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Accumulation of elements in the host–parasite system of Atlantic salmon *Salmo salar* and cestode *Eubothrium* sp. from the southern Baltic Sea and its impact on fish condition

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Abstract
Atlantic salmon (*Salmo salar*) is a fish species valued for human consumption. It is a predator that feeds intensively and, as a consequence, may be exposed to the accumulation of harmful factors, such as parasites and heavy metals. Salmon were collected during a standard ichthyological analysis in spring 2023 in the southern Baltic Sea. All 40 specimens were heavily infected with the intestinal cestode parasite *Eubothrium* sp. This study aimed to evaluate the concentrations of the following elements: toxic metals (Cd, Hg, and Pb) and the metalloid As, macroelements (Ca, K, Na, Mg, and P), and microelements (Cr, Cu, Fe, Mn, Sr, and Zn), in the tissues of salmon (liver and muscle) and *Eubothrium* sp. The relationships between elements concentrations in the parasites and salmon tissues were expressed as bioconcentration factors (BCFs). In the parasite-host system (with respect to the muscle tissue of salmon), cestodes primarily accumulate microelements, which may negatively affect the condition of the fish. A high BCF ratio of parasite/host muscle tissue for Cd concentration may be beneficial for the host because parasite accumulation may influence metal distribution and potentially reduce metal availability for host tissues. In the parasite-host system (with respect to the liver), parasites accumulate highly toxic Hg but also absorb microelements (Sr, Zn, and Mn) and macroelements at much higher concentrations than those found in the host.

Keywords
Salmo salar; *Eubothrium* sp.; Bioconcentration; Toxic metals; Macroelements; Microelements

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1. Introduction

Atlantic salmon (*Salmo salar*) is one of the most important fish species in the Baltic Sea its economic and ecological importance (Jacobson et al., 2018; ICES, 2025). In 2024, in the Baltic Sea, salmon was caught in commercial fisheries – 54 729 individuals (344 tonnes) and in recreational fisheries – 11 288 individuals (ICES, 2025). It is a valuable fish intended for human consumption. The consumption of salmon caught in the Baltic Sea is 0.07–0.5 kg/ per/year (Tuomisto et al., 2020). Salmon is a noble fish with a high content of omega-3 fatty acids (Domingo, 2007), delicate flesh, and a distinct flavour that is used in cuisines worldwide.

It is a limited species, with strictly defined fishing quotas (TAC – Total Allowable Catch is established by the EU for salmon from the Baltic Sea in the number of individuals that could be commercially caught in the next calendar year) (ICES, 2025). This anadromous fish breeds in the rivers around the Baltic Sea, but its main feeding grounds are located in the southern area of that sea (ICES, 2025). The condition of salmon stocks varies among rivers (in general, stocks are most productive in rivers feeding the Gulf of Bothnia, whereas stocks from rivers flowing into the southern Baltic Sea are in poor condition) (ICES, 2025). Therefore, the existence of mixed stocks in the southern Baltic Sea has consequences for the composition of the fish caught in that area. That region is characterised by a mixture of weak and strong populations (ICES, 2025). To protect stocks in poor condition by reducing mixed-stock fisheries, salmon fishing in the southern Baltic Sea has been banned since January 2022 (ICES, 2025).

From an ecological perspective, salmon in the Baltic Sea occupies a high trophic level as a piscivorous predator, but its ecological impact is limited compared to major predators such as grey seals, and it is itself subject to predation (e.g., by seals) (Lai et al., 2021). The Salmon's diet predominantly consist of fish (mainly sprat *Sprattus sprattus*, three-spined stickleback *Gasterosteus aculeatus*, herring *Clupea harengus*) and invertebrates (*Mysis mixta* and *Gammarus* sp.) (Nadolna-Ałtyn et al., 2022). Salmon is a predator that feeds intensively (Jacobson et al., 2018) and, as a consequence, may be exposed to harmful factors through bioaccumulation (the process by which a substance, usually harmful, gradually builds up in the tissues of a living organism over time) and biomagnification (the process by which the concentration of a substance, usually a toxic chemical, increases at each successive level of a food chain). Because of the importance of this species, scientific research is ongoing. Therefore, it is crucial to learn as much as possible about salmon in the sea, particularly in the southern Baltic feeding grounds.

The condition of fish in the sea translates into the condition of spawners migrating to their rivers of origin to breed and their ability to survive the migration and spawning (Mobley et al., 2021). The condition of fish is influenced by many factors, including the health of the fish, the presence of parasites (Susdorf et al., 2018), or pollutants, such as heavy metals (Sauliute and Svecevicius, 2017). Research conducted at the National Marine Fisheries Research Institute, Gdynia, Poland, revealed that salmon caught in the southern Baltic Sea have been found to be highly infected with the intestinal parasite *Eubothrium* sp. (100% of 172 fish analysed between 2020–2023) (unpublished data). In the Baltic Sea, so far only one species, *Eubothrium crassum*, has been detected (Setyawan et al., 2019; Rolbiecki et al., 2026), and our previous molecular analysis of *Eubothrium* sp. from salmon confirm that identification (unpublished data). *E. crassum* is widespread in Europe and North America (Rolbiecki et al., 2026). These cestodes primarily inhabit the pyloric caeca and the initial section of the intestine, competing with the fish for nutrients (Persson et al., 2007). It has been found that fish parasites can react to toxic compounds present in the aquatic environment, especially intestinal parasites that are directly impacted by food contaminants ingested by the host. Some parasites are able to accumulate contaminants, such as toxic metals (Sures and Taraschewski, 1995; Thielen et al., 2004), in concentrations higher than those found in the host (Sures et al., 1999; Podolska et al., 2016). Sures (2003) presented an overview focused on the accumulation of heavy metals by intestinal helminths in fish. Fish parasites (especially acanthocephalans, cestodes) show 'enormous heavy metal accumulation capacity' (Sures, 2003).

Generally, metals in biota can be divided into three groups: macroelements (Ca, K, Na and Mg), microelements (Cr, Cu, Fe, Mn, Sr, and Zn), and toxic metals (Cd, Hg, and Pb). Furthermore, two elements with an important impact on living organisms include the nonmetal phosphorus (P) and the metalloid arsenic (As). Trace metals such as Fe, Cu, Zn, Mn are essential for fish development, energy metabolism, and immune response (Chandrapalan and Kwong, 2021). Metals like Cu, Zn, and Cr are essential and vital for physiological processes; however, excessive concentrations may cause stress to fish and act as pollutants (Naz et al., 2023), can be toxic, present a serious problem in the aquatic environment, and may be harmful to human health. Fish absorb metals directly from the water (via the body surface and gills) or from food sources (via the digestive tract), and these metals are transported by the blood to other organs. Cd, Hg, and Pb are toxic to most organisms at low concentrations (Jezierska and Witeska, 2001).

