Article title: Heavy metals in fish nearby electronic waste may threaten consumer's health. Examples from Accra, Ghana.

Sophie L. Steinhausen[1], Narkie Agyeman[1], Pablo Turrero[2], Alba Ardura[1]*[+], Eva Garcia-Vazquez[1+]

*Corresponding author Alba Ardura, arduraalba@uniovi.es

[+] cosenior authors

1: University of Oviedo, Department of Functional Biology, Faculty of Medicine, C/ Julian Claveria s/n 33006 Oviedo, Spain.

2: Spanish National Distance-Learning University (UNED), Gijón Campus, Avda. Jardin Botanico 1345, 33203 Gijón, Spain.

Sophie Leonie Steinhausen,
sophie.steinhausen@imbrsea.eu
Tel. +49 (0) 157 32271258
Second author: Narkie Agyeman, University of Oviedo, Asturias, Spain
narkieagyeman@gmail.com
Tel. +34 664 16 45 19
Tirdh author: Dr. Pablo Turrero, University of Oviedo, Asturias, Spain
pturrero@geol.uniovi.es
Senior authorship*: Dr. Alba Ardura Gutiérrez, University of Oviedo, Asturias, Spain
arduraalba@uniovi.es
Tel. +34-985103076
Senior authorship: Prof. Eva Garcia – Vazquez, University of Oviedo, Asturias, Spain
egv@uniovi.es
Tel. +34-985102726

Full postal address:
Departamento de Biología Funcional
Área de Genética
Universidad de Oviedo
C/ Julián Clavería s/n 33006 Oviedo-Asturias, Spain

Abstract

Electronic waste sites are rich in heavy metals contained in electronic and electric equipment waste and pose a risk of pollution if metals enter in the environment nearby. The Korle lagoon, located in the center of Accra, is receiving waste effluents from industries, households and the adjacent e-waste burning site Agbogbloshie which is the biggest in the country. Thus, the risk of heavy metal contamination of the water body and subsequent uptake in the aquatic food chain is particularly relevant. Small-scale fishing, not entering the commercial chain, occur in the lagoon despite its consideration of biologically dead. We assessed if the exposure to heavy metals through these fish consumption is posing higher health risks than fish sold on Ghanaian markets. Using ICP-MS technology, we quantified concentrations of As, Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn in fish caught from the Korle Lagoon (*Trachinotus ovatus, Mugil curema* and *Mugil cephalus*) and compared them to fish from the Tema Newtown fishing market (*Scomber colias*, *Pseudotolithus senegallus)*. Cobalt and lead concentrations, typical e-waste metals, were higher in fish from the Korle lagoon, even though they were of lower trophic level. Calculated risk indices revealed risk of elevated arsenic and mercury exposure, particularly through *T. ovatus* from the Korle lagoon, if consumed daily as it is common in the region. This study suggests the need of monitoring programs of Ghanaian catch, with a special focus in environmental risk areas like Korle lagoon to ensure human food safety.

Keywords: E-waste, Heavy metals**,** Fish contamination**,** Food safety**,** Korle lagoon, Ghana

Funding source: This research received funds the Spanish Ministry of Science and Innovation Grant GLOBALHAKE PID2019-108347RB-I00.

Competing interests' statement: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the reported work reported of this paper.

Acknowledgements

This research was carried out in the University of Oviedo, Asturias (Spain). Sample acquisition was carried out by Ebenezer Ekuban, Ministry of Fisheries and Aquaculture Development in Accra, Ghana in February 2020. Thanks to Annabella Meana from the Unit of Mass Spectrometry of the University of Oviedo for her help with heavy metal analysis, and to Gonzalo Machado-Schiaffino for helping with funding acquisition.

1. Introduction

Through agriculture practices, mining, or improper waste disposal, heavy metals are released in the environment and concentrate in soil, water and the atmosphere (Tchounwou, et al., 2012). The improper handling, burning and dumping of electronic waste and electrical equipment (hereafter, WEEE) causes heavy metal accumulation up to unsafe levels in affected areas (e.g., Wong et al., 2007; Ha et al., 2009; Adesokan et al., 2016), altering ecosystem diversity (e.g., Liu et al., 2010) and putting at risk the health of populations nearby (e.g., Grant & Oteng-Ababio, 2016; Zielinski et al., 2018). Waste batteries are considered hazardous for their high level of cobalt, copper and lead many folds the regulatory threshold for hazardous waste, with chromium, nickel and thallium exceeding that threshold at a lower level (Kang et al., 2013). Toxic chromium and lead have been reported in high amounts from Japanese WEEE, with differences between devices; Pb was more abundant in TVs while Cr was concentrated in digital cameras or CD players (Oguchi et al., 2013). Cr and Pb in toxic levels are also reported from WEEE sites in developing countries together with Cu and Cd, amongst others (Vaccari et al., 2019). The environmental risk associated to heavy metals derived from WEEE management is especially important in Africa, where appropriate infrastructure for proper disposal and recycling are often absent (Asante et al., 2012).

In the aquatic environment, heavy metals are incorporated by aquatic biota and enter the food chain (Bandowe et al., 2014; Kwaansa-Ansah et al., 2019). Some elements like (methyl-) mercury can bioaccumulate along the trophic chain, their content being higher in fish of higher trophic levels (Le Croizier et al., 2016). The concentration of heavy metals in fish poses health risks for consumers worldwide (Copat et al., 2012; Kwaansa-Ansah et al., 2019; Miri et al., 2017; Türkmen et al., 2009; Saha et al., 2016; Ullah et al., 2017; Wang et al., 2005; Zhao et al., 2016). Thus, health benefits of a diet rich in fish (Castro-González & Méndez-Armenta, 2008) are compromised when acceptable levels for heavy metal ingestion are exceeded (Bosch et al., 2016; Vandermeersch et al., 2015; Zhao et al., 2016). The consequences for human health are diverse, ranging from impaired kidney function, liver damage or impacts on reproduction or the nervous system (Saha et al., 2016). Moreover, some heavy metals are also human carcinogens (Ackah, 2019; Bradl et al., 2005; Kwaansa-Ansah et al., 2019; Miri et al., 2017).

The problem derived from consumption of fish contaminated with heavy metals can be accentuated in countries that depend on fish for protein supply, like in West Africa (Golden et al., 2016). In Ghana, seafood consumption per capita is above the world’s and also above the African average (FAO, 2016), fish having high economic and nutritional importance as valuable protein and omega-3-fatty acid source (Castro-González & Méndez-Armenta, 2008). Fish are consumed throughout the country, from rural to urbanized areas (Bandowe et al., 2014; Bank of Ghana, 2008). They are bought in fish markets and also through non-commercial chains, such as fish caught with cast nets or beach seining in lagoons and sea outlets that are consumed by the local community (Kudo et al., 2018). Here we analyze the case of Accra, where WEEE is considered a resource for the local population, but its exploitation encompasses severe environmental health risks (Grant & Oteng-Ababio, 2016). Although previous studies failed to detect excessive levels of some metals like mercury in fish caught from Ghanaian waters (Gbogbo et al., 2018), the levels of all WEEE-associated metals have rarely been analyzed in fish living in areas directly affected by WEEE in Ghana.

The Agbogbloshie scrap market, the main area of WEEE disposal in Ghana (Asante et al., 2012), is located in the center of Accra (Ackah, 2019; Kudo et al., 2018). WEEE handling and burning releases high amounts of chemicals and heavy metals in the surrounding area (Boadi & Kuitunen, 2002; Little & Akese, 2019; Onuoha, 2016), including the adjacent heavily polluted Korle lagoon that receives the runoffs of Agbogbloshie (Kyere et al., 2017, 2018; Kudo et al., 2018). Previous studies have shown the clear effects of the WEEE in heavy metal pollution, because the sediments analyzed from the Korle lagoon are more contaminated near the Agbogbloshie than towards the sea outlet (Clottey, 2018; Fosu-Mensah et al., 2017).

There is little information about heavy metals in biota from this water body that has been declared as biologically dead for years (Aglanu & Appiah, 2014; Ansa et al., 2017; Boadi & Kuitunen, 2002; Essumang et al., 2009). Actually, the biological death of Korle waters is not totally true as small-scale fisheries for local consumption occur in the lagoon, sea outlet and adjacent shoreline today. Around 40% of workers living in Agbogbloshie and surrounding Old Fadama slum consume local fish more than five times per week (Yang et al., 2020). Therefore, the risk of contamination through these fish is particularly relevant.

The departure hypothesis was that consumers of fish from the Korle lagoon are exposed to higher risk due to contamination of WEE-associated heavy metals than those eating marketed fish. Expectation was that, for similar life history and bioaccumulation capacity, Korle lagoon fish were enriched in metals typical of WEEE and batteries like Co, Cr, Cu, Ni and Pb than fish living in Ghanaian waters outside that lagoon. We analyzed muscle, the most commonly edible fish tissue (Bandowe et al., 2014), and evaluated health risks derived from the consumption of those fish for different population sectors, including children and pregnant women.

