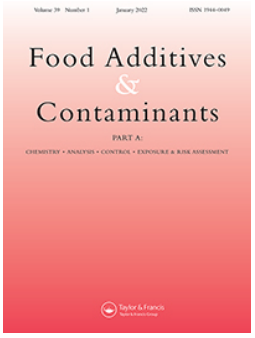

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Assessment of heavy metals in wild and farmed tilapia (*Oreochromis niloticus*) on Lake Kariba, Zambia: implications for human and fish health

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ABSTRACT

The aim of this study was to assess the levels of heavy metals in both wild and farmed tilapia on Lake Kariba in Zambia and to evaluate the impact of intensive fish farming on wild tilapia. Three sites for wild fish (2 distant and 1 proximal to fish farms) and two fish farms were selected. One hundred fish (52 from distant sites; 20 near fish farms; 28 farmed fish) were sampled and muscle tissues excised for analysis of heavy metals (Mg, Fe, Zn, Al, Cu, Se, Co, Mo, As, Cr, V, Ni, Hg, Pb, Li, Cd, and Ag) by acid (HNO_3) digestion and ICP-MS. All metals were found to be below the maximum limits (MLs) set by WHO/EU. Essential metals were higher in farmed tilapia, whereas non-essential metals were higher in wild tilapia. Significantly higher levels of essential metals were found in wild fish near the fish farms than those distant from the farms. Estimated weekly intake (EWI) for all metals were less than the provisional tolerable weekly intakes (PTWI). Target hazard quotients (THQ) and Hazard Indices (HI) were <1, indicating no health risks from a lifetime of fish consumption. Selenium Health Benefit Value (HBV_{Se}) was positive for all locations, indicating protective effects of selenium against mercury in fish. Total cancer risk (CR) due to As, Cr, Cd, Ni and Pb was less than 1×10^{-4}, indicating less than 1 in 10,000 carcinogenic risk from a lifetime consumption of tilapia from Lake Kariba. Hg levels (0.021 mg/kg) in wild tilapia at site 1 were higher than the Environmental quality standard (EQS = 0.020 mg/kg) set by EU, indicating possible risk of adverse effects to fish. Except for Hg, levels of metals in fish were safe for human consumption and had no adverse effects on fish.

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Introduction

Aquaculture is a fast-growing sector that contributes significantly to food security, provides an important source of high-quality protein and omega 3 fatty acids and leads to economic development. In 2018, the FAO (2020) estimated the global human consumption of fish to be 156 million tonnes. By 2005, one-quarter of wild fish stocks were underexploited, half fully exploited and the rest had been overexploited or depleted (FAO 2007). The decline in wild fish stocks contributes to the need for a growing aquaculture sector for protection of food security. Since 1970, world aquaculture has grown by an average of 7.5% per year (FAO 2020). The fastest growth has been in Africa and Asia, which have recorded double-digit growth in the past 20 years (FAO 2018, 2020). In 2018, total fish production from both fisheries and aquaculture reached 179 million tonnes (FAO 2020), and aquaculture contributed 46% (82 million tonnes) of the total production (FAO 2020). Apart from being a source of protein, essential fatty acids, minerals and vitamins (Béné et al. 2015; Chan et al. 2019; Vicente-Zurdo et al. 2019), fish also serve as a source of income for people in developing countries (Béné et al. 2015; FAO 2018). In 2018, the FAO (2020) estimated World fish trade at about USD 400 billion, with USD 250 billion coming from aquaculture production. Africa currently contributes about 7% to the total global fish production (FAO 2020), with Egypt being the largest producer of farmed fish on the African continent (Mohamed Shaalan et al. 2018). In 2014, Zambia was the sixth-largest producer of farmed fish on the continent and the biggest producer of tilapia in the Southern African

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Development Community (SADC) (Genschick et al. 2017). Zambian aquaculture produced 20,000 tonnes of fish in 2014, with commercial farms contributing 75% (FAO 2016; Genschick et al. 2017).

Despite the many positives recorded from the growth in aquaculture, it may also have negative impacts on the environment. Some of these are release of organic effluents or chemicals and antibiotics (from medical treatments) into waterbodies and being a source of diseases or genetic contamination of wild species (Berg et al. 1992; Kishimba et al. 2004; Subasinghe 2005; Jarić et al. 2011; Li et al. 2011; Nonga et al. 2011; Polder et al. 2014; Ssebugere et al. 2014; Mwakalapa. et al. 2018). The current aquaculture practices can lead to elevated levels of antibiotic residues, antibiotic-resistant bacteria, persistent organic pollutants, metals, parasites, and viruses in natural waters and fish (Sapkota et al. 2008; Basaran et al. 2010). Increased pollution with organic (persistent organic pollutants) and inorganic (heavy metals) contaminants can affect fish and human health (Vos et al. 2000; Watterson. et al. 2008).

Heavy metals are naturally occurring elements in the earth's crust. They have a relatively high density (at least 5 times) compared to water (Tchounwou et al. 2012). Heavy metal pollution occurs when the metals exceed the naturally occurring levels in the environment or are at levels that affect human and animal health (Nazir et al. 2015). Pollution can be due to natural processes such as erosion and volcanic eruption, or anthropogenic activities (Adriano 2001; Mansour and Sidky 2002; Nazir et al. 2015) such as mining, industry, improper waste management, etc. (Adriano 2001; Xiao et al. 2014; Maurya et al. 2019). Essential metals (Mg, Fe, Zn, Cu, Se, Co, Mo, Cr, and Ni) are required for normal biological functions in humans and animals but can be harmful when levels exceed threshold levels for toxicity (Waseem et al. 2014; Javed and Usmani 2017; Marengo et al. 2018). Non-essential metals (Al, As, V, Hg, Pb, Li, Cd, and Ag) have no known biological functions and can be toxic even in small amounts (Tchounwou et al. 2012; Waseem et al. 2014). They have the potential to disrupt normal biological functions such as endocrine signalling and enzyme activity, which may lead to adverse health effects in both humans and fish (Tchounwou et al. 2012; Javed and Usmani 2017; Arisekar et al. 2020). Freshwater pollution with accumulation of environmental toxicants in aquatic organisms is a global issue (Amundsen et al. 1997; Copaja et al. 2017; Marengo et al. 2018; Mwakalapa et al. 2019; Nakayama et al. 2013; Zhang et al. 2016). Therefore, monitoring of potentially toxic metals in fish is important for both environmental and public health (Maurya et al. 2019; Mwakalapa et al. 2019). Fish are among the most frequently used bioindicators of pollution in aquatic ecosystems (Stankovic et al. 2014) and provide data on bioaccumulation of heavy metals in wild and farmed fish. These data are needed for knowing the contamination status of waterbodies and for assessment of the health risk to aquatic organisms and humans. Limited scientific data are available on bioaccumulation of metals in wild and farmed fish from Zambia as well as sub-Saharan Africa. Furthermore, risk assessment for heavy metals through consumption of farmed and wild freshwater fish from Zambia has not been reported.