For consumer health reasons, the presence of metals, with particular emphasis on their occurrence in the tissues of commercially important fish, is of scientific and consumer interest. Metal concentrations in fish from the southern Baltic Sea have been analysed in sprat (*Sprattus sprattus*) (Polak-Juszczak, 2018; Polak-Juszczak and Szlinder-Richert, 2021), herring (*Clupea harengus*) (Polak-Juszczak, 2018; Polak-Juszczak and Szlinder-Richert, 2021), European flounder (*Platichthys flesus*) (Polak-Juszczak, 2017; Polak-Juszczak and Szlinder-Richert, 2021, 2024), European plaice (*Pleuronectes platessa*) (Polak-Juszczak, 2017), turbot (*Scophthalmus maximus*) (Polak-Juszczak, 2017), cod (Podolska et al. 2016; Polak-Juszczak, 2018; Polak-Juszczak and Podolska, 2021), eel (Polak-Juszczak and Nermer, 2016; Polak-Juszczak, 2018), garfish (Polak-Juszczak, 2023), and perch (Polak-Juszczak and Szlinder-Richert, 2024). Despite the fact that salmon is an important fish species in the area eagerly chosen by consumers, there is a lack of data in the scientific literature relating to the concentration of elements in this fish species.

The objectives of this study were (a) to evaluate the concentrations of selected elements (As, Ca, Cd, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, P, Pb, Sr, and Zn) in the liver and muscle of salmon and in the tissues of the parasite, cestode *Eubothrium* sp., and (b) to analyse the relationship between the condition of the fish and the concentration of elements in the tissues of the host and its parasites.

2. Material and methods

2.1 Collection of samples

In April and May 2023, salmon in the Polish EEZ of the southern Baltic Sea (ICES 39G6, 39G7, and 40G8) were caught for scientific purposes (Figure 1). Standard ichthyological analysis included measurements of total body length and weight, sex determination, gonad developmental stage assessment (on the Maier scale: 1–8), and stomach fullness examination (scale 0–4). Cestodes were isolated from the intestine of each salmon (prevalence of infection was 100%; parasite number was not counted) and identified based on their morphology and anatomy. Parasites were rinsed with water to eliminate the residuals of intestinal material that could artificially elevate measured concentrations of elements. Samples of *Eubothrium* sp., as well as the liver and muscle tissues of fish infected with

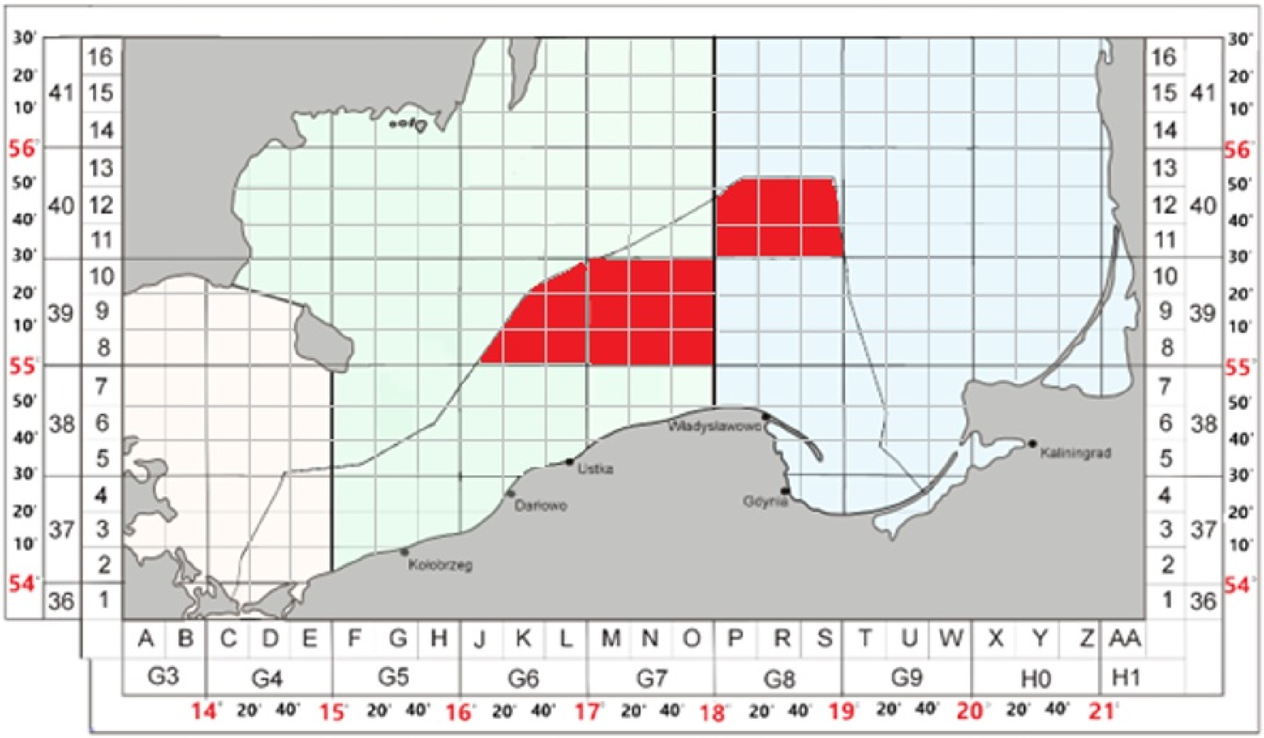

Figure 1. Sampling sites located in ICES 39G6, 39G7, and 40G8.

these parasites, were collected. In total, 40 sets of samples comprising salmon liver and muscle and the corresponding *Eubothrium* sp. tissue were collected and stored frozen until further analysis.

To compare the element accumulation capability of the parasites to that of the host, the bioconcentration factor (BCF) was calculated according to Sures and Siddall (1999) as the ratio of the concentrations of each element (C) in *Eubothrium* sp. relative to that in the tissues (liver and muscle) of the individual fish host (BCF = C [parasite] / C [host tissue]).

Relative accumulation capacity was used to illustrate the ability of an organism to store, absorb, or concentrate substances (e.g., metals). It was calculated as follows: Relative accumulation capacity is the concentration of a particular element in a particular tissue divided by system capacity (sum of all concentrations of particular element from all analysed tissues).