2. Materials and Methods

2.1 Study area

Korle lagoon (Figure 1) is located southwest of the central business district of Ghana’s capital Accra. The surrounding area and its inflowing waters are densely populated, with around 100 000 people living in the close by Old Fadama slum (Agyei-Mensah & Oteng-Ababio, 2012; Onuoha, 2016). In the upper part water flows in from the Odaw River and two drainage channels. Before flowing in the lagoon, the river tributary flows through the Accra and passes alongside the Agbogbloshie scrapyard, Old Fadama slum, an informal settlement and WEEE burning site located on the riverbanks (Karikari et al., 2006; Onuoha, 2016). To the south, the sandy shoreline of the lagoon is connected to the Gulf of Guinea through a tidally influenced outlet.

Tema Newtown fishing harbour (Figure 1) is a landing site for fisheries located in the Greater Accra Region, around 30 km far from the Korle lagoon. It receives landings from coastal waters of Ghana from local fishermen (Bandowe et al., 2014; Gbogbo et al., 2018).

Figure 1. Modified from Google Earth: Image © Maxar Technologies, Image © 2021 TerraMetrics. Data SIO, NOAA, U.S. Navy, NGA, GEBCO.

Top – Location where fish samples were taken: The Korle Lagoon (blue pin) and Tema Newtown fishing harbour (yellow pin).

Bottom – Zoom of Korle Lagoon location: Old Fadama slum and the WEEE burning site (Agbogbloshie).

2.2 Fish samples

Fish of different species consumed locally (n = 13) were sampled within Korle lagoon in February 2020. A local fisherman caught them with cast net close to the sea outlet (Figure 1). They were wrapped in plastic bags and kept in a cooler until freezing in the laboratory. The species were: *Trachinotus ovatus* (pompano), *Mugil curema* (white mullet), *Mugil cephalus* (flathead grey mullet).

Data of Ghanaian fish inhabiting outside Korle lagoon were obtained from two sources. Commercial samples of species caught from open waters and consumed locally (n = 10), sold fresh, were obtained from Tema Newtown landing site in the Greater-Accra region (Figure 1), in February 2020. These species were *Pseudotolithus senegallus* (Law croaker) and *Scomber colias* (Atlantic chub mackerel). A small piece (~25g) of muscle tissue was removed for each fish under the dorsal fin using plastic cutters, to avoid external metal contamination. All samples were maintained in sealable plastic bags, labeled and frozen at -20 ºC and handled only with plastic instruments to avoid cross contamination. The frozen samples were sent to the laboratory facilities at the University of Oviedo, Spain, maintaining the cold chain. On the other hand, in order to enrich this study, published data of other species from marine and brackish waters outside Korle lagoon sold in Ghanaian markets were taken from Bandowe et al. (2014) (n= 25): *Pomadasys perotaei* (parrot grunt), *Drepane Africana* (African sicklefish) and *Cynoglossus senegalensis* (Senegalese tonguesole). This comparison with more species and a larger sample size will allow to obtain more robust conclusions about the relative pollution status of Korle lagoon fish (more or less contaminated than fish from other Ghanaian waters).

In total eight species have been analyzed, five from this study:

- Koorle Lagoon: Pompano, white mullet and flathead grey mullet.
- Tema Newtown: Law croaker and Atlantic chub mackerel.

And three from previous studies: Parrot grunt, african sicklefish and senegalense tonguesole.

2.3 Species identification from DNA

Barcoding analysis was employed to ascertain the fish species identified from visual observation in this study. DNA was extracted from muscle tissues (Qiagen DNeasy® Blood & Tissue Kit) following the manufacturer´s instructions and the extraction was validated in an agarose gel. The cytochrome c oxidase subunit I mitochondrial gene (COI), was amplified with polymerase chain reaction (PCR) using forward and reverse COI-Fish primers (Ward et al., 2005). The PCR mix was 0.5M of primers, 0.25mM dNTPs, 2.5 mM $MgCl_2$, 1x Buffer GoTaq®Promega, 0.15µl of GoTaq® Polymerase (5u/µL) and 2µL of DNA, in a final volume of 20µL. PCRs were run in a thermal cycler from Applied Biosystems, model 2720, with an initial denaturation step at 95°C for 5 min then 35 cycles of denaturation at 95°C for 30 s, annealing at 57°C for 40 s, elongation at 72°C for 30 s, and final extension at 72°C for 15 min. Sequences were manually checked and processed with bioinformatics software (BioEdit), then BLASTed on NCBI (https://blast.ncbi.nlm.nih.gov/Blast.cgi) for species assignation to the best match hit.

2.4 Analysis of heavy metals

Trace metals in sediment of the Korle lagoon and the studied surrounding area were taken from Fosu-Mensah et al. (2017).

For each sample ~ 0.5g of muscle tissue was digested with nitric acid (HNO_3) to dissolve organic matrix and hydrogen peroxide (H_2O_2) using temperature-controlled microwave (Ethos One) heating in closed TFM vessels (Teflon tubes). As, Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn concentrations in the obtained solutions (~30 mL) were determined with Inductively Coupled Plasma Mass Spectrometry technology (ICP-MS, Agilent 7700x series spectrometer with autosampler, see details in Supplementary Table 1). Each sample was measured three times and results were obtained in µg kg^{-1} wet weight (w/w), as means of the three replicates with corresponding Relative Standard deviation below 20%. Limits of detection (LOD) were: As, 0.016; Cd, 0.003; Cr, 0.043; Co, 0.006; Cu, 0.020; Hg, 0.016; Ni, 0.053; Pb, 0.011; Zn, 0.143 µg kg^{-1}.

A certified reference sample (European Reference Material ERM® BB422 Fish muscle) was used to further validate the precision of the analytical method (Diop et al., 2016; Gbogbo et al., 2018). The measurements obtained for that sample were within the validation range of 15% related to the certified value. In mg kg^{-1} results were: 12.37 measured (12.7 certified) for As, 0.01 measured (0.01 certified) for Cd, 1.84 measured (1.67 certified) for Cu, and 18.18 measured (16 certified) for Zn. From the results of the certified sample, the measured value of Hg 0.77 deviated 28% from the certified value of 0.6, being outside of the 15% validation range (0.51-0.69). This indicates that Hg may be overestimated in our samples when they are >600 µg kg^{-1}. Although corrections are not done in other studies (Ackah, 2019; Liu et al., 2019), following a conservative approach we reduced Hg content in estimates of hazard indices by 28%.

2.5 Literature review

To give a complete background to our study, heavy metal concentrations (As, Cd, Cr, Co, Cu, Hg, Ni, Pb, Zn) in fish from Ghanaian inland and coastal waters were compiled from previous studies. Literature search was done in English using the terms “Ghana”, “fish”, “heavy metals” in Google Scholar, PubMed and WOS databases. No limits were set for publication year or type of papers. Quality criteria were peer-reviewed articles or published thesis dissertation reports – i.e., papers that passed an evaluation process. Concentrations of non-essential metals that are routinely analyzed in fish for consumption, either imported or from country’s landings (Cd, Hg, Pb), were compared to permissible levels. We used EC references (Directive EC No 1881/2006, https://eur-lex.europa.eu/legal-content/ES/TXT/HTML/?uri=CELEX:32006R1881&from=ES: 0.1 mg kg^{-1} of Cd, 0.5-1 mg kg^{-1} of total Hg and 0.3 mg kg^{-1} of Pb.

2.6 Health risk assessment

Calculations were done for different population sectors (children of 14.5 kg, adults of 64 kg and 70 kg body weight), following Wang et al. (2005) and Kumari et al. (2018). Exposure of pregnant women to mercury was also calculated after recommended weekly intake level (up to 3 servings of 114 g; BW= 64kg) set by USEPA (2019). Following previous studies (Copat et al., 2012; Miri et al., 2017), the effect of cooking on the contaminants was not considered.

Despite of methylmercury, which is the most abundant part of the total mercury (Gilmour and Henry, 1991: Carbonell at al., 2009) inorganic arsenic in fish muscles is generally a small percentage of the total (e.g., Storelli and Marcotrigiano, 2000; Copat et al., 2013); following the precautionary approach implemented in other studies (Ackah, 2019; Liu et al., 2019), we assumed that the metals are abundant in their specific harmful forms: arsenic as inorganic arsenic, mercury as organic mercury (methylmercury) and chromium as chromium (VI).

2.6.1 Estimated weekly intake.

The estimated weekly intake (EWI) of heavy metals (as mg kg^{-1} bodyweight) were calculated with the following equation:

$$EWI = \frac{C_m \times CR}{BW} \times 7$$

Where EWI = exposure to metal *m* through ingesting the contaminated fish (mg kg^{-1} BW per week), C_m = mean concentration of the metal in the fish tissue (mg kg^{-1} w/w), CR = mean daily consumption rate of fish (kg day^{-1}), BW= body weight of individual consumer, as 70 kg adult average, 64 kg for women in reproductive age and 14.5 kg for children (Gbogbo et al., 2018; Kwaansa-Ansah et al., 2019; Miri et al., 2017; USEPA, 2000; WHO, 2007).