In Zambia and the rest of Africa, aquaculture is practiced in fishponds, tanks and in cages on lakes. Lake Kariba on the Zambia–Zimbabwe border is one location where farming of *Oreochromis niloticus* (Nile tilapia) in cages is practiced on an intensive scale. The aims of this study were to (1) assess and compare the levels of heavy metals in both wild and farmed tilapia, (2) evaluate the impact of intensive fish farming on wild tilapia near the farms and (3) compare the results with existing maximum residue levels and threshold values set for humans and fish health.

Materials and methods

Description of sampling area and species

Lake Kariba is a man-made lake located on the southern border of Zambia with Zimbabwe (−17° S 28° E). It was built between 1958 and 1963 for the purpose of hydroelectric generation. The lake is 320 km long with an area of 5400 km^2, and an average depth of 29 m. The lake controls about 90% of the Zambezi river runoff, and water flows from west to east. The climate is sub-tropical with annual rainfall between 400 and 700 mm and temperature between 13°C and 40°C. Fish (*O. niloticus*) were collected from five locations (sites 1–3, and farms 1 and 2) along the lake (Figure 1). Sites 1 and

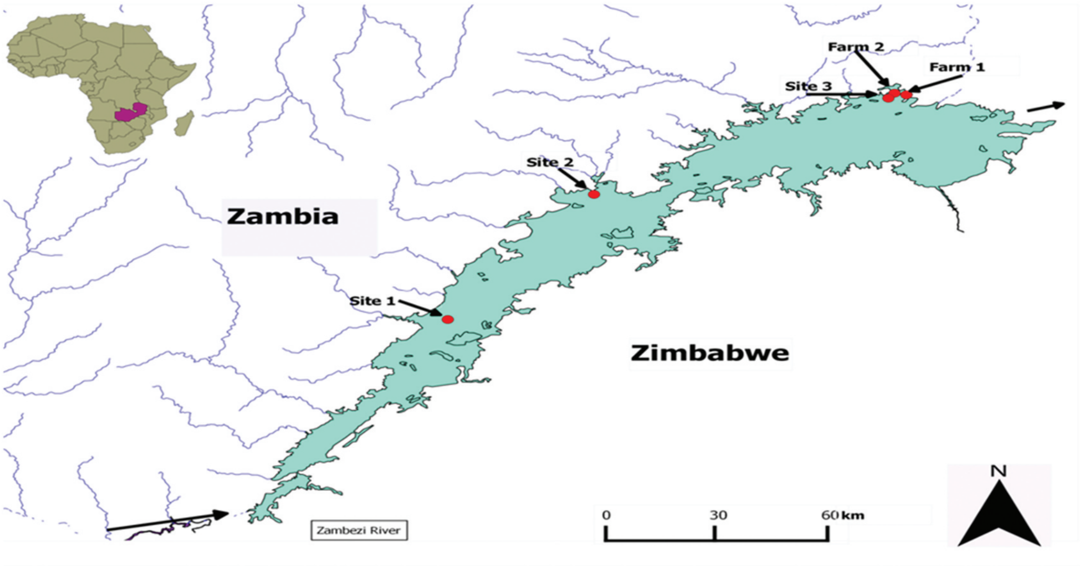

Figure 1. Map of Lake Kariba showing the 5 locations (sites 1–3 and farms 1 and 2) where tilapia was collected on the Zambian side. (Courtesy of Eliezer Brown Mwakalapa 2019).

2 are in Sinazongwe and Gweembe districts, respectively, over 100 km from site 3. The human populations in sites 1 and 2 are 98,246 and 50,136, respectively (Zambia Central Statistical Office 2012). Site 3 is in Siavonga district, on the eastern end of the lake and has a population of 58,864. Farms 1 and 2 are also located in Siavonga district and use cages for farming tilapia in the lake. *O. niloticus* is an omnivorous fish native to river Nile, with a worldwide distribution (FAO, 2005). It feeds on zooplankton and phytoplankton and higher plants (like algae). The fish thrives in tropical and subtropical climates with environmental temperatures of 9–42°C, living in shallow waters. It is found both as wild and farmed fish. Its fast growth and resistance to harsh conditions makes it favourable for aquaculture. Other activities on and around the lake are commercial fishing of kapenta (*Limnothrissa miodon*), farming, livestock, and wildlife managing. In addition, active coal mining is taking place at site 1. Site 3 also has a feed processing plant.

Ethical consideration and permission for the study

The study proposal was approved by the University of Zambia, School of Veterinary Medicine research committee. Wild tilapia was bought from fishermen. Permission from local district fisheries and veterinary officers was obtained before sampling in their areas. Managers at the fish farms gave their permission for samples to be collected from their farms.

Sample collection

A total of 172 wild and farmed tilapia were collected from June to July 2016. Live wild tilapia was bought from fishermen, placed in ice water and dissected back at the shore. Dip netting was used to catch farmed tilapia then dissected at the shore. Fish length and weight were recorded (Table 1). The scale used in the field could only weigh fish up to 1 kg, fish beyond this were assigned 1 kg. Therefore, only length was used for statistics. Stainless-steel forceps and scalpel blades were used to dissected muscle tissue of approximately 10 g. The tissue was placed in clean 15-ml Eppendorf tubes, then transported on ice in a cooler box to the University of Zambia, Veterinary Medicine School and stored at −20°C. Later, samples were transported on ice to the Laboratory of Environment Toxicology at the Norwegian University of Life Science (NMBU) in Oslo, Norway, and stored at −20°C until analysis. Permission to transport samples to Norway was obtained from the Ministry of Livestock and Fisheries, Zambia, and Norwegian Food Safety Authority.

Table 1. Location and fish characteristics: Sampling time, mean and range of individual length and number of pooled muscle samples from farmed (farms 1 and 2) and wild tilapia distant (sites 1 and 2) and near farms (site 3) from Lake Kariba. Zambia.

Location	Sampling time 2016	Mean of individual length (cm)	Range individual length (cm)	No. of individual samples	No. of fish per pool	No. of pooled/ individual samples
Site 1	June	35.57	28–45	29	2–3	10
Site 2	June	30.66	17–42	23	2–3	10
Site 3	June	27.6	24–33	20	2	10
Farm 1	June	23.6	13–29	16	1–3	10
Farm 2	June	27.13	22.5–36	12	1–2	10

Sample analysis

After selection of fish based on similar weight/length from each location, 100 muscle samples were pooled in equal amounts as shown in Table 1. Heavy metal analysis was done at the Laboratory for Soil and Water analysis, Faculty of Environmental Sciences and Natural Resource Management (MINA), Norwegian University of Life Sciences (NMBU), Campus Ås, Norway.

Extraction and analysis of heavy metals

The following heavy metals were analysed: Mg, Fe, Zn, Al, Cu, Se, Co, Mo, As, Cr, V, Ni, Hg, Pb, Li, Cd, and Ag. Approximately 200 mg of muscle samples were weighed in ultrapure Teflon tubes (pre-rinsed in 7 M nitric acid (HNO_3) and in Milli-Q water®). Internal standard (^{74}Se, In) and 5 mL Ultrapure HNO_3 were added. The mixture was digested at 260°C in an UltraCLAVE (Milestone S.r.L, Sorisole (BG) – Italy). After digestion, 1 mL of UltraPure concentrated HCl was added (to prevent loss of Hg) and then diluted to 50 mL with distilled water. The samples were analysed using an Agilent 8800 ICP-MS.