Simple linear regression analysis was performed to evaluate the effect of the concentration of all analysed elements, with particular emphasis on toxic metals in host tissues (liver and muscle) and the Fulton's Condition Factor (FCF) of salmon. Correlation coefficients with a p-value < 0.05 were considered statistically significant. Calculations were performed using the GenStat statistical package. For each fish, the FCF was calculated as follows: FCF = W/L3 × 100, where W is the total body mass, and L is the total length of the fish. Standard error (SE) was calculated as the sample standard deviation (SD) divided by the square root of the sample size (N): SE = SD/square root (N).

2.2 Concentrations of elements in tissues

The concentrations of elements were determined in the muscles, liver, and parasites of salmon. The assayed samples comprised tissues from individual specimens. Muscles were excised from the fish and homogenised. Subsamples of the homogenised tissues were preserved for Hg determination. Metal analyses were performed in class 10,000 clean rooms. Clean rooms ensure air pollution control, particularly for contaminants such as dust, dirt, bacteria, and chemical vapours, in accordance with the ISO 14644-1 standard for the qualification of clean rooms and zones. This standard has been in effect in Poland since 2016.

Approximately 2 g of wet weight (ww) sample, 6 mL of 65% nitric acid (HNO_3, Suprapur, Merck, Rahway, NJ, USA), and 2 mL of 30% hydrogen peroxide (H_2O_2) were placed in PTF vessels. The sample in the vessel was then subjected to a Microwave Digestion System (MDS 2100 and MARS 5) according to mineralization programs specified for fish. The solutions were diluted appropriately with 0.1 M HNO_3 and transferred to 25 mL volumetric flasks. The concentrations of the elements (Cd, Pb, As, Fe, Cr, Cu, Zn, Sr, Mn, K, P, Ca, Na, and Mg) were determined using optical emission spectrometry with induction plasma (Varian

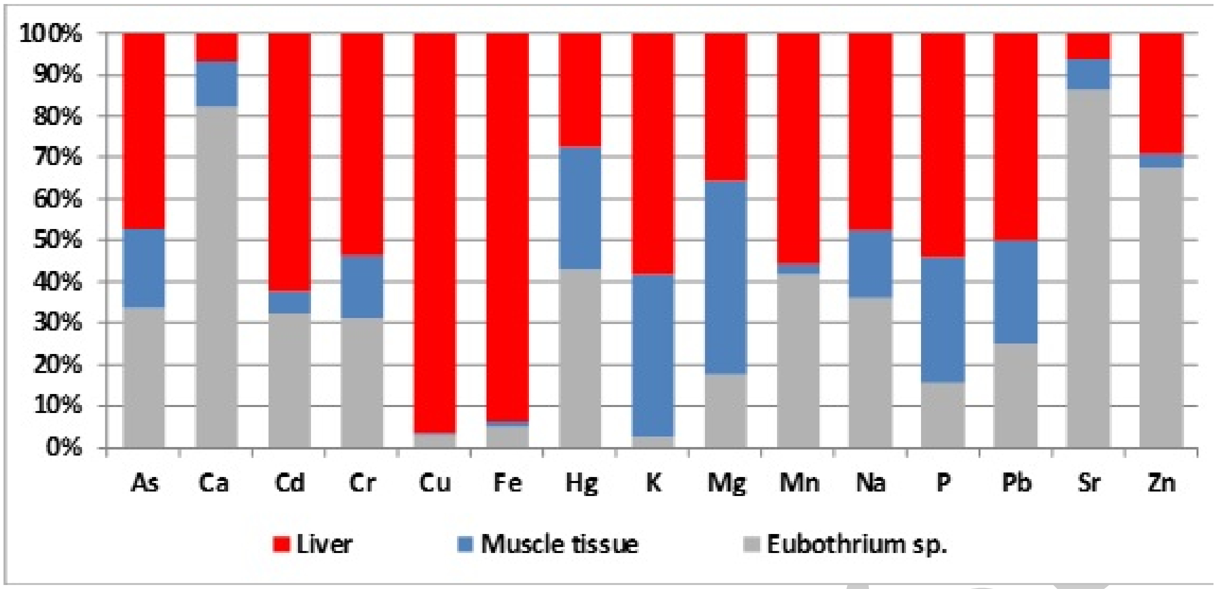

Figure 2. Relative accumulation capacity: *Eubothrium* sp., the host muscle tissue, and liver.

ICP-OES, Vista MPX, Agilent Technologies, Santa Clara, CA, USA).

Total Hg content was assayed using the cold vapour atomic absorption method in an AMA 254 mercury analyser. The analyses were conducted according to the following procedure: tissue samples of approximately 100 mg were placed in the combustion chamber of the analyser, where they were dried and then burned at a temperature of 600°C in an oxygen atmosphere. The measurements were conducted as follows: drying time, 70 s; decomposition time, 120 s; and waiting time, 50 s (Polak-Juszczak, 2018).

Average values with variations in three replicates of less than 10% were calculated to interpret the results. Each measurement series was preceded by the analysis of freeze-dried reference materials, and the parameters of the method applied were designated: limit of detection, recovery (Table 1). All concentrations presented in the Results section have been expressed on a wet-weight basis.

3. Results

The collected salmon individuals comprised 24 females and 16 males, with body lengths ranging from 45 to 109 cm. The total body weight of analysed fish ranged from 2.6 to 14.2 kg. Gonad developmental stages of examined fish were 2 – resting stage (55.9% of fish) and 3 – beginning of preparation for spawning (44.1% of fish). Stomach fullness in majority of the fish (61.8%) was 1, meaning 25% of the stomach was filled with feed; in 20.6% of the fish, the stomach was half full; in 5.9% of cases it was 3, meaning 3/4 of the stomach was full; in 11.8% of cases the stomach was empty.

Length and weight of the fish were used to calculate the

Table 1. Limits of detection and recoveries of analysed elements.

Metal	Certified metal	Certified value	Recovery (%)	Limit of detection (mg/kg)
As	IAEA 436	1.98 ± 0.17	110.8	0.05
Ca	SRM 1566b	838 ± 20	104.3	0.5
Cd	CRM 422	0.017 ± 0.002	110.8	0.001
Cr	IAEA 436	0.194 ± 0.058	99.5	0.01
Cu	CRM 422	1.05 ± 0.07	97.4	0.1
Fe	CRM 422	5.46 ± 0.3	92.0	0.25
Hg	SRM 1566b	0.037 ± 0.001	98.6	0.001
Hg	CRM 422	0.559 ± 0.016	98.8	0.001
K	SRM 1566b	6520 ± 90	98.8	1
Mg	SRM 1577b	601 ± 28	104.8	0.01
Mn	IAEA 436	0.543 ± 0.028	93.0	0.002
Na	SRM 1577b	2420 ± 60	97.9	1
P	SRM 1577b	11000 ± 300	104.1	0.1
Pb	CRM 422	0.085 ± 0.015	89.2	0.01
Sr	SRM 1566b	6.8 ± 0.2	102.9	0.01
Zn	CRM 422	19.6 ± 0.5	98.1	0.75

SRM 1566b – Oyster tissue, National Institute of Standards & Technology, USA.
SRM 1577b – Bovine Liver, National Institute of Standards & Technology, USA.
CRM 422 – Cod muscle, European Commission – Joint Research Centre, Geel, Belgium.
IAEA 436 – Tuna fish, International Atomic Energy Agency, Vienna, Austria.