Mean daily consumption was estimated considering dietary habits of fish consumption in Accra (Yang et al., 2020). Provisional Tolerable Weekly Intake values (PTWI) (in µg kg^{-1} BW) are set by the Joint FAO/WHO Expert Committee on Food Additives (2011). If a range for PTWI was indicated, the lowest value was used for precautionary approach (e.g., 350 µg kg^{-1} BW for copper). EWI values higher than PTWI can be considered not tolerable.

2.6.2 Target Hazard Quotient (THQ)

THQ values, following the US EPA Region III Risk-based concentration table (USEPA, 2000) were evaluated for every metal using the following equation:

$$THQ = \frac{EF \times ED \times CR \times C_m}{RfDo \times BW \times AT}$$

Where EF = exposure frequency of consumption (365 days $year^{-1}$), ED = exposure duration total (6 years for children and 27.6 for average worker age (Yang et al., 2020), CR = consumption rate = number of fish meals (224 g meal size; 85g for children (USEPA, 2000)) $person^{-1}$ weekly, (USDA, 1998; Zhao et al., 2016), C_m is the concentration of heavy metal *m* in the sample (mg kg^{-1} w/w), RfDo is the oral reference dose for non- carcinogenic effects (inorganic As = 0.003 mg kg^{-1} day-1, Cd = 0.001 mg kg^{-1} day^{-1} (USEPA, 2000), Co= 0.06 mg kg^{-1} day^{-1} (0.02 mg kg^{-1} day^{-1} in Mohd Kusin, Azani, Hasan, & Sulong, 2018), Cr(VI) = 0.005 mg kg^{-1} day^{-1} (Copat et al., 2012), Cu = 0.0371 (USEPA, 1995), Methyl-Hg = 0.001 mg kg^{-1} day^{-1} (USEPA, 2000), Ni = 0.02 mg kg^{-1} day^{-1} (USEPA, 1995), Zn = 0.3 mg kg^{-1} day^{-1} (USEPA, 1995), BW = body weight, AT = time of exposure to the chemical (365 days $year^{-1}$ x ED).

No RfDo value is reported for lead as no safe exposure limit to the metal could be established by USEPA (2007). However, many studies worked with RfDo value around 0.004 for this metal (Harmanescu et al., 2011; Liu et al., 2020; Mohd Kusin et al., 2018; Ullah et al., 2017), so we will use 0.0035.

THQ values greater than 1 imply that non-carcinogenic health effects could occur as the exposure concentration is higher than the reference dose RfDo (Gbogbo et al., 2018; Zhao et al., 2016). A combined THQ has been calculated, adding all the values obtained for all the analyzed metals, assuming that the risk will be greater for people exposed simultaneously to high concentrations of more than one trace metal.

2.6.3 Carcinogenic risks

A lifetime exposure to some contaminants might induce cancer (Bradl et al., 2005). Potential carcinogens considered are (inorganic) arsenic, chromium VI, and inorganic compounds of lead (Kwaansa-Ansah et al., 2019; Miri et al., 2017; USEPA, 2000, 2007). The daily consumption (CRlim) indicates the consumption rate of fish that does not pose a greater risk than the acceptable lifetime risk level ARL (Alipour & Pourkhabbaz, 2015; USEPA, 2000). Cancer slope factors are presented as mg kg^{-1} day^{-1} (Miri et al., 2017; Stern, 2010; USEPA, 1994). The formula is:

$$CRlim = \frac{ARL \times BW}{CSF \times C_M}$$

Where CRlim = allowable limit of fish consumption rate (kg day^{-1}); ARL = maximum acceptable lifetime risk level (10^{-5}); CSF = cancer slope factor Pb (0.0085 mg kg^{-1} day^{-1}), (inorganic) As (1.5 mg kg^{-1} day^{-1}), Cr (VI) (0.5 mg kg-1 day^{-1}).

2.7 Statistics

Results of heavy metals in fish from Korle lagoon and markets were visualized in a scatter plot constructed after non-metric multidimensional scaling (nMDS) using Euclidean distance. Comparison between the Korle lagoon and marketed fish means of WEEE-associated metal contents was done using Mann-Whitney test, after discarding normality in all metal datasets with Shapiro-Wilk tests. Statistics was done with the free software PAST (Hammer et al., 2001).

3. Results

3.1 Metal contents in the fish analyzed and implications for consumer's health.

Successful PCR amplification of the DNA barcode applied was achieved in the fish analyzed. COI sequences are publicly available on GenBank® (publication date 04-2021) with the accession numbers MT796634 - MT796649 corresponding to *Trachinotus ovatus*, *Mugil curema*, *Mugil cephalus* – from Korle Lagoon, and *Pseudotolithus senegallus* and *Scomber colias* – from Tema Newtown fishing market.

Regarding Korle lagoon samples (Table 1), *T. ovatus* and *Mugil curema* individuals were small, while *M. cephalus* individuals were a little bit bigger. The three species are commonly found in brackish waters and coastal lagoons, and the omnivorous mullets are of a lower trophic level than the carnivorous Pompano (Table 1). Tema Newtown market species, *P. senegallus* and *Scomber colias* (Table 1), are carnivorous fish distributed in marine Ghanaian waters (FAO 34 Eastern Central Atlantic). *P. senegallus* is recorded as vulnerable in the IUCN red list (2020). The other three marine species sampled from different Ghanaian markets (Bandowe et al., 2014) added for comparison with our data were: the benthopelagic *Pomadasys perotaei* and *Drepane Africana*, and the demersal *Cynoglossus senegalensis*. Their heavy metal contents can be found in the Supplementary Table 2.

Common name	**Species**	**n**	**Habitat**	**Range of tail length (cm)**	**Trophic level**	**Fishing site**	**Reference**
Flathead grey mullet	*Mugil cephalus*	6	Benthopelagic	21 - 25	2.1 ± 0.17	Korle Lagoon	This study
White mullet	*Mugil curema*	4	Benthopelagic	12 - 13	2.0 ± 0.0	Korle Lagoon	This study
Pompano	*Trachinotus ovatus*	3	Pelagic-neritic	9 - 14	3.7 ± 0.58	Korle Lagoon	This study
Atlantic Chub mackerel	*Scomber colias*	4	Pelagic	26 - 28	3.9 ± 0.63	Coastal waters	This study
Law croaker	*Pseudotolithus senegallus*	6	Demersal	21 - 45	3.9 ± 0.67	Coastal waters	This study
Parrot grunt	*Pomadasys perotaei*	n/a	Benthopelagic	n/a	3.3 ± 0.49	Coastal waters	Bandowe et al. (2014)
African sicklefish	*Drepane africana*	n/a	Benthopelagic	n/a	3.1 ± 0.41	Coastal waters	Bandowe et al. (2014)
Senegalese tonguesole	*Cynoglossus senegalensis*	n/a	Demersal	n/a	3.6 ± 0.58	Coastal waters	Bandowe et al. (2014)

Table 1. Fish species considered in this study. Fish size range in cm only for the samples from this study (n/a: not available). Trophic levels and habitat retrieved from www.fishbase.se.

The mean concentrations of heavy metals in fresh muscle of fish from the Korle lagoon and the market samples analyzed in our study are shown in Table 2. The highest mean content of As (1890 µg kg^{-1}) was found for *P. senegallus*, and Cd above detectable levels was found only in *S. colias* (mean 7.4 µg kg^{-1}), both from open waters. For all the other metals analyzed the highest mean corresponded to *T. ovatus* sampled from Korle lagoon: 14 µg kg^{-1} of Co, 62 µg kg^{-1} of Cr, 773.7 µg kg^{-1} of Cu, 156.4 µg kg^{-1} of Hg, 104 µg kg^{-1} of Ni, 111.5 µg kg^{-1} of Pb and 12371 µg kg^{-1} of Zn (Table 2). The results were generally consistent with the observed decrease of heavy metal pollution in Ghanaian waters regarding pre-2000 published data (see section 3.3), since none of the analyzed fish exhibited mean contents above tolerable limits for human consumption (from EU regulations 0.1, 1 and 0.3 mg kg^{-1} w/w tissue for Cd, Hg and Pb respectively; note that the results in Table 2 are given in μg kg^{-1}).