Quality control and quality assurance

Method accuracy was verified by analysing certified reference materials in the same way, at the same time as the sample series. Fish Protein Certified Reference Material for Trace Metals (CRM Dorm-3, National Research Council Canada, Institute for National Measurement Standards, M-12, Ottawa, ON K1A 0R6, Canada) and fish muscle (ERM-BB422, European Commission – Joint Research Centre, Institute for Reference Materials and Measurements (IRMM), 2440 Geel, Belgium) were used. The quantified values show good agreement with the certified values. LOD and LOQ were quantified from 3 to 10 times STDEV in the method blanks, $n = 6$. The mean of LOD and LOQ were calculated using average of the sample weights in a 50 ml dilution.

Human and fish health risk assessment

The mean metal concentrations in fish muscle (mg/kg ww) were compared to maximum limits (ML) set by WHO and EU (FAO/WHO 2002; EC EC 2006) for human consumption. Noncarcinogenic risks, estimated weekly intake (EWI), target hazard quotient (THQ) and hazard index (HI) were calculated as described by Mwakalapa et al. (2019), using formulas (1)–(3). EWIs were compared to provisional tolerable weekly intakes (PTWI) set by WHO. Target hazard quotient is the ratio between the estimated daily intake (EDI) and the oral reference dose (RfD, mg/kg bw/day) (Saha et al. 2016; USEPA 2018). RfD is an estimate of a daily oral exposure to a toxic substance that is likely to be without an appreciable risk of harmful effects during a lifetime (Varol et al. 2017; Mwakalapa et al. 2019). The HI also referred to total target hazard quotient (TTHQ), which is the sum of individual metal THQs. Values of THQ and HI >1 pose a risk of developing non-carcinogenic effects in one's lifetime (Saha et al. 2016; Copat et al. 2018). Selenium health benefit Values (HBV_{Se}) for all site were calculated as described by Ralston (Ralston et al. 2016), using formula (4). A positive HBV_{Se} indicates protective effects of selenium against mercury in the fish, while a negative value indicates that mercury poses a threat to human health (Ralston et al. 2019; Yabanli and Tay 2021). The daily average fish ingestion per person (fish ingestion rate) is 30.14 g/day (Kaminski et al. 2018; Tran et al. 2019), life expectancy (exposure duration) of 64 years, exposure frequency to heavy metals of 365 days/year, and average body weight of an adult 70 kg were used in the calculations.

$$EWI = \frac{MC * IRD * 7}{BW} \tag{1}$$

where MC = mean metal concentration, IRD = daily average fish ingestion per person, and BW = average adult body weight.

$$THQ = \frac{E_F * E_D * F_{IR} * \mathrm{C}}{\mathrm{RfD} * W_{AB} * T_A} * 10^{-3} \tag{2}$$

where E_F = Exposure frequency, E_D = exposure duration, F_{IR} = fish ingestion rate, C = mean metal concentration, RfD = oral reference dose, W_{BA} = average body weight of an adult and T_A = average exposure time with noncarcinogenic effect (E_F*E_D).

$$HI = \sum_{i=1}^{n} THQi \tag{3}$$

$$\mathrm{HBV_{Se}} = ([\mathrm{Se} - \mathrm{Hg}]/\mathrm{Se}) * (\mathrm{Se} + \mathrm{Hg}) \tag{4}$$

The carcinogenic risk/cancer risks (CR) due to lifetime exposure to arsenic, chromium, cadmium, nickel and lead were calculated as described by (Saha et al. 2016), using formula (5). The total cancer risk (TCR) due to fish consumption from the lake, was calculated as the sum of the individual cancer risks (Bamuwamye et al. 2015), using formula (6). Carcinogenic risks (CR) are estimated as the incremental probability of an individual to develop cancer, over a lifetime, as a result of exposure to a potential carcinogen (Ahmed et al. 2016). According to USEPA (2018), acceptable lifetime cancer risk levels range from 10^{-4} (1 in 10,000) to 10^{-6} (1 in 1,000,000) chance of an individual developing cancer (Varol et al. 2017). Cancer risk values greater than 10^{-4} are unacceptable and those less than 10^{-6} indicate a negligible risk of cancer in an individual's lifetime. Cancer slope factors (CSF) $(\mathrm{mg/kg/day})^{-1}$ 1.5 (As), 6.3 (Cd), 0.5 (Cr), 1.7 (Ni) and 0.0085 (Pb) from the Integrated Risk Information System USEPA (2018) database were used in the calculation of CR (Raknuzzaman et al. 2016).

$$CR = CSF \times EDI \tag{5}$$

where CSF = Cancer slope factor, EDI = Estimated daily intake (EWI/7).

$$TCR = \sum_{i=1}^{n} CRi \tag{6}$$

Risk to fish health was assessed using Environmental Quality Standards (EQS) set by EU (Ec 2006). EQS are concentrations of a particular pollutant or group of pollutants in water, sediment or biota that should not be exceeded in order to protect humans, aquatic species (fish) and the environment (EC EC 2006; Lyche et al. 2019).

Statistical analysis

Data was organised in MS Excel 2016 spread sheets. JMP 14 statistical software was used for further analysis. Readings below the limit of detection (<LOD) were assigned a value of half the LOD. Since the data were not normally distributed, non-parametric tests Wilcoxon/Kruskal–Wallis test (rank sum) for differences among locations and Wilcoxon pair test for differences between locations were used. Spearman rank correlation was used to assess the correlation between variables; $p < .05$ values were considered significant.

Results

Concentration of heavy metals in muscle

Fish biometric data is presented in Table 1. Wild tilapia from sites 1 and 2 had significantly greater total length ($p < .01$) than those from site 3 and farmed tilapia. Descriptive statistics (mean, median, minimum and maximum) are shown in Table 2. Concentration of heavy metals in fish muscle in descending order was as follows: Mg >Fe >Zn >Al >Cu >Se >Co >Mo >As >Cr >V > Ni >Hg >Pb >Li >Cd >Ag. Except for Pb, all other metals were present in all samples.

Essential metals

Essential metals (Cu, Fe, Zn and Mo) were higher in farmed and the wild tilapia sampled near the fish farms (site 3) compared to wild fish sampled at locations away from the farms, sites 1 and 2 (Figure 2). The highest levels of Fe were in farmed fish farm 1

Table 2. Descriptive statistics of heavy metal concentrations in muscles of wild and farmed tilapia (mg/kg ww) and maximum limits (ML) set by WHO/FAO, EU, FDA.