FCF (see: 2.1 Collection of samples). Salmon individuals were collected in three adjacent ICES rectangles: 39G6,

Table 2. Metal concentrations (mg/kg ww) in tissues of salmon (*Salmo salar*) from the southern Baltic Sea and its parasite *Eubothrium* sp.; N – number of analysed samples (fish); SE – standard error.

	N	Mean	Min.	Max.	SE
As					
Muscle tissue	40	0.430	0.172	0.886	0.022
Liver	40	1.049	0.450	1.672	0.037
Eubothrium sp.	40	0.748	0.137	2.237	0.079
Ca					
Muscle tissue	40	61.71	47.18	108.1	2.05
Liver	40	37.63	11.05	75.92	2.39
Eubothrium sp.	40	463.2	161.6	886.8	26.20
Cd					
Muscle tissue	40	0.004	0.002	0.008	0.000
Liver	40	0.049	0.023	0.142	0.004
Eubothrium sp.	40	0.025	0.012	0.038	0.001
Cr					
Muscle tissue	40	0.019	0.012	0.031	0.001
Liver	40	0.069	0.027	0.259	0.007
Eubothrium sp.	40	0.040	0.010	0.212	0.006
Cu					
Muscle tissue	40	0.128	0.088	0.179	0.004
Liver	40	34.80	13.93	60.48	2.010
Eubothrium sp.	40	1.032	0.436	1.616	0.051
Fe					
Muscle tissue	40	2.61	1.39	5.33	0.11
Liver	40	177.9	26.10	538.8	16.50
Eubothrium sp.	40	9.39	6.31	13.95	0.30
Hg					
Muscle tissue	40	0.047	0.028	0.166	0.004
Liver	40	0.044	0.020	0.094	0.003
Eubothrium sp.	40	0.068	0.020	0.134	0.004
K					
Muscle tissue	40	3030	2705	3516	27.0
Liver	40 4522	3430	5372	76.0	
Eubothrium sp.	40	209.5	25.6	407.8	17.5
Mg					
Muscle tissue	40	236.8	204.8	287.2	3.2
Liver 40	181.3	118.1	239.7	4.2	
Eubothrium sp.	40	88.9	44.8	132.1	3.4
Mn					
Muscle tissue	40	0.038	0.021	0.056	0.001
Liver 40	0.884	0.558	1.163	0.025	
Eubothrium sp.	40	0.666	0.167	1.378	0.047
Na					
Muscle tissue	40	402.3	285.2	613.7	9.9
Liver	40	1168	595.3	1793	34.4
Eubothrium sp.	40	890.7	130.5	1855	67.9
P					
Muscle tissue	40	2196.0	1838.0	2848.0	39.0
Liver	40	3962.0	2701.0	5150.0	92.0
Eubothrium sp.	40	1139.8	631.2	1714.2	36.4
Pb					
Muscle tissue	40	0.028	0.006	0.059	0.002
Liver	40	0.057	0.001	0.123	0.004
Eubothrium sp.	40	0.029	0.009	0.084	0.002
Sr					
Muscle tissue	40	0.106	0.040	0.417	0.012
Liver	40	0.094	0.007	0.432	0.026
Eubothrium sp.	40	1.249	0.223	3.937	0.139
Zn					
Muscle tissue	40	4.00	2.74	6.67	0.12
Liver	40	39.42	24.08	71.09	1.54
Eubothrium sp.	40	91.05	41.23	160.8	4.97

39G7 and 40G8. The linear models were applied and did not reveal statistically significant differences in the condition of salmon caught in these rectangles. Similarly, the gonad developmental stage and stomach fullness did not reveal statistically significant differences in the condition of the analysed fish.

The element concentrations in the tissues of salmon (from liver and muscles) and *Eubothrium* sp. are presented in Table 2. The levels of toxic metals (Cd, Pb and Hg) and As in salmon muscle were low. The highest concentrations of toxic metals (except for Hg) were recorded in the liver. The Cd concentration in salmon liver was 12 times higher than that in muscle, Pb was twice as high, and the toxic metalloid As was 2.5 times higher. Hg occurs at similar levels in salmon muscle and liver but predominates in parasites. This level is approximately 65% higher than in the muscles or liver. Furthermore, *Eubothrium* sp. parasites accumulate Cd and As in a way comparable to the liver. The concentration of Cd in *Eubothrium* sp. was six times higher, and As was two times higher, compared to salmon muscle tissue.

Macroelements: Salmon muscle and liver were dominated by K and P. Na and Mg were present at significantly lower levels. Unlike in the parasites, the Ca content was low. Among the macroelements, parasites primarily accumulated Ca and Na. They contained lower levels of K, Mg, and P than the muscles and liver.

Microelements: Salmon muscle contained the most Cr and Sr, whereas Cu and Fe were predominant in the liver. Differences in trace element concentrations have also been observed in salmon parasites. They contained 22 times more Zn than the muscle and twice as much Zn as the liver. The Fe content in parasites was 3.5 times higher than that in muscle, whereas Cu, Mn, and Sr were over 10 times higher (Table 2).

Relative accumulation capacity refers to the ability of an organism to store, absorb, or concentrate substances (e.g., metals). Figure 2 represents concentration (%) in particular, analysed tissues (*Eubothrium* sp., muscle tissue and liver of the host). The highest relative accumulation capacity of *Eubothrium* sp. in comparison with the muscle tissue of salmon was recorded for Sr, Ca, and Zn (Figure 2). The bioconcentration (BCF) values calculated for parasite/host muscle tissue were highest for Zn (mean: 23.7; females: 25.6; males: 20.8), Mn (mean: 18.7; females: 17.21; males: 20.9), and Sr (mean: 16.03; females: 15.35; males: 17.05) (Figure 3a–c). The relative accumulation capacity of *Eubothrium* sp. in comparison with the liver of salmon was highest for Sr and Ca (Figure 2). The highest BCFs for the parasite/host liver were recorded for Sr (mean: 34; females: 31.7; males: 37.3) and Ca (mean: 15.4 in both sexes) (Figure 3d–f).