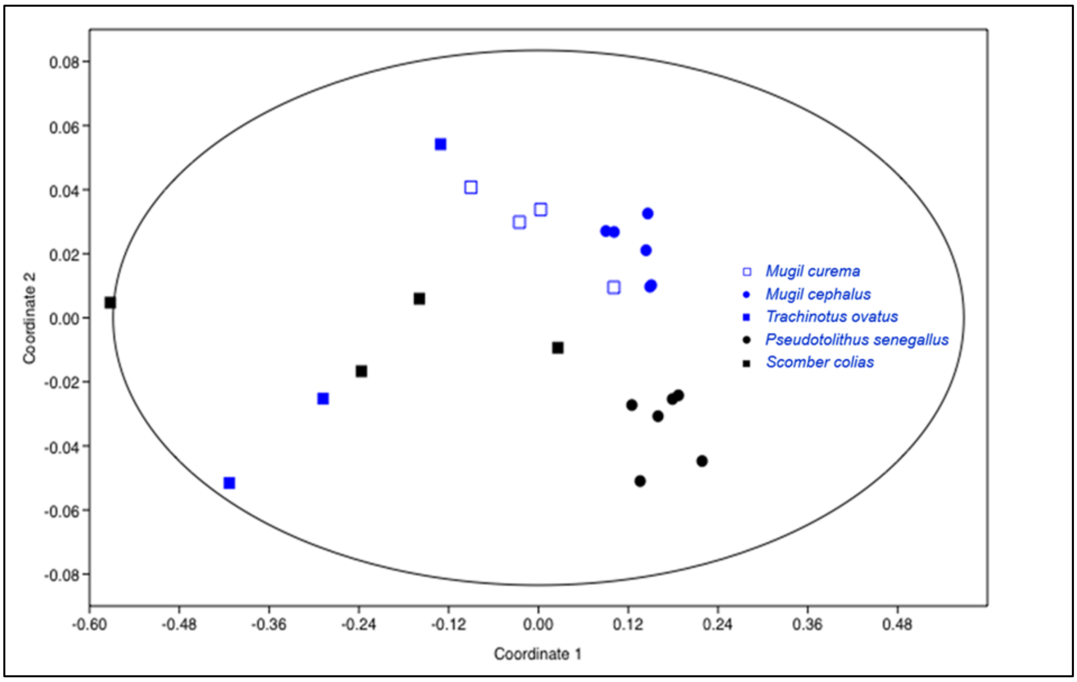
	Sampling point	**As**	**Cd**	**Co**	**Cr**	**Cu**	**Hg**	**Ni**	**Pb**	**Zn**
Mugil cephalus (n=6)	Korlee lagoon	705.41 (197.04)	0	7.95 (3.21)	18.96 (8.57)	263.39 (59.06)	17.87 (5.39)	32.74 (11.04)	30.68 (32.2)	3708.65 (608.59)
Mugil curema (n=4)	Korlee lagoon	536.93 (291.58)	0	12.74 (8.13)	20.60 (14.61)	467.67 (154.71)	32.76 (4.89)	54.55 (49.58)	18.79 (9.57)	6544.61 (1690.72)
Trachinotus ovatus (n=3)	Korlee lagoon	637.27 (168.57)	0	13.98 (9.48)	61.84 (59.82)	773.65 (249.81)	156.39 (138.28)	104.07 (134.98)	111.51 (100.86)	12370.88 (3146.5)
Pseudotolithus senegallus (n=6)	Tema Newtown market	1890.35 (229.42)	0	0.67 (0.74)	31.18 (27.68)	194.03 (43.93)	30.47 (13.91)	86.43 (41.39)	9.46 (5.91)	2913.47 (740.3)
Scomber colias (n=4)	Tema Newtown market	1244.18 (92.65)	7.39 (3.07)	7.73 (1.12)	19.55 (6.9)	606.53 (230.9)	84.39 (15.81)	78.77 (25.73)	10.56 (4.72)	11536.1 (5360.6)

Table 2. Mean metal concentrations (μg kg^{-1} w/w muscle tissue) in fish from the Tema Newtown fishing market (open waters) and the Korle Lagoon. Results are given as mean metal content (SD in parenthesis). 0 = <LOD, limit of detection.

The individuals analyzed in this study were principally grouped by sampling sites (Korle lagoon versus open waters) then by species, as visualized in the scatter plot constructed after nMDS (Figure 2A, above). The multidimensional analysis had very low stress of 0.008, Axis 1 $r^2 = 0.996$ and Axis 2 $r^2 = 0.004$. With most fish from Korle lagoon in the upper half – except two pompanos- and marketed fish in the lower half, it suggests differences in metal profile by sites.

Considering mean concentrations of eight metals and adding other three species sampled from different points in Ghana (Bandowe et al., 2014) (Figure 2B, below), the separation between habitats (Korle lagoon versus open waters) was confirmed. Despite different trophic levels and ways of life of the eight species (Table 1), the species sampled from Korle lagoon occupied with no exception the upper part of the scatter plot (Figure 2B), supporting our hypothesis of different contamination in Korle lagoon and in other Ghanaian waters.

A)



B)

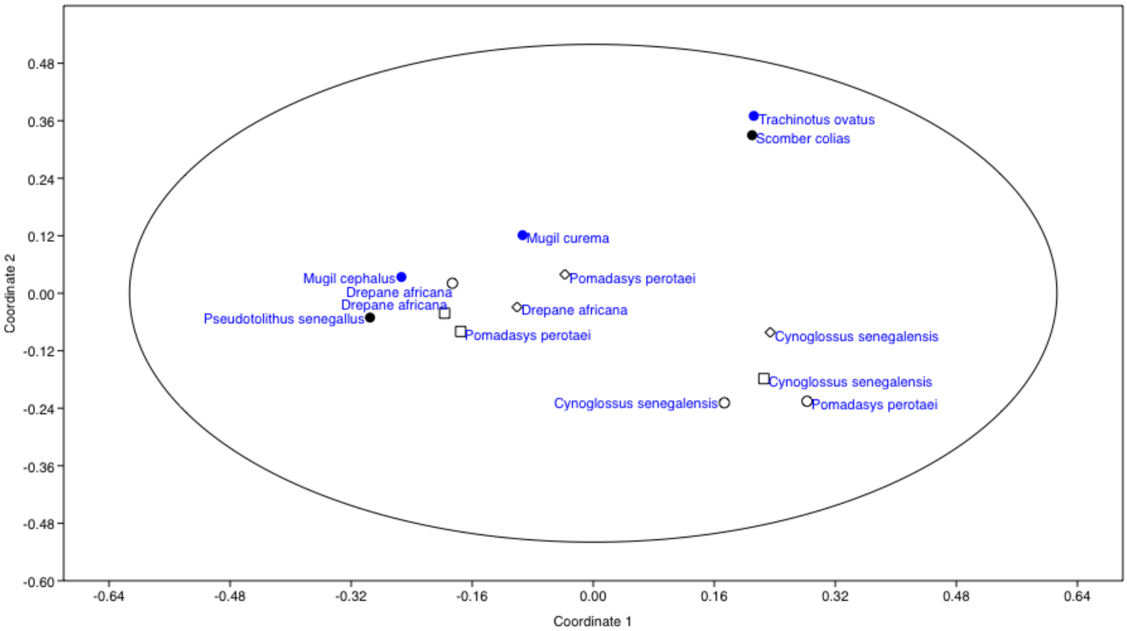


Figure 2. Scatter plot with 95% ellipse created from Euclidean distances. **2A)** Above, individual fish samples considering their content in As, Cd, Co, Cr, Cu, Hg, Ni, Pb and Zn. Blue: Korle lagoon, being dots *Mugil cephalus*; squares *Mugil curema*; filled squares *Trachinotus ovatus*. Black: Tema Newtown samples, being dots *Pseudotolithus senegallus*; filled squares, *Scomber colias*. **2B)** Below, fish species from Korle lagoon and other Ghanaian waters considering their mean content of As, Cd, Co, Cr, Cu, Ni, Pb and Zn, as: Korle lagoon, blue dots; Tema market (this study), black dots; Tema market, black squares; Takoradi market, black diamonds; Elmina market, black circles. Data of Tema, Takoradi and Elmina taken from Bandowe et al. (2014) were transformed from dry wet weight using 75% moisture.

Although mean contents of individual heavy metals were below current EU tolerable limits for consumption (Table 2), indeed the risk depends on consumption levels and the consumer's weight and age. Combined THQ values estimated for children of 14.5 kg and adults of 64 and 70 kg overcame the threshold of 1 considered safe (Table 3), indicating that the consumption of the analyzed Ghanaian fish encompasses health risks if eaten daily, as many people living near Korle lagoon do (Yan et al., 2020). Taking each metal independently, the estimated weekly intake of As through fish consumption exceeded permissible threshold levels for all the species sampled in this study, except *T. ovatus* and *M. curema* in adults of 70 kg (Table 3). The other metal over maximum tolerable weekly levels of ingestion was Hg, which exceeded the limit of 1.6 µg kg^{-1} in *T. ovatus* from Korle lagoon and *S. colias* from the market. This metal is especially toxic for the fetus (Bradl, 2005). The exposure of pregnant women to mercury through fish intake was below the threshold value of THQ (≥ 1) if consumed three times a week as recommended by USEPA (2019) (meal size ~ 114g) (Figure 3). However, it was close to 0.9 for Pompano from the Korle lagoon, suggesting that the consumption during pregnancy should not be recommended.