		Essential metals									Non-essential metals							
Location		Mg	Cr	Fe	Co	Ni	Cu	Zn	Mo	Se	As	Al	Ag	Cd	Hg	Pb	Li	V
Site 1	Mean	249	0.095	5.23	0.033	0.018	0.25	4.76	0.003	0.15	0.022	4.81	0.0011	0.0007	0.021	0.009	0.006	0.015
	Median	250	0.015	5.15	0.034	0.012	0.25	4.45	0.003	0.16	0.022	4.4	0.0011	0.0006	0.006	0.009	0.006	0.016
	Min	210	0.009	3.1	0.018	0.009	0.2	3.6	0.002	0.13	0.018	2.4	0.0005	0.0005	0.004	0.008	0.005	0.013
	Max	270	0.8	9.4	0.041	0.068	0.32	7.1	0.004	0.17	0.028	8.5	0.0024	0.0018	0.16	0.011	0.008	0.017
Site 2	Mean	263	0.016	5.34	0.036	0.019	0.33	4.75	0.011	0.18	0.042	4.28	0.0016	0.0022	0.008	0.009	0.006	0.048
	Median	260	0.012	4.9	0.034	0.018	0.32	4.7	0.006	0.17	0.042	4.25	0.0012	0.0021	0.005	0.01	0.006	0.021
	Min	240	0.008	3.4	0.027	0.011	0.26	3.7	0.004	0.16	0.024	1.5	0.001	0.0009	0.004	0.0015	0.004	0.015
	Max	290	0.051	8.2	0.054	0.031	0.45	6.1	0.044	0.22	0.057	8.7	0.0034	0.0045	0.026	0.012	0.011	0.19
Site 3	Mean	231	0.021	8.16	0.044	0.009	2.14	8.49	0.054	0.14	0.023	0.78	0.0004	0.0005	0.009	0.004	0.009	0.005
	Median	225	0.02	8.2	0.042	0.009	2.15	8.1	0.045	0.14	0.023	0.91	0.0003	0.0005	0.01	0.002	0.008	0.005
	Min	180	0.007	4.3	0.027	0.006	1.2	6.6	0.03	0.11	0.012	0.3	0.0002	0.0003	0.006	0.002	0.006	0.002
	Max	290	0.039	14	0.061	0.011	3.2	11	0.086	0.16	0.04	1.4	0.0007	0.0006	0.012	0.009	0.013	0.011
Farm 1	Mean	244	0.02	9.38	0.066	0.01	2.57	6.99	0.058	0.18	0.043	1.3	0.0011	0.0008	0.007	0.008	0.006	0.016
	Median	240	0.016	9.55	0.054	0.008	2.55	6.75	0.054	0.18	0.032	1.25	0.0007	0.0004	0.002	0.01	0.006	0.007
	Min	180	0.007	4.8	0.024	0.006	0.78	5.6	0.025	0.13	0.021	0.47	0.0003	0.0003	0.001	0.002	0.004	0.004
	Max	320	0.053	17	0.17	0.019	4.3	9.3	0.092	0.28	0.15	2.7	0.005	0.0022	0.041	0.011	0.006	0.052
Farm 2	Mean	260	0.038	5.78	0.043	0.011	3.5	7.06	0.05	0.15	0.028	1.64	0.0004	0.0004	0.002	0.007	0.007	0.005
	Median	255	0.015	5.5	0.043	0.01	2.65	7.1	0.047	0.16	0.031	0.91	0.0004	0.0003	0.002	0.009	0.008	0.004
	Min	240	0.008	2.4	0.011	0.006	0.5	4.3	0.021	0.12	0.005	0.38	0.0001	0.0003	0.001	0.002	0.008	0.002
	Max	300	0.24	8.5	0.068	0.024	9	10	0.086	0.2	0.05	8.7	0.0011	0.0005	0.003	0.011	0.008	0.012
WHO and FAO	ML			45			30	30						0.1	0.5	0.3		
EU	ML													0.05	0.5	0.3		
FDA	ML														1			

(9.38 mg/kg) and wild fish sampled at site 3 (8.16 mg/kg). Fe levels in fish from these locations were significantly higher ($p < .05$) than in fish sampled from sites 1 and 2. Likewise, Zn levels in farmed fish and wild fish from site 3 were significantly higher ($p < .01$) than in wild fish from sites 1 and 2. The highest Zn level was at site 3 (8.49 mg/kg) and lowest at site 2 (4.75 mg/kg). Cu levels in farmed and wild fish from site 3 were also significantly higher ($p < .01$) than wild fish from sites 1 and 2. The highest Cu level was at farm 2 (3.5 mg/kg) and the lowest at site 1 (0.25 mg/kg). Se in wild fish from site 3 (0.14 mg/kg) had significantly lower ($p < .05$) levels than those from sites 1, 2 and farm 1. The highest Se level 0.178 mg/kg

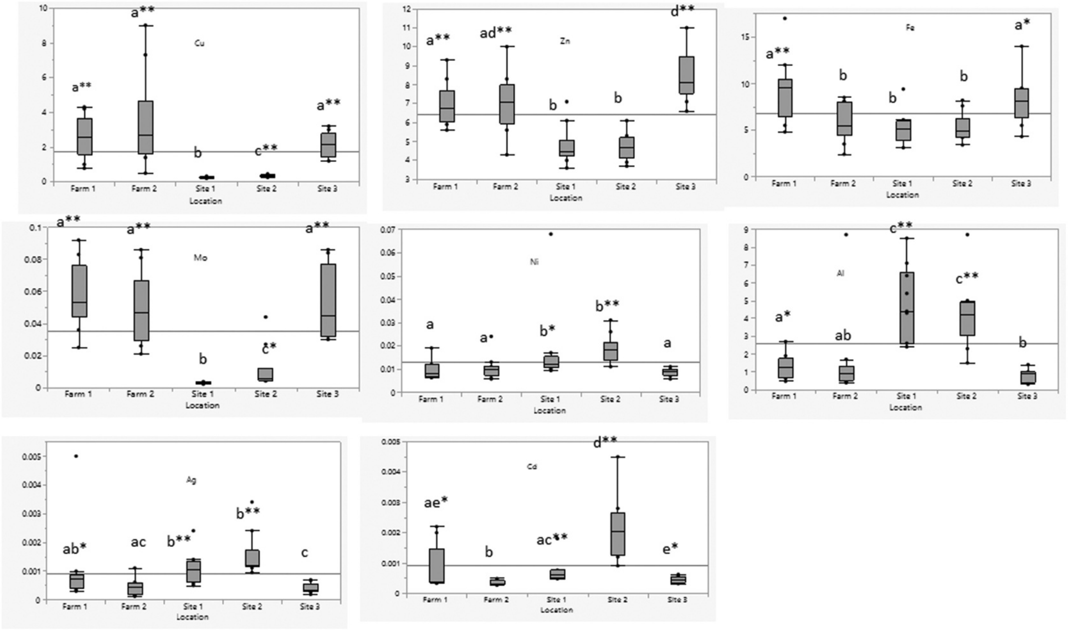

Figure 2. Concentration of heavy metals (Cu, Fe, Zn, Ni, Mo, Al and Cd) in muscle tissue of farmed and wild tilapia from Lake Karbia. Site with the same letter (a,b,c,d, or e) showed no significant difference in metal concentration at ** $p < .01$ and * $p < .05$.

was in farm 1. The highest Co level was at farm 1 (0.07 mg/kg) and lowest at site 1 (0.03 mg/kg). The Co levels in fish from farm 1 were significantly higher ($p < .01$) than wild fish from sites 1 and 2. Mo levels in farmed and wild fish from site 3 were significantly higher ($p < .01$) than wild fish from sites 1 and 2. Highest Mo level was at farm 1 (0.06 mg/kg) and lowest at site 1 (<0.01 mg/kg). Cr and Mg showed no significant difference among all locations.