Mean concentrations of elements accumulating primarily in the tissue of *Eubothrium* sp., compared with those in host tissues, were highest for Ca (parasite: 463.2 mg/kg; host muscles: 61.7 mg/kg; host liver: 37.6 mg/kg); Sr (parasite: 1.25 mg/kg; host muscles: 0.1 mg/kg; host liver: 0.94 mg/kg); and Zn (parasite: 91 mg/kg; host muscles: 4 mg/kg; host liver: 39.4 mg/kg) (Table 2, Figure 4).

For toxic elements, the relative accumulation capacity of *Eubothrium* sp. was greater than that of the host tissues for Cd, As, and Hg (Figure 2). The highest BCF (6.8) was recorded for Cd (parasite/host muscle tissue), whereas the mean BCFs for As, Hg, and Pb did not exceed 2 (Figure 5a). The relative concentration for the parasite/host liver was highest for Hg (mean: 1.8); for Pb, As, and Cd, it was below 1 (Figure 5b).

The mean concentration of Cd was highest in the liver of salmon (0.049 mg/kg) and lowest in muscle tissue (0.004 mg/kg), while in *Eubothrium* sp. tissue it reached 0.25 mg/kg (Table 2), which was higher than that in the host muscle tissue and corresponded to the highest BCF value calculated for this system. A similar relationship was observed for As: the highest mean concentration was found in the host liver (1.049 mg/kg), the lowest in muscle tissue (0.43 mg/kg), and a greater concentration was noted in cestodes (0.78 mg/kg) than in host muscle tissue. The mean concentration of Hg in *Eubothrium* sp. reached 0.068 mg/kg, which was higher than that in both host tissues (muscle: 0.047 mg/kg; liver: 0.044 mg/kg). No accumulation capacity of *Eubothrium* sp. was reported for lead: mean concentrations were similar in the parasite (0.29 mg/kg) and host muscle tissue (0.29 mg/kg), with both being much lower than in the liver of the host (0.57 mg/kg). The mean tissue concentrations of the toxic elements (As, Cd, Hg, and Pb) are presented in Table 2 and Figure 6.

Simple linear regression analysis revealed a significant negative correlation between the FCF of salmon and the concentrations of Cd ($R = -0.334$, $p = 0.035$) and Pb ($R = -0.578$, $p < 0.001$) in the liver of the host (Figure 7a–b). There was no statistically significant correlations between the FCF of salmon and other analysed elements.

4. Discussion

Maximum levels for contaminants in fish, including salmon, were regulated in the European Union under Commission Regulation (EC) No 1881/2006 (European Commission, 2006), which sets limits of 0.50 mg/kg for Hg, 0.30 mg/kg for Pb, and 0.05 mg/kg for Cd in fish muscle tissue. That regulation has been replaced by Commission Regulation (EU) 2023/915 (European Commission, 2023), but listed limits for salmon did not change. The listed limits were not exceeded in the fish analysed in the present study.

Salmon is a nutritionally valuable source of essential mineral elements, contributing meaningfully to human dietary requirements while remaining low in Na. The mineral composition of salmon varies somewhat by species and preparation, but typical values for Atlantic salmon indicate relatively low Na concentrations (approximately 39–56 mg per 100 g edible portion) alongside higher lev-

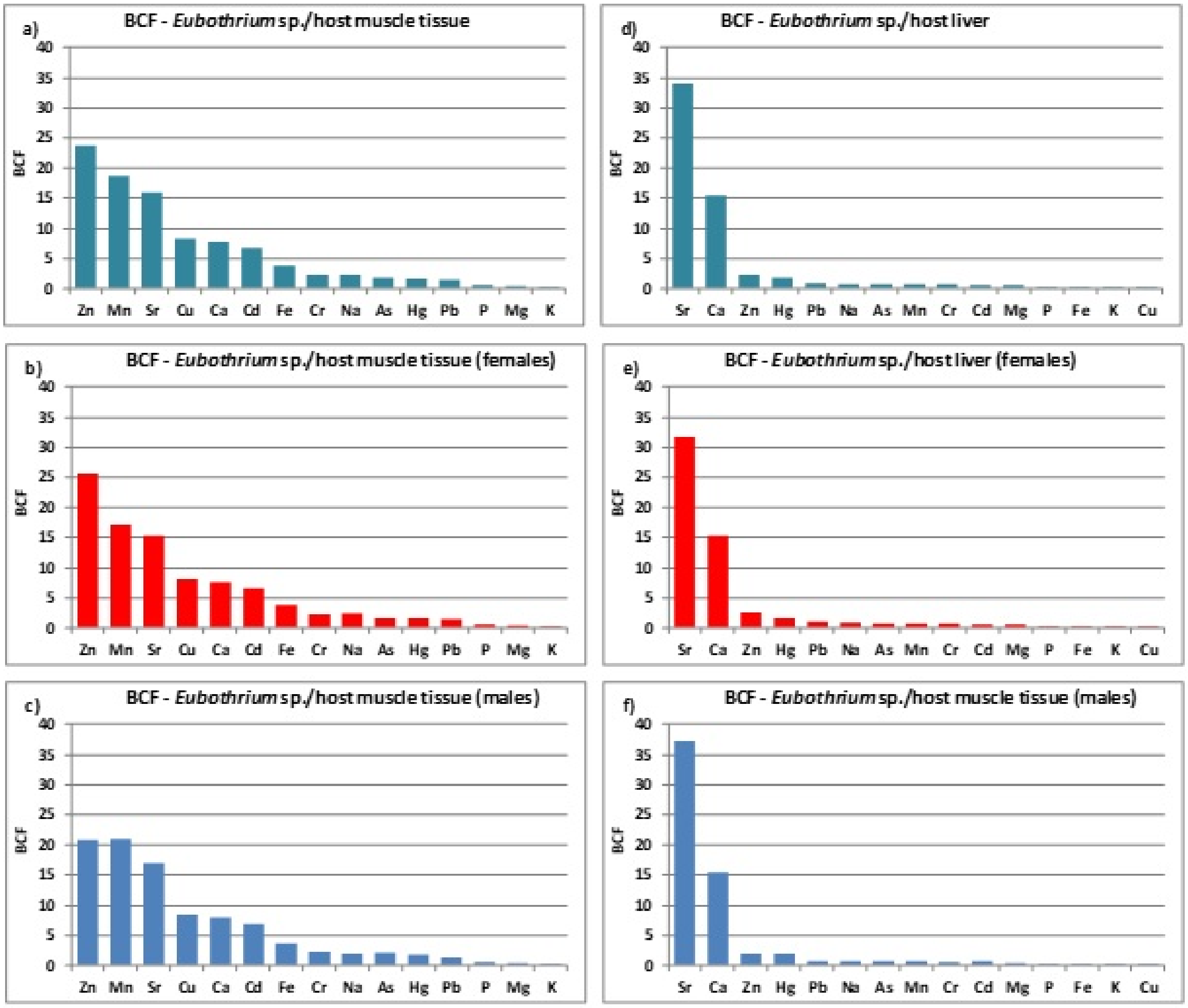

Figure 3. Relative metal concentrations in the tissues of salmon and *Eubothrium* sp., expressed as bioconcentration factor (BCF). Parasites and host muscle tissue (a–c); parasites and host liver (d–f).