Metal	PTWI	*T. ovatus*	*M. curema*	*M. cephalus*	*S. colias*	*P. senegallus*
				Adults of 70 kg		
As	15	14.27/6.80	12.03/5.73	**15.80**/7.52	**27.87**/13.27	**42.34**/20.16
Cd	7	-/-	-/-	-/-	0.17/-	-/-
Co	a	0.31/-	0.29/-	0.18/-	0.17/-	0.02/-
Cr	23.3	0.92/0.01	0.46/0.01	0.42/0.01	0.44/0.01	0.70/0.02
Cu	350 - 3500	17.33/0.02	10.48/0.04	5.90/0.02	13.59/0.05	4.35/0.02
Hg	1.6 - 4	**3.50**/0.57	0.73/1.05	0.40/0.57	**1.89**/2.70	0.68/0.98
Ni	35	2.33/0.01	1.22/0.01	0.73/0.01	1.76/0.01	1.94/0.01
Pb	25	2.50/0.03	0.42/0.02	0.69/0.03	0.24/0.01	0.21/0.01
Zn	2100 – 7000	277.11/0.04	146.60/0.07	83.07/0.04	258.41/0.12	65.26/0.03
CTHQ		12.15	6.93	8.2	16.18	21.23
				Adults of 64 kg		
As	15	**15.61**/7.43	13.15/6.26	**17.28**/8.23	**30.48/14.52**	**46.31/22.05**
Cd	7	-/-	-/-	-/-	0.18/-	-/-
Co	a	0.34/-	0.31/-	0.19/-	0.19/-	0.02/-
Cr	23.3	1.01/0.03	0.50/0.01	0.46/0.01	0.48/0.01	0.76/0.02
Cu	350 - 3500	18.95/0.07	11.46/0.04	6.45/0.02	14.86/0.06	4.75/0.02
Hg	1.6 - 4	**3.83**/5.47	0.80/1.15	0.44/0.63	**2.07**/2.95	0.75/1.07
Ni	35	2.55/0.02	1.34/0.01	0.80/0.01	1.93/0.01	2.12/0.02

Pb	25	2.73/0.11	0.46/0.02	0.75/0.03	0.26/0.01	0.23/0.01
Zn	2100 – 7000	303.09/0.14	160.34/0.08	90.86/0.04	282.63/0.13	71.38/0.03
CTHQ		13.29	7.57	8.97	17.70	23.22
Children of 14.5 kg						
As	15	**26.15**/12.45	**22.03**/10.49	**28.95**/13.78	**51.05**/24.31	**77.57**/36.94
Cd	7	-/-	-/-	-/-	0.30/-	-/-
Co	-[a]	0.57/-	0.52/-	0.33/-	0.32/-	0.03/-
Cr	23.3	1.69/0.05	0.85/0.02	0.78/0.02	0.80/0.02	1.28/0.04
Cu	350 - 3500	31.75/0.12	19.19/0.07	10.81/0.04	24.89/0.10	7.96/0.03
Hg	1.6 - 4	**6.42**/9.17	1.34/1.92	0.73/1.05	**3.46**/4.95	1.25/1.79
Ni	35	4.27/0.03	2.24/0.02	1.34/0.01	3.23/0.02	3.55/0.03
Pb	25	4.58/0.19	0.77/0.03	1.26/0.05	0.43/0.02	0.39/0.02
Zn	2100 – 7000	507.63/0.24	268.55/0.13	152.18/0.07	473.38/0.23	119.55/0.06
CTHQ		2.25	12.69	15.03	29.64	38.89

Table 3. PTWI: Values over Provisional Weekly Tolerable Intake. CTHQ: Combined Total Hazard Quotient (THQ) values based on daily consumption of the analyzed fish for different population sectors. EWI/THQ: Estimated Weekly Intake (EWI) and Total Hazard Quotient (THQ) of the analyzed metals (in µg kg^{-1} body weight per week) for different population sectors. Population sectors: adults of 64 or 70 kg and a daily fish intake of 224g, and for children with 14.5 kg and daily intake of 85g fish, for the five species analyzed in this study. Values over Provisional Weekly Tolerable Intake (PWTI) listed in the second column are marked in bold. All values are based on mean concentrations in wet weight. a No PTWI value proposed for cobalt. – not detection.

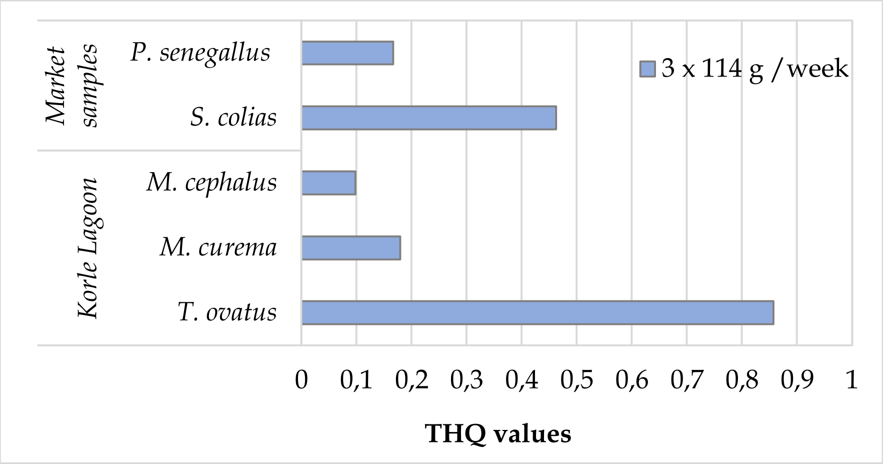


Figure 3. Calculated THQ values for mercury exposure based on recommended intake levels by USEPA (2019) of three weekly fish meals (meal size 114g) for different species. Based on reduced mercury concentrations (see 3.2.1.).

Regarding carcinogenic risks through exposure to (inorganic) As, Cr (VI) or Pb, CRlim estimates (that take into account the cancer slope factor, CSF, for each element) indicated a higher risk – thus less safe allowable fish consumption per day- due to As, then Cr and finally Pb (Table 4). Korle lagoon fish were more problematic than the rest only for Pb (Table 4). From these estimates, daily consumption of standard meal sizes of any of those species would be totally discouraged; eating as little as about 2 grams a day would encompass too much As intake (if all As was inorganic, something that has not been analyzed here).

Origin	Species	As (inorganic)	Cr (VI)	Pb
Korle lagoon	*T. ovatus*	0.001	0.034	0.739
	M. curema	0.002	0.068	43.828
	M. cephalus	0.001	0.075	2.657
Open waters	*S. colias*	0.0004	0.072	77.986
	P. senegallus	0.0002	0.045	87.054

Table 4. CRlim: allowable fish consumption rate (kg day^{-1}).