Non-essential metals

Non-essential metals (Al, Ag, Ni and Cd) were higher in wild tilapia at sites 1 and 2 (Figure 2). Al was significantly higher in wild fish from sites 1 and 2 than farmed and wild fish from site 3. The highest level of Al was at site 1 (4.81 mg/kg) and lowest at farm 1 (0.78 mg/kg). As levels in wild fish from site 2 and farm 1 (site 3) were significantly higher than wild fish from sites 1 and 3. The highest As level was at farm 1 (0.04 mg/kg). V levels at sites 1, 2 and farm 1 (site 3) were significantly higher ($p < .01$) than other locations, with the highest level at site 2 (0.0476 mg/kg). Ni level at sites 1 and 2 was significantly higher than farmed and wild fish from site 3. The highest level was at site 2 (0.0186 mg/kg). Hg levels in wild fish (all sites) were significantly higher ($p < .05$) than farmed fish (site 3). The highest Hg level was at site 1 (0.021 mg/kg). The level of Pb in wild fish from site 3 was significantly lower ($p < .01$) than sites 1,2 and farm 1, with the highest level at site 2 (0.00925 mg/kg). Site 3 had significantly higher levels ($p < .01$) of Li than sites 1, 2 and farm 1, with the highest level of 0.00933 mg/kg. Cd levels at farm 2 were significantly lower ($p < .05$) than the other locations. Ag levels at sites 1 and 2 were higher ($p < .01$) than fish from sites 3 and farm 2. The highest level was at site 2 (0.00155 mg/kg).

Correlation among metals and fish length

Fish length had a significant positive correlation (Spearman's correlation) with Ni and Al, but significant negative correlation with Cu, Fe, Zn, Co and Mo. Significant positive correlation was also found for Fe, Cu, Zn, Co and Mo. Al had significant positive correlation with Cd, Ag, Hg and Ni. Al, Cd and Ni had significant negative correlation with Zn, Cu and Mo.

Risk assessment

Human health

Compared to maximum limits set by WHO/FA0, EU and FDA, all the measured metals in fish muscle were below these limits (Table 2). EWIs of all analysed muscles were also below the PTWI (Table 3). The calculated THQ and HI for all metals were less than the threshold of 1 (Table 4) posing no risk to human health. HBV_{Se} was positive for all locations, indicating protective effect of Se against Hg. Cancer risk due to consumption of As, Cr, Cd, Ni and Pb in fish were less than 1×10^{-4} (Table 5) showing no risk of cancer.

Fish health

The European Union has set an Environmental Quality Standard (EQS) of 0.02 mg/kg of mercury in fish in the environment for assessment of fish health (EC EC 2006). The mean Hg level in wild fish from site 1 (0.021 mg/kg) was higher than the EQS set by the EU (Table 2). This may cause adverse effects in the fish.

Discussion

Metal concentration in muscle of farmed and wild tilapia from Lake Kariba

The study found significant difference in metal concentrations, with essential metals higher in farmed tilapia and non-essential metals higher in wild tilapia. Essential metals (Cu, Zn, Fe, Co and Mo) were higher in farmed and wild fish (site 3) near the farms, than in wild fish (sites 1 and 2) far from the farms. Essential metals are necessary for various biological functions and are therefore added as trace elements to fish feed (Yildiz 2008; Fallah et al. 2011), which may explain the higher levels in farmed fish (Sapkota et al. 2008; Burridge et al. 2010). Feed spillage from the fish farms is accessed by the wild tilapia nearby, thereby exposing them to higher levels of essential metals than the wild fish far from the fish farms (Basaran et al. 2010; Ballester-Molto et al. 2017). Non-essential

Table 3. Estimated weekly intake (EWI) of heavy metals and Selenium health benefit values (HBV_{Se}) from consumption of muscle tissue from wild and farmed tilapia from Lake Kariba, Zambia.

	Site 1	Site 2	Site 3	Farm 1	Farm 2	PTWI
Li	1.91×10^{-5}	1.87×10^{-5}	2.81×10^{-5}	1.76×10^{-5}	2.18×10^{-5}	
Mg	7.5×10^{-1}	7.93×10^{-1}	6.96×10^{-1}	7.35×10^{-1}	7.84×10^{-1}	
Al	1.45×10^{-2}	1.29×10^{-2}	2.35×10^{-3}	3.92×10^{-3}	4.95×10^{-3}	1 (EFSA 2008)
V	4.64×10^{-5}	1.43×10^{-4}	1.52×10^{-5}	4.77×10^{-5}	1.45×10^{-5}	
Cr	2.86×10^{-4}	4.83×10^{-5}	6.43×10^{-5}	5.87×10^{-5}	1.16×10^{-4}	0.023 (Lin et al. 2004)
Fe	1.58×10^{-2}	1.61×10^{-2}	2.46×10^{-2}	2.83×10^{-2}	1.74×10^{-2}	5.6 (JECFA 2017)
Co	9.92×10^{-5}	1.09×10^{-4}	1.32×10^{-4}	2×10^{-4}	1.28×10^{-4}	0.21 (Finley et al. 2012)
Ni	5.43×10^{-5}	5.61×10^{-5}	2.6×10^{-5}	2.94×10^{-5}	3.19×10^{-5}	0.035 (JECFA 2017)
Cu	7.66×10^{-4}	1×10^{-3}	6.45×10^{-3}	7.74×10^{-3}	1.05×10^{-2}	3.5 (JECFA 2017)
Zn	1.43×10^{-2}	1.43×10^{-2}	2.56×10^{-2}	2.1×10^{-2}	2.13×10^{-2}	7 (JECFA 2017)
As	6.57×10^{-5}	1.26×10^{-4}	6.78×10^{-5}	1.3×10^{-4}	8.32×10^{-5}	0.01498 (JECFA 1989)
Se	4.58×10^{-4}	5.30×10^{-4}	4.07×10^{-4}	5.36×10^{-4}	4.58×10^{-4}	
Mo	8.95×10^{-6}	3.43×10^{-5}	1.62×10^{-4}	1.75×10^{-4}	1.5×10^{-4}	
Ag	3.34×10^{-6}	4.66×10^{-6}	1.2×10^{-6}	3.2×10^{-6}	1.33×10^{-6}	
Cd	2.19×10^{-6}	6.57×10^{-6}	1.4×10^{-6}	2.48×10^{-6}	1.1×10^{-6}	0.0056 (JECFA 2011)
Hg	6.33×10^{-5}	2.36×10^{-5}	2.66×10^{-5}	2.05×10^{-5}	6.69×10^{-6}	0.004 (EFSA 2012; JECFA, 2017)
Pb	2.75×10^{-5}	2.79×10^{-5}	1.1×10^{-5}	2.41×10^{-5}	2.01938E-05	0.0105 (EFSA 2010)
HBV_{Se}	1.92×10^{-3}	2.23×10^{-3}	1.71×10^{-3}	2.25×10^{-3}	1.92×10^{-3}	

Table 4. Total hazard quotient (THQ) and hazard index (HI) for analysed heavy metals from consumption of wild and farmed tilapia.

