscle         | 2                         |                              |
|            |   | Bones          | 8                         |                              |
|            | <i>Carrasius auratus</i> (ww)   | Liver          | 3650                      |                              |
|            |   | Muscle         | 400                       |                              |
|            |   | Bones          | 700                       |                              |
|            | <i>Cyprinus carpio</i> (ww)   | Liver          | 183                       |                              |
|            |   | Muscle         | 7                         |                              |
|            |   | Bones          | 14                        |                              |
| Slovenia   | <i>Leuciscus cephalus</i> (ww)<br>(stream Brebovščica, Gorenja Dobrava) | Muscle         | 0.069–0.42                | Štok and Smodiš 2011         |
|            |   | Muscle         | 0.18–0.43                 |                              |
|            | <i>Salmo trutta</i> (ww)<br>(stream Brebovščica, Gorenja Dobrava)       | Muscle         | 0.056–1.05                |                              |
|            |   | Muscle         | 0.11–0.27                 |                              |
|            | <i>Barbus barbus</i> (ww)<br>(stream Poljanska Sora, Žabja vas)         | Muscle         | 0.10–0.82                 |                              |
|            |   | Muscle         | 0.08–0.12                 |                              |
|            | <i>Oncorhynchus mykiss</i> (ww)<br>(stream Selška Sora, Železniki)      | Muscle         | 0.063–0.34                |                              |
| Indian     | <i>Cyprinus carpio</i> (dw)   | Fillet tissue  | 9.39                      | Gha-jar-beygi et al. 2022    |

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## Declarations

**Ethical approval** The authors further confirm that any aspect of this study covered in this manuscript that has involved human patients or animals has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

**Informed consent** Authors confirm that the named authors have read and approved the paper. The author confirms that the named authors have approved the order of authors listed in the manuscript.

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## Authors and Affiliations

Trung-Tien Chu<sup>1</sup> · Van-Hao Duong<sup>1</sup> · Thanh-Xuan Pham-Thi<sup>1</sup> · Munawar Suhail Ahmed<sup>2</sup> ·  
Mohamed Saiyad Musthafa<sup>2</sup> · Thanh-Duong Van<sup>3</sup> · Xuan-Huan Nguyen<sup>4</sup> · Trung-Thanh Tran<sup>4</sup> · Thuy-Anh Tran-Thi<sup>4</sup> ·  
Van-Luc Nguyen<sup>4</sup> · Hong Nguyen-Thi<sup>5,6</sup> · Nga Phung-Thi<sup>7</sup> · Thanh-Nam Nguyen<sup>4</sup>

✉ Thanh-Nam Nguyen  
nguyenthanhnam@hus.edu.vn  
Trung-Tien Chu  
chutrongtienmdc@gmail.com  
Van-Hao Duong  
haodv@vnu.edu.vn  
Thanh-Xuan Pham-Thi  
phamxuan179893@gmail.com  
Munawar Suhail Ahmed  
suhailsch13@gmail.com  
Mohamed Saiyad Musthafa  
saiyad\_musthafa@rediffmail.com  
Thanh-Duong Van  
thanhduong96mdc@gmail.com  
Xuan-Huan Nguyen  
nxhuan.sh@gmail.com  
Trung-Thanh Tran  
thanhttran@hus.edu.vn  
Thuy-Anh Tran-Thi  
tranthuyanh81@hus.edu.vn

Van-Luc Nguyen  
vanluc9599@gmail.com  
Hong Nguyen-Thi  
nguyenthihong01@dentu.edu.vn  
Nga Phung-Thi  
ptnga@thanhdouni.edu.vn

- <sup>1</sup> VNU School of Interdisciplinary Sciences and Arts, Vietnam National University, Hanoi 100000, Vietnam
- <sup>2</sup> Unit of Research in Radiation Biology & Environmental Radioactivity (URRBER), P.G. & Research Department of Zoology, The New College (Autonomous), Affiliated to University of Madras, Chennai 600 014, Tamilnadu, India
- <sup>3</sup> Institute of Earth Sciences, Vietnam Academy of Science and Technology, Hanoi 100000, Vietnam
- <sup>4</sup> VNU University of Science, Vietnam National University, Hanoi 100000, Vietnam
- <sup>5</sup> Environment and Sustainable Development Research Group, Dong Nai Technology University, Bien Hoa City, Vietnam
- <sup>6</sup> Faculty of Technology, Dong Nai Technology University, Bien Hoa City, Vietnam
- <sup>7</sup> Thanh Do University, Hanoi, Vietnam