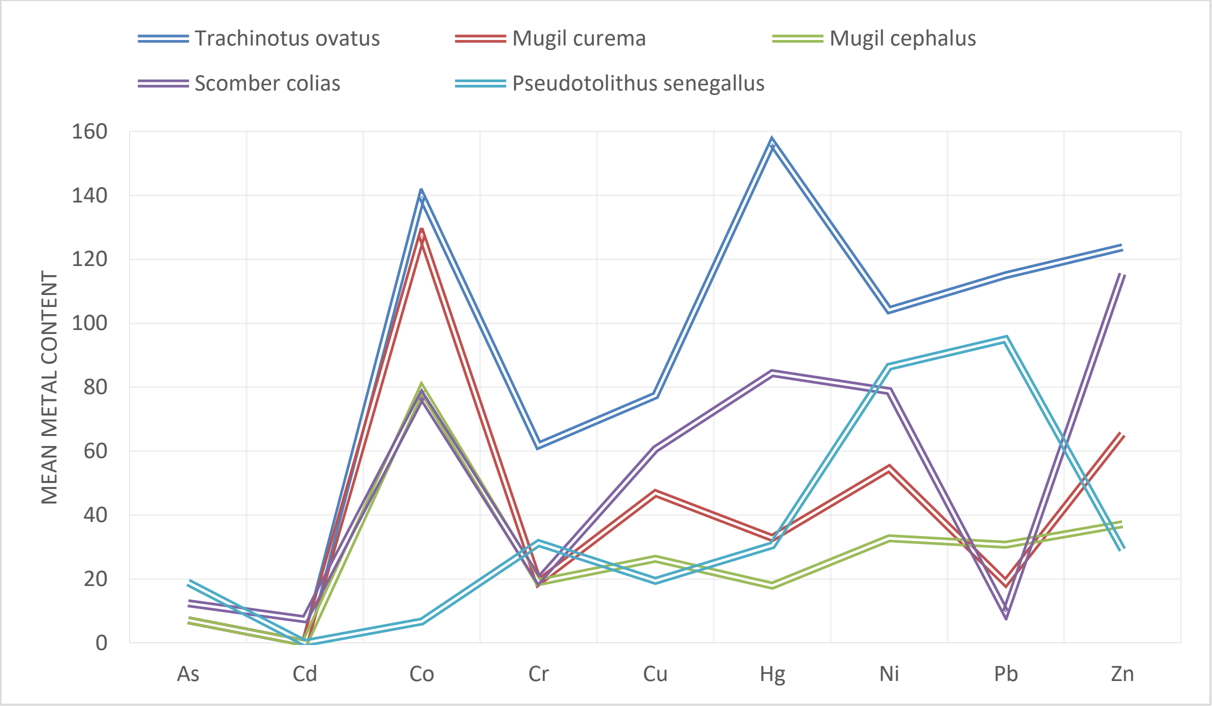
3.3. Ecological considerations

In this section we will relate fish metal contents with those reported for the environment in Korle lagoon. Metal fingerprints obtained from the species analyzed in this study and from sediments in previous studies (Fosu-Mensah et al., 2017) are presented in Figure 4. Although the fish species analyzed in our study were very different, metal fingerprints of Korle lagoon fish were relatively similar to each other with a pronounced peak in cobalt content (Figure 4A). These profiles were quite different of those from fish sold in the market that were caught from open waters. Being different to each other, profiles of fish from open waters had a lower content in Co and Pb than Korle lagoon species, even though both *Scomber colias* and *Pseudotolithus senegallus* are of higher trophic levels than the species sampled from Korle lagoon. The difference between Korle's and market's fish was significantly different for these two metals: Co mean of 10.82 µg kg^{-1} (SD 6.5) versus 3.49 µg kg^{-1} (SD 3.7) respectively (Mann-Whitney U =18, z = 2.887 with p = .004), and Pb mean of 45.68 µg kg^{-1} (SD 59.5) in Korle's versus 9.90 µg kg^{-1} (SD 5.2) in marketed fish (Mann-Whitney U = 23, z = 2.57 with p = 0.01).

Mean contents of the other WEEE-associated metals (Cu, Cr and Ni) were lower in omnivorous than in carnivorous species, but *T. ovatus* from Korle lagoon was by far the most polluted of the three carnivorous species for these three metals (Figure 4A). Significant differences between sites (open waters versus Korle fish) were not found for these three metals (data not shown). Other metals varied between species according to their respective trophic levels and irrespective of the capture waters. Arsenic was higher in fish of high trophic level caught outside Korle lagoon: mean 1890.3 μg kg^{-1} (SD 229.4) for *P. senegallus* and 1244.2 μg kg^{-1} (SD 92.6) for *S. colias*, while it was 637.3 (SD 168.5) for *T. ovatus*, 705.4 (SD 211.8) for *M. cephalus* and 536.9 (SD 291.6) for *M. curema* (Table 2, Table 3). Cd was detected only in *S. colias*, and Hg was lower in the two mullets than in the rest of species (Figure 4A).

Fosu-Mensah et al. (2017) analyzed six different samples of sediments about 300 m apart: S1 close to e-waste site of Agbogbloshie, S2 in a garden area, S3 in a reclaimed waste dump site, S4 in a recreational site, S5 in the estuary area of the Korle Lagoon and S6 a control taken 700 m away (deeply described in Fosu-Mensah et al., 2017). These authors did not measure cobalt in their study. For the rest of the elements, higher amount of all of them were detected in the sediments near the e-waste site of Agbogbloshie in comparison with estuary sediments, with prominent peaks for Cd, Cu, Ni and Pb (Figure 4B), (data taken from Fosu-Mensah et al., 2017). Comparing sediments with fish, we can see that peaks in Cu and Ni occurred in the two mullets (*Mugil* sp.), that are benthopelagic species with an expectedly greater accumulation of metals present in the sediment (Table 1). *Trachinotus ovatus*, of higher trophic level and pelagic-neritic, exhibited a higher content of all metals than the two omnivorous mullets and a peak in Hg unlike the mullets, with a similar pattern like sediments (Figures 4A & 4B). In general, benthopelagic species exhibited heavy metal profiles more similar to that of sediments in the e-waste site than pelagic species did.

A)



B)

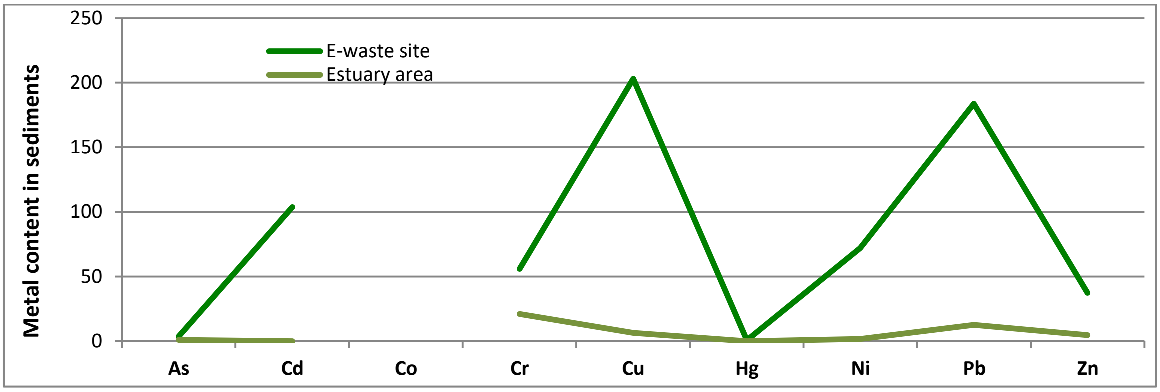


Figure 4. Heavy metal fingerprints of: **A)** fish caught from Korle lagoon and from open waters–marketed fish; **B)** sediments in different zones of Korle lagoon (taken from Fosu-Mensah et al., 2017). Data are presented as mean mg kg^{-1}. For visual presentation, in fish As and Zn concentrations are multiplied by 10^{-2} and Cu concentration by 10^{-1}.

Finally, research about heavy metal pollution in fish caught from Ghana waters seems to be relatively recent. In the literature search done in this study we found data of heavy metals in fish for 85 samples of Ghanaian fish (comprising at least 920 individuals) that were published in 12 peer-reviewed articles and five thesis reports (Supplementary Table 2). The mean number of metals analyzed in those publications was 3.5 (standard deviation 2.1). Papers containing the majority of samples and more metals in average were published in the last decade (Supplementary Figure 1). Before 2000 only two peer-reviewed studies describing heavy metals in Ghanaian fish were found in this search: one thesis (Ndanu, 1998) and one article (Amonoo-Neizer & Amekor, 1993). In the decade of 2000, two articles (Voegborlo et al., 2007; Tay et al., 2008) provided information about seven different species. The number of publications and samples analyzed increased after 2010, being especially abundant after 2015: 36 samples analyzed in six articles (half of the total number of publications), from different zones of Ghana, between 2016 and 2020. This evolution of publications shows the interest of this topic.

Focusing on the three metals with limits for safe consumption Cd, Hg and Pb, the number of samples reporting these metals in muscle (the commonly edible tissue) in different species and Ghanaian waters were scarce (Supplementary Table 2). Although these data including different species with different eating habits are not appropriate to establish an improvement of environmental conditions, it seemed that fish pollution evolved positively in Ghana, decreasing over time (Table 5). Based on this literature review, all the data about these metals published before 2000 belong to the study of Ndanu (1998), corresponding to 20 samples of eight different species where near all the fish analyzed (90-100%) were over the tolerable limits for consumption from EU regulations: 0.1, 1 and 0.3 mg kg^{-1} w/w tissue for Cd, Hg and Pb respectively (Table 5). In the next decade (2000-2010) fewer samples were reported for these metals, apparently less contaminated with Cd and Hg while Pb pollution persisted. Between 2011 and 2020 there was a reduction in the proportion of samples with mean content of Pb above tolerable limits for human consumption (down to 25%) (Table 5), while 50% for samples contained Hg over tolerable limits.

		Cd	**Hg**	**Pb**
Before 2000	**Range**	0.07-0.45	5-31	0.6-5.7
	N	20	20	20
	% over limit	90%	100%	100%
2000-2010	**Range**	nd-0.035	0.11 (one sample)	nd-1.09
	N	6	1	6
	% over limit	17%	0%	83.3%
2011-2020	**Range**	nd-2.17*	nd-3.71	nd-2.7
	N	30	14	28
	% over limit	26.7%	50%	25%

Table 5. Proportion of Ghanaian fish samples with mean content of Cd, Hg and Pb above tolerable limits for consumption (EU normative 1881/2006: 0.1, 1 and 0.3 mg kg^{-1} w/w tissue for Cd, Hg and Pb respectively), from the literature review. *: value based on a master thesis study (Aboagye, 2012) not a published article. nd: not detected.