els of K (≈ 360–628 mg/100 g), P (≈ 250 mg/100 g), and moderate amounts of Mg (≈ 28–37 mg/100 g), Ca (≈ 8–15 mg/100 g), Fe (≈ 0.3–1.0 mg/100 g), Zn (≈ 0.4–0.8 mg/100 g), and Se (≈ 35–47 μg/100 g). These values are consistent with broader datasets on fish composition reported by the Food and Agriculture Organization (FAO), which show that fish muscle is generally characterized by low sodium and relatively high potassium and phosphorus concentrations (FAO, 1989). From a nutritional perspective, these mineral levels can be evaluated against international dietary recommendations established by the World Health Organization (WHO) and FAO. According to the joint report of FAO/WHO (2003), adult Na intake should be limited to less than 2 g per day (equivalent to approximately 5 g of salt), whereas K intake should be at least 3.5 g per day. Recommended intakes for other minerals include approximately 1000 mg/day for Ca, 260–420 mg/day for Mg, 8–18 mg/day for Fe (depending on sex and physiological status), and 8–14 mg/day for Zn, depending on dietary bioavailability. When these guidelines are compared with the mineral content of salmon, it becomes clear that salmon contributes minimally to sodium intake while providing a meaningful contribution to potassium and phosphorus requirements.

Despite the fact that salmon from the Baltic Sea is valuable for consumers, little is known about the concentration of toxic metals, micro- and macroelements, and other elements in the tissue of that fish. Trace metal concentrations (in μg/g on a wet weight basis) in muscle tissues of salmon from the Baltic Sea region have been reported in the 1980s; among others listed were: Fe 3.0; Mn 0.13; Pb 0.01; Cu 0,09; Zn 11.2; Cd 0.003 (Szefer and Falandysz,

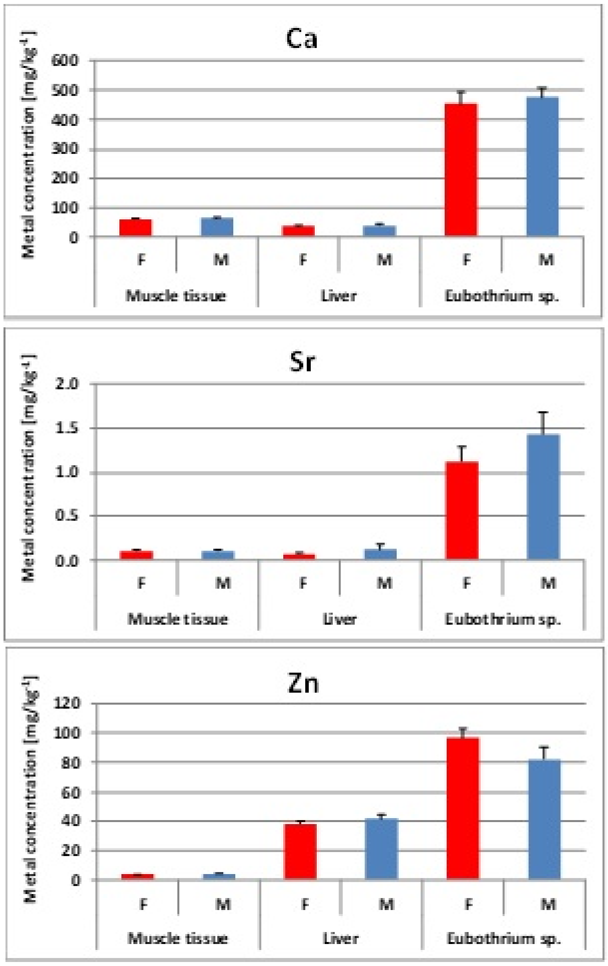

Figure 4. Mean concentrations of elements (Ca, Sr, Zn) (mg/kg +se ww), primarily accumulating in the tissue of *Eubothrium* sp., compared to the muscle tissue and liver of the host. F – females, M – males.

1985). Studies conducted by Łuczyńska et al. (2011) revealed the following levels of elements: Mn 0.057–0.118 mg/kg ww, Cu 0.315–0.417 mg/kg ww, Zn 2.8–4.02 mg/kg ww, Fe 1.2–1.67 mg/kg ww, Ca 7.6–10.3 mg/100g ww, Mg 22.1–24.5 mg/100g ww, Na 30.0–54.6 mg/100g ww, K 324.4–427.0 mg/100g ww.

The presented study showed that the concentrations of the toxic elements Cd, Hg, and As in salmon varied depending on the tissue and tended to accumulate in the liver of salmon (except for Hg). MeHg, the organic form of mercury, is the dominant form of Hg in fish and is efficiently absorbed and retained. MeHg binds tightly to sulfhydryl (–SH) groups in proteins (e.g., cysteine); therefore, protein-rich fish muscles (not liver) are the main storage site for Hg (Polak-Juszczak, 2012). In general, toxic element concentrations in salmon were low, comparable to those found in the muscle tissues of most Baltic fish species (Łuczyńska et al., 2022). Only species from areas outside the Baltic Sea, such as halibut, tuna, and mackerel, contained high levels of Cd, Hg, and As (Polak-Juszczak and Barcz, 2026). High concentrations of Cd (Foran et al., 2004), Hg (Kelly et al., 2008), and As (Valiente-Diaz et al., 2025) in salmon have also been reported. Similarly, the concentrations of the microelements differed significantly depending on the fish tissue, with the highest levels found in the liver. Microelements in salmon were observed at levels similar to those in other fish species (Łuczyńska et al., 2011). Differences were noted in Cr concentrations: salmon muscle contained Cr at levels lower than those in fish from the Baltic and other regions for herring, sprat, halibut, tuna, mackerel, pollock, hake, sea trout and zander (Tkachenko et al., 2019; Polak-Juszczak and Barcz, 2026). The relatively low Cr concentrations observed in salmon muscle are consistent with known patterns of Cr distribution in fish. Bakshi and Panigrahi (2018) have demonstrated that Cr preferentially accumulates in metabolically active organs such as the liver, gills, and kidney, while muscle tissue typically exhibits the lowest concentrations. This pattern is attributed to the higher abundance of metal-binding proteins, such as metallothioneins, in detoxification organs, whereas muscle tissue has a limited capacity for metal binding. Additionally, Cr generally exhibits low bioaccumulation in fish compared to other metals, further contributing to its low levels in muscle tissue. Differences in ecological niche and exposure pathways, particularly the pelagic feeding behavior of salmon compared to benthic species, may also contribute to lower chromium concentrations (Canli and Atli, 2003).