	Site 1	Site 2	Site 3	Farm 1	Farm 2	RfD (USEPA 2018)
Li	1.36×10^{-6}	1.33×10^{-6}	2.01×10^{-6}	1.26×10^{-6}	1.56×10^{-6}	0.002
Mg	2.19×10^{-6}	2.31 × 10-6	2.03×10^{-6}	2.14×10^{-6}	2.28×10^{-6}	
Al	2.07×10^{-6}	1.84×10^{-6}	3.36×10^{-7}	5.6×10^{-7}	7.07×10^{-7}	1
V	1.33×10^{-6}	4.1×10^{-6}	4.35×10^{-7}	1.36×10^{-6}	4.13×10^{-7}	0.005
Cr	1.36×10^{-5}	2.3×10^{-6}	3.06×10^{-6}	2.8×10^{-6}	5.51×10^{-6}	0.003
Fe	3.22×10^{-6}	3.28×10^{-6}	5.02×10^{-6}	5.77×10^{-6}	3.56×10^{-6}	0.7
Co	4.72×10^{-5}	5.2×10^{-5}	6.27×10^{-5}	9.52×10^{-5}	6.11×10^{-5}	0.0003
Ni	3.88×10^{-7}	4.0×10^{-7}	1.86×10^{-7}	2.1×10^{-7}	2.28×10^{-7}	0.02
Cu	2.73×10^{-6}	3.57×10^{-6}	2.30×10^{-5}	2.76×10^{-5}	3.77×10^{-5}	0.04
Zn	6.83×10^{-6}	6.82×10^{-6}	1.22×10^{-5}	1.0×10^{-5}	1.0×10^{-5}	0.3
As	3.13×10^{-5}	6.0×10^{-5}	3.23×10^{-5}	6.2×10^{-5}	3.96×10^{-5}	0.0003
Se	1.31×10^{-5}	1.52×10^{-5}	1.16×10^{-5}	1.53×10^{-5}	1.31×10^{-5}	0.005
Mo	2.56×10^{-7}	9.81×10^{-7}	4.62×10^{-6}	5.0×10^{-6}	4.29×10^{-6}	0.005
Ag	9.55×10^{-8}	1.33×10^{-7}	3.43×10^{-8}	9.15×10^{-8}	3.79×10^{-8}	0.005
Cd	3.13×10^{-7}	9.39×10^{-7}	2.01×10^{-7}	3.54×10^{-7}	1.52×10^{-7}	0.001
Hg	9.04×10^{-5}	3.37×10^{-5}	3.8×10^{-5}	2.92×10^{-5}	9.56×10^{-6}	0.0001
Pb	1.12×10^{-6}	1.14×10^{-6}	4.49×10^{-7}	9.84×10^{-7}	8.24×10^{-7}	
Hazard index	2.18×10^{-4}	1.9×10^{-4}	1.98×10^{-4}	2.6×10^{-4}	1.91×10^{-4}	

RfD: Reference dose set by USEPA (2018).

metals (Al, Ni, Cd, Hg) were higher in wild fish sampled far from the fish farms. The higher Hg level at site 1 (0.021 mg/kg) (Table 2) could possibly be due to coal mining in the area as coal mining has been reported to release Hg to the environment (Liu et al. 2014; Plessl et al. 2019). This calls for further studies. Furthermore, wild tilapia can live up to 9 years compared to farmed tilapia, which is harvested within 6 months of cage-rearing on the lake. The wild tilapia can therefore accumulate contaminants with long biological half-lives such as Hg and Cd over a longer life-span compared to farmed tilapia. Positive associations between Hg and Cd concentrations in tilapia and age as well as size are documented in other studies (Hamada et al. 2018). However, in the present study, we did not find any association between fish size (length) and Hg, whereas Cd and length showed significant association.

Comparison of metal concentration in muscle of tilapia with other regions

Sub-Saharan Africa

Levels of Cu, Fe, Zn and Mo in wild tilapia were similar to results reported in an earlier study on the same lake (Nakayama et al. 2010) but 10 (Cu) and two (Zn) times lower than findings by Berg et al. (1995) (Table 6). The 21 years lapse between the study by Berg et al. (1995) and our study may account for changes in metal content in the lake. This downward temporal trend could be due to changes in mining techniques along the drainage area of Lake Kariba, which are more environmentally friendly today. Berg et al. (1995) also sampled in an area where cage and pond aquaculture were being practiced, which could have influenced levels of metals in the wild tilapia. Wild tilapia from Tanzania (Mapenzi et al. 2020) and Kenya (Nyingi et al. 2016) had three to 20 times higher levels of Fe, Cu and Zn than the present study, which may be explained by their location in areas with more industrial mining, agriculture and human activities. Cr level was 10 times lower than an earlier study in Kariba (Nakayama et al. 2010). The level of Cd was similar to those detected 6 years earlier (Nakayama et al. 2010), but more than 20 times lower than 21 years earlier in the lake, suggesting a reduction of Cd levels the last 20 years (Berg et al. 1995). Hg has not previously been analysed in tilapia from Zambia, but the levels were about 20 times lower than in wild tilapia from Tanzania (Mshana Grayson 2015) and two times lower than Ethiopia (Dsikowitzky et al. 2012). Pb levels were similar to findings 6 years earlier in Lake Kariba (Nakayama et al. 2010), but over 100 times lower than 21 years earlier in the same lake (Berg et al. 1995). Pb was also more than seven times lower than in Tanzania (Mapenzi et al. 2020), Kenya (Nyingi et al. 2016) and Ethiopia (Dsikowitzky et al. 2012). Ni in this study was ten times lower than earlier findings in Lake Kariba (Berg et al. 1995; Nakayama et al. 2010). The decrease of Pb, Cr and Ni levels was contrary to expectations, since the number of kapenta fishing boats rose from 423 in 2009 to 962 in 2013; these are thought to be the sources of Pb, Cr and Ni (Chali et al. 2014; Paulet 2014). The levels of metals in wild tilapia from Lake Kariba were thus lower than the levels in tilapia from other countries in the region. We also report lower levels of Cd (20x) and Pb (100x) compared with a previous study from the same lake. The Hg concentration was not measured in the previous study, but the levels found in the present study were lower than tilapia from Tanzania and Ethiopia.

As stated above, the farmed tilapia had significant higher levels of essential metals and significant lower levels of non-essential metals compared to the wild tilapia sampled far from the fish farms.

Farmed tilapia in this study had similar levels of the essential metals, Cu and Zn to those found earlier in fish from Lake Kariba (Berg et al. 1995), but five to 12 times higher than in farmed tilapia from Uganda (Birungi et al. 2007) (Table 7). This could be due to differences in composition of trace elements in the fish feeds. For Pb, Cd and Ni, levels were more than 200 times less than those found earlier in Lake Kariba (Berg et al. 1995). This is similar to observations above in wild tilapia where levels were also higher in the earlier study by Berg et al. (1995), which indicates a substantial decline in the contamination of non-essential metals in Lake Kariba.