Regarding typical WEEE metals, Co was analyzed in two papers that reported 16% of the 85 samples; Cr in three papers (13% of samples); Cu in nine papers (33% of samples); Ni in two papers (12% of samples); and Pb in 12 papers (63% of samples) (Supplementary Table 2). Fish from nearby Korle lagoon were analyzed only in one paper, a thesis published in 2012: specifically, Cd, Cu, Pb and Zn were quantified in 32 Boe drum (*Pteroscion peli)* and 32 greater amberjacks (*Seriola dumerili)* sampled from the estuary between 2011 and 2012 (Aboagye, 2012). The mean values reported for Cd and Pb in the two species were over tolerable limits for consumption (Supplementary Table 2).

4. Discussion

This study, although based on relatively limited sample sizes (similar to those of Bandowe et al., 2014), revealed some important novelties. Our results indeed confirmed the lagoon is not (or no longer) a biologically dead water body as reported from other studies

(Aglanu & Appiah, 2014; Ansa et al., 2017; Boadi & Kuitunen, 2002; Essumang et al., 2009). Results confirmed the departure hypothesis of WEEE metal content in fish living near e-waste sites and highlights the risks that the ingestion of those fish may pose to inhabitants nearby. To our knowledge this is the first time that edible fish caught inside Korle lagoon, the closest water body to Agbogbloshie, are analyzed. Aboagye (2012) analyzed Cd, Cu, Pb and Zn in fish caught from the estuary, not inside the lagoon, and their results were similar to ours regarding high Pb concentration.

4.1. Health risk derived from consumption of polluted fish

Our results revealed health risks to humans through the consumption of fish from the Korle Lagoon and Ghanaian markets, particularly if fish are consumed daily as it is common in coastal regions of the Gulf of Guinea (Golden et al. 2016). With a lower consumption rate, risk would decrease. However, with at least weekly consumption as more than 90% of people from Agbogbloshie do (Yan et al., 2020), it would never drop below the THQ of 1 threshold, especially for children. Of the three fish sampled inside Korle lagoon, pompano and flathead grey mullet would pose a significant health risk to most of the population if consumed in a regular way. Only white mullets *M. curema*, the lowest in the food chain of all the analyzed species, would be more or less safe for adults. Pregnant women should not eat pompano from Korle lagoon.

The main risk of the five species analyzed would be derived from As, which is a metal not specifically associated with the Korle lagoon in our study. It was not analyzed by Aboagye (2012) thus we cannot compare this metal with previous data in fish of this zone. In soils around Agbogbloshie its concentration is not relevant, being far below carcinogenic levels (Ackah, 2019). Arsenic compounds are used widely (Tchounwou et al., 2012), and have been also mentioned in e-waste products (Asante et al., 2012), although it is not a typical e-waste metal but rather associated to industrial waste and refining of metals and is expected in countries rich in mining as Ghana. Bandowe et al. (2014) also found high As concentrations in Senegalese tonguesole in three markets, and in parrot grunt in Elmina landing beach. This metal is very abundant in the marine environment, especially in its inorganic form, in sediments and in anoxic environments (WHO, 2018). Although the Korle Lagoon experiences anoxic periods (Aglanu & Appiah, 2014; Clottey, 2018), Korle lagoon fish were not more affected by As than fish sampled from markets. Actually, since arsenic biomagnifies along the trophic chain (Hepp et al., 2017), high As concentration in low trophic-level fish as Mugilidae, the majority of Korle fish, was not expected.

Overall, the consumption of fish from the Korle Lagoon seems to be just one more source of pollution to local population that are already exposed to high levels of contaminants, such as inorganic As through improper recycling activities without improper equipment (Yang et al., 2020). Industries (e.g. textile factories), agriculture pesticide residues (Bruce-Vanderpuije et al., 2019; Essumang et al., , 2009) and uncontrolled sewage and wastewater discharges with fecal contamination (Karikari et al., 2006) are contributing to a mixture of contaminants in the area. For these reasons, cumulative hazard based on exposure to multiple contaminants and their potential additive effects or interactions should be considered in the future.

Other studies of Ghanaian fish did not detect any significant health risk derived from their consumption, that was considered generally safe regarding heavy metals (Gbogbo et al., 2018; Kwaansa-Ansah et al., 2019). Here our results from marine species were not so optimistic, but do not imply recommendations against fish consumption; instead point at the convenience of setting consumption rate advice by species. In general, small pelagic fish such as Chub mackerel, commonly fished in Ghana and with a lower price range, are more accessible to the Ghanaian population than others, such as croaker (Ashitey, 2019); our results of health risk indices would be good news since they suggest that eating frequently chub mackerel is safer than eating much croaker. The inhabitants of the Gulf of Guinea region are particularly reliant on fish, thus most vulnerable to malnutrition if fish resources are depleted or not accessible (Golden et al., 2016). Regarding these challenges, we would propose further intake recommendations species by species – especially for pregnant women - and monitoring heavy metals in fish catches aligned with official health risk indices, such as the Food and Agriculture Organization (FAO), World Health Organization (WHO) to ensure safe nutritional supply of consumers.

4.2. WEEE metal signatures and species features

We found high cobalt concentrations in Korle lagoon - at least in comparison with other Ghanaian fish, confirming our hypothesis of WEEE signature metals affecting Korle lagoon fish. This result is unusual in Ghana. In the few studies that have analyzed cobalt from Ghanaian fish muscle, Gbogbo et al. (2018) did not find detectable cobalt concentration in other Ghanaian fish; similarly, Bandowe et al. (2014) did not find detectable levels of cobalt in muscle of bottom dwelling fish that are particularly susceptible to bioaccumulation of pollutants. Only Kwaansa-Ansah et al. (2019) found similar levels of those of our study in Asafo, an area intensely affected by agricultural pollution (pesticides, fertilizers, etc.).

Studies in mining areas show high levels of cobalt in human fluids (e.g., Banza et al., 2009, 2018), and consumption of polluted lake fish is an important source of this and other metals in these zones (Cheyns et al., 2014). Our data of cobalt in edible fish would expand the source to WEEE sites (not only mines), and the vector would be diet, probably added to acquiring metals by respiration in dust –from burning- and from drinking water if taken from the lagoon.

Results found for Pb, another strong WEEE signature metal (Khag et al., 2013; Oguchi et al., 2013; Vaccari et al., 2019), also supported the impact of e-waste in the Korle lagoon, being significantly higher in this lagoon's fish than in other samples. Consequently, Pb pollution posed a higher risk to consumers of Korle lagoon fish, than to those consuming market's fish (Table 4). Pb pollution in Ghanaian fish was problematic in the past (see Table 5) and seemed to have different sources. For example, Anim-Gyampo et al. (2013) warned of high Pb levels in Navrongo freshwater fish polluted with agriculture residues, although Pb content in agriculture - polluted fish from Asafo markets (Kwaansa-Ansah et al., 2019) was lower than that found in Korle lagoon fish in our results.

To be able to relate the results with the exposure to WEEE metals in Korle lagoon, the differences found between Korle lagoon and market fish in our study must be explained considering species-specific traits. As expected from metal bioaccumulation along the food chain, carnivorous species contained generally more metal than the omnivorous ones, with an important exception: the omnivorous mullets caught from Korle lagoon contained more Co and Pb, two important WEEE metals, than carnivorous species caught outside Korle lagoon. The difference between all Korle's and all marketed fish for mean content of these metals was statistically significant, despite lower trophic level of species from Korle lagoon. This points directly at an effect of exposure to e-waste waters. The species considered are highly euryhaline and, although caught near the mouth where their metals are relatively diluted, these individuals surely move up the lagoon and visit e-waste waters.

Another important specific feature is the environment where fish live. Given the pollution conditions reported for the lagoon (Fosu-Mensah et al., 2017), we could expect to detect the effects in species that are in contact with the sediments, with a greater accumulation of metals compared to pelagic species or species caught in the open sea. Our results supported this expectation, since benthopelagic species showed a greater accumulation of metals present in the sediment, according to Aboagye (2012) who found similar metal concentrations in fish caught at the estuary.

Even if the main focus of this study is not an environmental point of view, because we are comparing different species from different habitats and with different eating habits, it is important to highlight that the results reported from fish muscle in samples of different studies show different degrees of pollution that might suggest a decrease in the last decade, perhaps reflecting big efforts for the improvement of aquatic environmental health in the country. However, this could also be related to multiple factors such as origin, dietary habits and the diversity of considered species. More studies comparing metal concentrations in the same species from other less contaminated environments are necessary, in order to minimize those biases.

As a final remark, from the conservation side Korle lagoon should be recovered as any other wetland, also for the use and enjoyment of the local population. If ongoing restoration efforts, mainly through dredging (Abraham et al., 2006), succeed and greater biodiversity is to be returned to Korle Lagoon, it must be considered that some pollutants might persist in the sediment for a long time. Published data (Fosu-Mensah et al., 2017) showed a much higher level of several metals in Korle lagoon sediments than those found in fish in our study. Since contaminants accumulate in sediments, restoration efforts through dredging must consider resuspension of contaminated sediment, particularly in areas close to e-waste burning sites.