The macroelements Ca, K, Mg, and P in salmon muscle were at levels comparable to those in most other fish species, while Na was present at a lower level (Łuczyńska et al., 2011). Studies conducted by Łuczyńska et al. (2011) revealed that Na concentration in muscles of salmon was 30.0–54.6 mg/100 g wet weight. The observed lower sodium concentrations in Baltic salmon compared with other fish species may be explained by strong physiological regulation of monovalent ions in marine teleosts. Salmon maintain internal Na^+ homeostasis through active ion transport mechanisms in gill chloride cells and renal excretion, preventing accumulation in muscle tissue (Evans et al., 2005). Unlike species more closely associated with benthic habitats or estuarine environments, pelagic salmon experience more stable ionic conditions and rely on efficient osmoregulatory control rather than tissue storage of sodium (Marshall and Grosell, 2006). Consequently, interspecific differences in Na concentration are primarily driven by species-specific osmoregulatory strategies rather than environmental exposure differences (Griffith, 2017). Salmon livers contained less Ca and Mg than the muscles and more K, Na, and P – that pattern is generally consistent with known fish physiology. Concentrations of elements in analysed salmon compared with fish representing other species and/or regions might differ. The

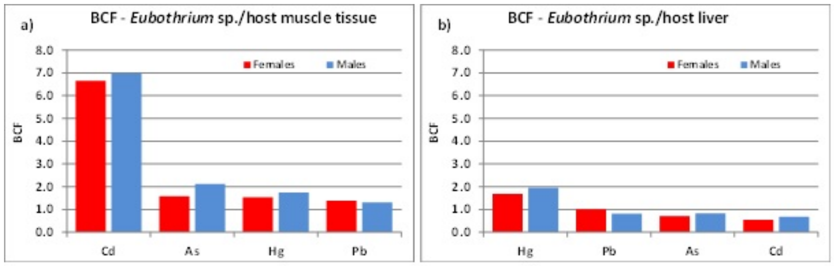

Figure 5. Relative concentrations of toxic elements in the tissues of salmon and *Eubothrium* sp., expressed as bioconcentration factor (BCF). Parasites and host muscle tissue (a); parasites and host liver (b).

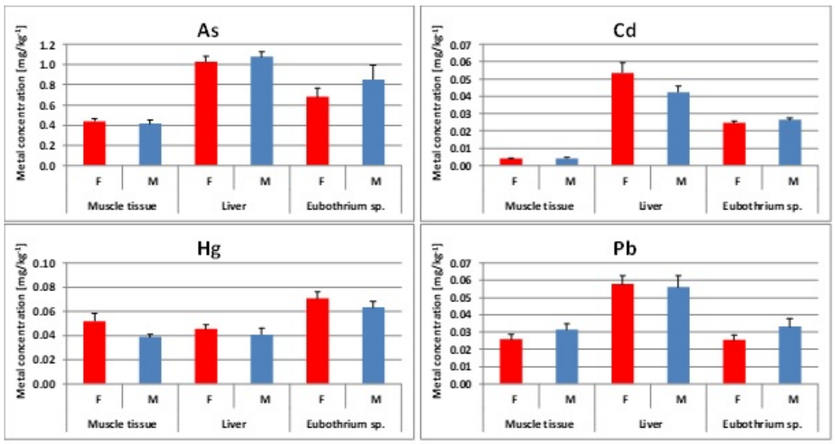

Figure 6. Mean concentrations of toxic elements (As, Cd, Hg, and Pb) (mg/kg + se ww) in the tissues of salmon and *Eubothrium* sp. F – females, M – males.

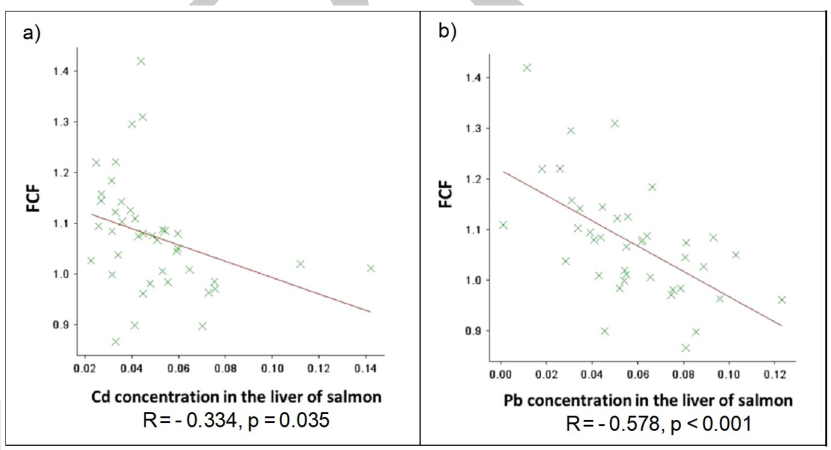

Figure 7. Fitted and observed relationships between the FCF of salmon and the concentrations (mg/kg ww) of cadmium (a) and lead (b) in the liver of the host.

explanation might be the fact that metal accumulation in tissues depends primarily on their environmental concentrations and exposure times. Furthermore, concentration in a given region changes over time. In accumulation processes, a significant role is played by environmental factors such as water salinity, pH, hardness, and temperature. Furthermore, biological aspects of individuals such as sex, size, maturation, and spawning periods also influence the accumulation of metals in fish tissues (Polak-Juszczak and Barcz, 2026).

Knowledge about salmon parasite fauna is also limited and restricted to only a few publications (Setyawan et al., 2019; Nadolna-Ałtyn et al., 2023, 2024). Certain intestinal fish parasites can accumulate metals at concentrations higher than those in host tissues or the environment (Sures et al., 1999; Podolska et al., 2016). This study on the metal content in a host (salmon) – parasite (*Eubothrium* sp.) system was conducted for the first time. There was no possibility to obtain results related to element concentrations from uninfected fish, because every analysed salmon was infected with *Eubothrium* sp.