North Africa

Levels of Cu, Fe, V, Al and Co in wild tilapia were similar to findings in Egypt (Ibrahim et al. 2020), whereas Se, Cr, As, Cd, Hg, Pb and Ni were two times lower than in Egypt (Hamada et al. 2018; Ibrahim et al. 2020) (Table 6). Tributaries that drain into river Nile carry effluents from industries and agriculture, as well as sewage. This may account for higher levels of Cd, Hg and Pb in Egypt.

The levels of Pb, Hg and Cd in farmed tilapia from Egypt (Authman et al. 2012; Hamada et al. 2018) were over 100 times higher than in the current study probably due to industrial and agricultural effluents as well as sewage, which have been reported

Table 5. Estimation of cancer risk (CR) posed by a lifetime of consumption of wild and farmed tilapia from Kariba due to As, Pb, Cd, Cr and Ni.

	Site 1	Site 2	Site 3	Farm 1	Farm 2	CSF (USEPA 2018)	Acceptable risk range (USEPA 1995)
As	1.41×10^{-5}	2.71×10^{-5}	1.45×10^{-5}	2.79×10^{-5}	1.78×10^{-5}	1.5	1×10^{-4} to 1×10^{-6}
Pb	3.34×10^{-8}	3.39×10^{-8}	1.34×10^{-8}	2.93×10^{-8}	2.45×10^{-8}	0.0085	
Cd	1.97×10^{-6}	5.92×10^{-6}	1.26×10^{-6}	2.23×10^{-6}	9.6×10^{-7}	6.3	
Cr	2.04×10^{-5}	3.45×10^{-6}	4.59×10^{-6}	4.19×10^{-6}	8.27×10^{-6}	0.5	
Ni	1.32×10^{-5}	1.36×10^{-5}	6.31×10^{-6}	7.15×10^{-6}	7.74×10^{-6}	1.7	
Total CR	4.97×10^{-5}	5.01×10^{-5}	2.67×10^{-5}	4.15×10^{-5}	3.48×10^{-5}		

CSF, cancer slope factor.

Table 6. Comparison of mean concentration of heavy metals in muscle (mg/kg ww) of wild tilapia from other studies.

Country	Location	Li	Mg	Al	V	Cr	Fe	Co	Ni	Cu	Zn	As	Se	Mo	Ag	Cd	Hg	Pb	Reference
Zambia[1]	Lake	0.0063	249	4.81	0.0154	0.095	5.23	0.033	0.018	0.25	4.76	0.022	0.152	0.003	0.00111	0.001	0.021	0.009	This study
Zambia[2]	Lake	0.0062	263	4.28	0.0476	0.016	5.34	0.036	0.019	0.33	4.75	0.042	0.176	0.011	0.00155	0.002	0.008	0.009	This study
Zambia[3]	Lake	0.0093	231	0.78	0.0050	0.021	8.16	0.044	0.009	2.14	8.49	0.023	0.135	0.054	0.0004	0.001	0.009	0.004	This study
Zambia[a]	Lake					1.05		nd	0.174	0.42	4.45					0.0004		0.008	(Nakayama et al. 2010)
Zimbabwe[a]	Lake								2.18	1.45	10.29		1.01			0.671		1.51	(Berg et al. 1995)
Tanzania[a]	Lake									0.32	28.3							0.32	(Mapenzi et al. 2020)
Kenya	Lake						63.9			5.8	17.1					1.90		6.11	(Nyingi et al. 2016)
Egypt[a]	River			2.59	0.0064	0.326	2.03	0.004	0.481	0.11	0.85	0.367	0.159	0.034		<0.012		0.008	(Ibrahim et al. 2020)
Egypt	River															0.15	1.18	0.54	(Hamada et al. 2018)
Ethiopia[a]	Lake					0.07						0.055	0.046			0.044	0.051	0.063	(Dsikowitzky et al. 2012)
China	Lake					0.51			3.5	1.38	29.5	0.03				0.03		8.62	(Leung et al. 2014)
Malaysia[a]	Lake					1.208			0.636	0.5	9.54					0.006		0.03	(Taweel and Shuhaimi-Othman 2011)
Saudi Arabia[a]	River									0.37	4.72					0.083		0.35	(Mohammed 2009)
Saudi Arabia[a]	River					0.048				0.23						0.002	0.001	0.008	(Abdel-Baki et al. 2011)

Sites 1–3 from this study.

[a] Converted to wet weight from dry weight using the estimated percentage 78.8% as moisture content (Miao et al. 2010)

Nd, not detected.

Table 7. Comparison of mean concentration of heavy metals in muscle (mg/kg ww) of farmed tilapia from other studies.

Country	Location	Li	Mg	Al	V	Cr	Fe	Co	Ni	Cu	Zn	As	Se	Mo	Ag	Cd	Hg	Pb	Reference
Zambia[1]	Cages	0.0058	244	1.3	0.0158	0.019	9.38	0.066	0.0098	2.568	6.99	0.043	0.178	0.0581	0.00106	0.00082	0.0068	0.008	This study
Zambia[2]	Cages	0.0072	260	1.643	0.0048	0.038	5.78	0.043	0.0106	3.5	7.06	0.028	0.152	0.0498	0.00044	0.00035	0.0022	0.007	This study
Zimbabwe[a]	Pond								2.29	1.62	11.69		0.45			0.78		1.51	(Berg et al. 1995)
Zimbabwe[a]	Cage								2.52	1.79	12.53		1.06			0.73		1.51	(Berg et al. 1995)
Egypt	Pond			4.98					1.19							3.72	1.23	1.23	(Authman et al. 2012)
Egypt	Canal															0.08	0.94	0.29	(Hamada et al. 2018)
Uganda	Cage					0.56				0.57	0.58								(Birungi et al. 2007)
Malaysia[a]	Pond					1.316			0.593	0.562	6.57					0.0021		0.023	(Taweel and Shuhaimi-Othman 2011)
Taiwan	Pond					2.46		1.57	2.27	3.17	61.4	1.27	2.7			0.01		0.14	(Ling et al. 2013)

Farms 1 and 2 in this study.

[a] Converted to wet weight from dry weight using the estimated percentage 78.8% as moisture content (Miao et al. 2010).

to cause metal contamination in water in these areas (Authman et al. 2012; Hamada et al. 2018). Farmed Egyptian tilapia had also 5–100 times higher levels of Al and Ni than in the present study (Authman et al. 2012).