BCF shows which elements are predominantly accumulated by the parasite compared with the host tissue. It is the first time, that BCF was calculated for this host (salmon) – parasite (*Eubothrium* sp.) system. In the case of toxic metals, a high BCF parasite/host tissue is beneficial for the host, because the parasite accumulate accumulates that toxin and, as a result, there is lessare fewer toxic elements that could be accumulated by the host. In the case of elements important for the host, the a high BCF parasite/host tissue is harmful for the host, because parasite parasites compete with the host for the vital substances. In decreasing order, the BCF values for individual elements in *Eubothrium* sp. compared to fish muscle tissue followed the order Zn > Mn > Sr > Cu > Ca > Cd > Fe > Cr > Na > As > Hg > Pb > P > Mg > K, whereas, with respect to salmon liver, the BCF values followed the series Sr > Ca > Zn > Hg > Pb > Na > As > Mn > Cr > Cd > Mg > P > Fe > K > Cu, regardless of the sex of the host. Analysis of the data regarding the concentration of specific elements revealed that *Eubothrium* sp. has the ability to accumulate them at much higher concentrations than the host tissue (liver and muscle). *Eubothrium* sp. accumulates, to the greatest extent, macro- and microelements that are crucial for the health of fish (Ca, Mg, Sr, and Zn), which may negatively affect fish health. This may cause deficiencies of these elements in fish (Sures et al., 1999). The ability of *Eubothrium* spp. to accumulate essential macro- and microelements implies a host–parasite competition for nutritionally important ions, which can have several physiological consequences for salmon. Reduced availability of Ca and Mg for fish may provide lead to impaired skeletal development, neuromuscular function, and enzyme activity (Lall, 2002). Altered Sr dynamics, that which is chemically similar to Ca, cause potential interference with bone mineralization (Dahl et al., 2001). Lower Zn levels in fish lead to disruption of metalloenzymes, immune function, and antioxidant defenses (Lall, 2002).

Our results reveal high concentrations of Ca and Sr in parasite tissue compared to the concentrations in host tissue. In fish, Sr^{2+} and Ca^{2+} compete for the same transport systems, showing "completely competitive" uptake kinetics (Chowdhury and Blust, 2001). Cestodes (like *Eubothrium*) lack a digestive tract and absorb nutrients across the tegument, relying heavily on passive/active ion uptake from host intestinal contents. Because Ca^{2+} transport pathways are abundant and essential, Sr^{2+} is co-transported and accumulated. Intestinal parasites are continuously exposed to host chyme rich in dissolved ions, and as a consequence there is higher availability of Ca/Sr than in host muscle tissue. Our results reveal low concentrations of Pb in parasites. Pb can mimic Ca chemically, but high Ca availability inhibits Pb uptake. Fish tissues (especially liver, kidney, and even muscle to a lesser extent) can bind Pb to metallothioneins or store it in inert forms. In contrast, parasites often lack equally developed detox pathways for Pb, leading to either reduced uptake or rapid elimination rather than storage.

Hg concentrations in parasite and muscle tissue of the salmon were reported at comparable levels. Hg occurs predominantly as methylmercury (MeHg), which is highly lipophilic and strongly binds to thiol (−SH) groups in proteins, especially muscle proteins. This is the reason why fish muscle is the main storage site for Hg (Polak-Juszczak, 2018). *Eubothrium* sp. absorbs substances through the tegument from intestinal contents, not from host tissues directly. Only a limited fraction of MeHg is present in intestinal chyme at any given time, and as a result, the parasite does not have access to a much higher Hg pool than the host muscle.

Eubothrium sp. can accumulate higher concentrations of toxic elements (Cd, As, and Hg) than salmon tissue. Intestinal helminths, including cestodes, are known to absorb and concentrate metals directly across their tegument at levels far exceeding those found in host organs (Sures et al., 1999). As a result, part of the toxic metal burden taken up from food can be sequestered within the parasite rather than remaining bioavailable to the host. This may be beneficial for the host, as it may reduce the concentration of pollutants and mitigate their negative effects on the fish's body. This suggests that *Eubothrium* sp. is involved in metal detoxification. The phenomenon related to the accumulation of heavy metals by intestinal helminths in fish has been earlier reported for other host-parasite systems (Sures, 2003). It should be emphasised that our results revealed a significant negative correlation between the condition of salmon and the concentrations of Cd and Pb in the liver of the host.

Because of their ability to accumulate heavy metals, fish parasites have been used as bioindicators of these pollutants in aquatic ecosystems (Sures, 2004, 2008; Canpolat, 2024). High metal accumulation rates in cestodes have been reported worldwide. The cestode *Bothriocephalus acheilognathi* from the largemouth yellowfish *Labeobarbus kimberleyensis* in the Vaal Dam, South Africa, accumulates higher concentrations of lithium, beryllium, manganese, selenium, mercury, thallium, lead, and uranium compared with the host tissue sediment, and water (Retief et al., 2006). *Proteocephalus macrocephalus* (Cestoda), in comparison to its fish hosts, the eel *Anguilla anguilla* in Ria de Aveiro, Portugal, accumulates higher concentrations of Cr, Ni, and Zn (Eira et al., 2009). Moreover, higher levels of Cr in the liver and muscles have been reported in non-infected fish than in infected individuals (Eira et al., 2009). The cestode *Senga parva* from 30 snakehead fish, *Channa micropeltes* (Lake Kenyir, Malaysia), accumulated Pb, Zn, and Mn to a greater extent than in water and fish tissues (Yen Nhi et al., 2013). The concentrations of heavy metals (Cu, Mn, Cd, Ni, and Pb) in the cestode *Polyonchobothrium* clarias from the African sharptooth catfish *Clarias gariepinus* (Egypt) were higher than those in fish tissues and the values recommended by the FAO/WHO (Abdel-Gaber et al., 2016). Additionally, in the case of the cestode *Proteocephalus percae* from European perch *Perca fluviatilis* in the water reservoir Ružín in Slovakia, most trace elements were found at higher levels in parasites than in fish (Brazova et al., 2024).

Our results represent the latest research on heavy metal concentrations in wild salmon captured in the southern Baltic Sea. The concentrations of metals were analysed for the first time in the host (salmon) – parasite (*Eubothrium* sp.) system. These studies revealed that *Eubothrium* sp. can accumulate some metals (including toxic ones); therefore, they may be a promising candidate as an indicator of selected metal pollution in marine environments. However, it requires further investigation taking into account additional criteria (e.g., specificity, sensitivity, reproducibility, spatial consistency).

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Supplementary material

Supplementary material associated with this article can be found here.

Conflict of interest

None declared.

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