Asia and Middle East

Levels of Cu, Zn and As in wild tilapia were similar to those found in Saudi Arabia (Mohammed 2009; Abdel-Baki et al. 2011), China (Leung et al. 2014) and Malaysia (Taweel and Shuhaimi-Othman 2011) (Table 6). Cr was comparable to levels in Saudi Arabia (Abdel-Baki et al. 2011), but five to 16 times lower in China (Leung et al. 2014) and Malaysia (Abdulali Taweel and Shuhaimi-Othman 2011). Levels of Cd were similar to findings in Saudi Arabia (Abdel-Baki et al. 2011) but three to 40 times lower than in China (Leung et al. 2014), Malaysia (Abdulali Taweel and Shuhaimi-Othman 2011) and Saudi Arabia (Mohammed 2009). Levels of Hg in wild tilapia were 10 to 20 times higher than those found in Saudi Arabia (Abdel-Baki et al. 2011) but 4 to 8 times lower than the Hg levels detected in wild tilapia from Malaysia (Naji et al. 2014). Pb levels were similar to those in Saudi Arabia (Abdel-Baki et al. 2011), but substantially lower than in China (Leung et al. 2014), Malaysia (Abdulali Taweel and Shuhaimi-Othman 2011) and Saudi Arabia (Mohammed 2009). It was noted that levels of Pb in China were almost 1000 times higher (Leung et al. 2014). In the present study, Ni was more than 30 times lower than in China (Leung et al. 2014) and Malaysia (Abdulali Taweel and Shuhaimi-Othman 2011), while As was comparable to levels in China (Leung et al. 2014). The higher levels of Pb, Ni, Hg and Cd in wild tilapia from Asia are probably due to discharge of untreated industrial, agricultural and domestic effluents to aquatic environments.

The Cu levels in farmed fish from Lake Kariba were comparable to those in Taiwan (Ling et al. 2013), but five times higher than in Malaysia (Taweel et al. 2013) (Table 7). Zinc levels were similar to those in Malaysia (Taweel et al. 2013), but nine times lower than in Taiwan (Ling et al. 2013). Co and Se levels were also lower than those in Taiwan (Ling et al. 2013). The variation in the levels of essential metals in farmed fish is probably due to differences in the content of these chemicals in the local fish feed. Levels of non-essential metals, As, Cd, Pb, Cr and Ni were substantially lower than findings in China (Cheung et al. 2008; Kwok et al. 2014; Geng et al. 2015), Malaysia (Taweel and Shuhaimi-Othman 2011) and Taiwan (Ling et al. 2013). The levels of Hg detected in farmed tilapia from China are also substantially higher than the levels detected in the present study as well as other studies from sub-Saharan Africa. The higher levels of heavy metals in farmed fish from Asia may be due to the higher level of industrial and agricultural activities, which increase the risk of pollution of aquatic environments. Difference in feed composition may also affect levels in different areas.

Correlations

In the present study, essential metals (Fe, Cu, Zn, Co and Mo) showed positive correlation, which may be explained by a common source of trace elements from the fish feed (Yildiz 2008; Fallah et al. 2011). Non-essential metals (Al, Cd, Ag, Hg and Ni) also had positive correlation but showed negative correlation with essential metals (Zn, Cu and Mo). The wild fish had higher levels of non-essential metals probably due to a longer life span resulting in longer exposure, whereas they had lower essential metals probably because they were not exposed to commercial feed. This may explain the negative correlation between non-essential and essential metals. Since wild fish were larger than the farmed fish (Table 1) and had lower levels of essential metals (Zn, Cu and Mo), this accounted for the negative correlation observed between length and Zn, Cu and Mo.

Possible health risk assessment

Human health risk

The concentrations of metals in the muscle of wild and farmed tilapia from Lake Kariba (Table 2) were below the threshold values for adverse effects set by WHO/FAO (FAO/WHO 2002) and EU(EC EC 2006). We estimated the EWI (Table 3) and showed that the EWI was much lower than the PTWI. The THQs, which is the ratio of the exposure levels (EWI) of the individual potential harmful metal and the level at which no adverse effects are expected (PTWI), were below 1 for all metals.

Likewise, the HI (Table 4), which is the sum of THQs for all metals was also below 1, indicating that the fish can be consumed regularly without any significant health risk from both single metal exposure and cumulative effect of exposure to multiple metals. HBV_{Se} from all sites were positive, indicating protecting effects of selenium against mercury in the fish (Ralston et al. 2016; Yabanli and Tay 2021). Mercury has been shown to inhibit selenium-dependent enzymes (selenoenzymes) that protect against and reverse oxidative brain damage and perform other vital functions such as foetal brain development, growth, thyroid hormone metabolism and calcium regulation (Squadrone et al. 2015; Ralston et al. 2016, 2019). Selenium sequesters mercury, forming an insoluble selenium-mercury (HgSe) compound, that is excreted from the body (Ralston et al. 2016; Yabanli and Tay 2021). Thus, a Se:Hg molar >1, indicates excess Se and its protective effect against Hg (Squadrone et al. 2015; Yabanli and Tay 2021). The estimated TCR for As, Cd, Cr, Ni and Pb was less than $1 \times 10^{x}–4$ (Table 5), indicating that the risk of humans developing cancer during their lifetime, as a result of consuming wild and farmed tilapia from Lake Kariba was less than 1:10,000 (Varol et al. 2017).

Fish health risk

The mean concentration of Hg at site 1 (0.021 mg/kg) was slightly higher than the EQS_{Biota} (0.02 mg/kg) set by the EU (EC EC 2006). An EQS is the concentration of a particular pollutant or group of pollutants in water, sediment or biota that should not be exceeded in order to protect human health and the environment (Lyche et al. 2019). Environmental quality standards (EQS) are therefore guidelines set by the EU for monitoring pollution in water and biota (aquatic organisms). Chemical pollution of surface water poses a threat to the aquatic environment and may induce acute and chronic toxicity in aquatic organisms (Ec 2006). Relatively small concentrations of Hg (<160 mg/kg ww) can adversely affect the reproduction, development, growth, metabolism, neurobehavior, and immune responses of fish (Weis 2009; Rhea et al. 2013). Though the mean at site 1 was above the EQS, only one sample (0.16 mg/kg) was above the EQS. However, this finding is still a cause of concern, since it is above the EQS and may induce adverse effects in fish and other sensitive aquatic organisms.

Conclusions

The study presents the first comparison of heavy metals in wild and farmed tilapia on Lake Kariba in Zambia. This will serve as a baseline for future studies and developing of guidelines for the rapidly developing aquaculture sector in Zambia as well as sub-Saharan Africa. Heavy metal levels in all fish were below the ML set by WHO/EU. Essential metals (Cu, Zn, Fe, Mo and Co) were higher in farmed fish, while non-essential metals (Cd, Pb, Al, Ni and Hg) were higher in wild fish. Wild tilapia near the fish farms also had higher levels of essential metals compared to those distant from the farms suggesting that spill-over of feed and waste from the farms has the potential to contaminate the wild fish in the vicinity. It is therefore vital that proper guidelines are put in place to limit the effects on wild fish. Levels of Cd, Hg and Pb in Lake Kariba were also lower than those reported in North Africa and Asia. EWI of all metals were far below the PTWI. The THQ and HI were all below 1, showing no risk of non-carcinogenic effects from consumption of individual or combination of metals in fish, during a lifetime. HBV_{Se} were all positive, indicating protective effects of Se against Hg in fish. Total cancer risks were below 1×10^{-4}, showing less than 1:10,000 risk of carcinogenic effects from fish consumption during a lifetime. Levels of Hg in some wild fish were higher than the EQS set by the EU. Long-term exposure to Hg may therefore cause adverse effects in wild fish and other aquatic organisms. The findings of this study show that tilapia from the lake are safe for human consumption and there are no adverse effects on fish health.

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