5. Conclusions

Heavy metals considered WEEE signature like Co and Pb were more concentrated in fish from the Korle Lagoon than in fish samples from Accra markets, evidencing an effect of the e-waste Agbogbloshie site. As, Hg, Cr and Pb contributed significantly to increase health risk hazards estimated and are of potential health concern. Following the precautionary approach – assuming that metals are abundant in their toxic form – key findings are that: i) the daily consumption of some fish, especially pompano from the Korle lagoon, can be potentially harmful for consumers due to high levels of arsenic, lead and mercury; ii) within this study, mullets pose the lowest risks; iii) health implications depend also upon the consumed species, consumption frequency and exposure duration; iv) it is of great importance to find the balance between nutritional value and risks through fish consumption from Ghanaian fisheries. We would recommend the frequent monitoring of fish catches in Ghana to ensure nutritional supply for consumers and prevent health hazards through heavy metals. Future work should focus on quantification of heavy metal in Korle lagoon fish, especially those of higher trophic level and if biota return to the lagoon after restoration measures. Furthermore, the health risk assessment should be complemented with a better understanding of the contamination state of the area and various sources of contaminant exposure to local population related to ongoing restoration efforts. This study will hopefully support the implementation of regulatory measures for fishery resources to protect consumer health (Bosch et al., 2016).

References

Aboagye, R. H. (2012). Heavy Metal Concentration in the Sediments and Flesh of Boe Drum (Pteroscion peli) and Greater Amberjack (*Seriola dumerlili*) from the Korle Lagoon Estuary, Accra, Ghana. Thesis. Kwame Nkrumah University of Science and Technology.

Abraham, E. M., Drechsel, P., & Cofie, O. (2006). The challenge of urban flood control: The case of Accra's Korle Lagoon. *5th* Worldwide Workshop for Young Environmental Scientist in France, 1–8. International Water Management Institute. Retrieved from http://publications.iwmi.org/pdf/H038739.pdf

Ackah, M. (2019). Chemosphere Soil elemental concentrations, geoaccumulation index, non-carcinogenic and carcinogenic risks in functional areas of an informal e-waste recycling area in Accra, Ghana. *Chemosphere, 235,* 908–917. https://doi.org/10.1016/j.chemosphere.2019.07.014

Adesokan, H. K., Alabi, P. I., & Ogundipe, M. A. (2016). Prevalence and predictors of risk factors for Brucellosis transmission by meat handlers and traditional healers' risk practices in Ibadan, Nigeria. J*ournal of preventive medicine and hygiene, 57(3),* 164 - 171.

Aglanu, L. M., & Appiah, D. (2014). The Korle Lagoon in Distress: The Stress of Urban Solid Waste on Water Bodies in Accra. *International Journal of Innovation and Applied Studies*, *7*(2), 717–728

Agyei-Mensah, S., & Oteng-Ababio, M. (2012). Perceptions of health and environmental impacts of e-waste management in Ghana. *International Journal of Environmental Health Research*, *22*(6), 500–517. https://doi.org/10.1080/09603123.2012.667795

Akoto, O., Bismark, E. F., Darko, G., & Adei, E. (2014). Concentrations and health risk assessments of heavy metals in fish from the Fosu Lagoon. *International Journal of Environmental Research 8* (2), 403-410.

Alipour, H., & Pourkhabbaz, A. (2015). Estimation of Potential Health Risks for Some Metallic Elements by Consumption of Fish. *Water Quality, Exposure and Health*, 179–185. https://doi.org/10.1007/s12403-014-0137

Amonoo-Neizer, E. H., & Amekor, E. M. K. (1993). Determination of Total Arsenic in Environmental Samples from Kumasi and Obuasi, Ghana. *Environmental Health Perspectives, 1(101),* 46–

Anim-Gyampo M, Kumi M, Zango MS. (2013). Heavy metals concentrations in some selected fish species in Tono Irrigation Reservoir in Navrongo, Ghana. *Journal of Environment and Earth Science, 3*(1), 109–119.

Ansa, E. D. O., Sakyi, R. L., Asmah, M. H., Acheampong, M. A., & Lamptey, E. (2017). An assessment of Environmental Conditions and the Benthic Fauna of the Odaw River Basin. *West African Journal of Applied Ecology, 25*(2), 17–29.

Asante, K. A., Agusa, T., Biney, C. A., Agyekum, W. A., Bello, M., Otsuka, M., Takaaki, I., Takahashi,S, Tanabe, S. (2012). Multi-trace element levels and arsenic speciation in urine of e-waste recycling workers from Agbogbloshie, Accra in Ghana. *Science of the Total Environment, 424,* 63–73. https://doi.org/10.1016/j.scitotenv.2012.02.072

Ashitey, E. (2019). *G*hana Fish and Seafood Report. USDA Foreign Agricultural Service. *GAIN Report Global Agricultural Inforamtion Network.*

Awuah, G. K. (2016). Assessment of Heavy Metal Concentrations in Sediment, Water and Fish from Ankobra and Tano River Basins in Ghana. University of Ghana.

Bandowe, B. A. M., Bigalke, M., Boamah, L., Nyarko, E., Saalia, F. K., & Wilcke, W. (2014). Polycyclic aromatic compounds (PAHs and oxygenated PAHs) and trace metals in fish species from Ghana (West Africa): Bioaccumulation and health risk assessment. *Environment International*, *65*, 135–146. https://doi.org/10.1016/j.envint.2013.12.018

Bank of Ghana (2008). The Fishing Sub-Sector and Ghana's Economy. ISBN: 0855-658X

Banza, C.L.N., Nawrot, T.S., Haufroid, V., Decrée, S., De Putter, T., Smolders, E., Kabyloa B.I., Luboya, O.N., Ilunga, A.N., Mutombo, A.M., Nemery, B. (2008). High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. *Environmental Research, 109,* 745-752. https://doi.org/10.1016/j.envres.2009.04.012

Banza CLN, Casas L, Haufroid V, De Putter T, Saenen ND, Kayembe-Kitenge T, Musa Obadia P, Mukoma DKW, Ilunga JML, Nawrot TS, Numbi OL, Smolders E, Nemery B. (2018). Sustainability of artisanal mining of cobalt in DR Congo. *Nature Sustainability, 1*(9), 495-504.

Boadi, K. O., & Kuitunen, M. (2002). Urban waste pollution in the Korle Lagoon, Accra, Ghana. *The Environmentalist*, *22*(4), 301–309. https://doi.org/10.1023/A:1020706728569

Bosch, A. C., O'Neill, B., Sigge, G. O., Kerwath, S. E., & Hoffman, L. C. (2016). Heavy metals in marine fish meat and consumer health: A review. *Journal of the Science of Food and Agriculture*, *96*(1), 32–48. https://doi.org/10.1002/jsfa.7360

Bradl, H., Kim, C., Kramar, U., & Stüben, D. (2005). Heavy Metals in the Environment: Origin, Interaction and Remediation. Chapter 2 - Interactions of Heavy Metals. *Interface Science and Technology, 6,* 28–164. https://doi.org/10.1016/S1573-4285(05)80021-3

Bruce-Vanderpuije, P., Megson, D., Reiner, E. J., Bradley, L., Adu-Kumi, S., & Gardella, J. A. (2019). The state of POPs in Ghana- A review on persistent organic pollutants: Environmental and human exposure. *Environmental Pollution*, *245*, 331–342. https://doi.org/10.1016/j.envpol.2018.10.107

Carbonell, G., Bravo, J.C., Fernández, C. et al. (2009). A New Method for Total Mercury and Methyl Mercury Analysis in Muscle of Seawater Fish. *Bulletin of Environmental Contamination and Toxicology*, *83*, 210-213. https://doi.org/10.1007/s00128-009-9720-x

Castro-González, M. I., & Méndez-Armenta, M. (2008). Heavy metals: Implications associated to fish consumption. *Environmental Toxicology and Pharmacology*, *26*(3), 263–271. https://doi.org/10.1016/j.etap.2008.06.001

Cheyns, K., Nkulu, C.B.L., Ngombe, L.K., Asosa, J.N., Haufroid, V., De Putter, T., Nawrot, T., Kimpanga, C.M., Numbi, O.L., Ilunga, B.K., Nemery, B. & Smolders E. (2014). Pathways of human exposure to cobalt in Katanga, a mining area of the D.R. Congo. *Science of The Total Environment 490*, 313-321. https://doi.org/10.1016/j.scitotenv.2014.05.014

Copat, C., Arena, G., Fiore, M., et al. (2013). Heavy metals concentrations in fish and shellfish from eastern Mediterranean Sea: Consumption advisories. F*ood and Chemical Toxicology, 53,* 33-37. https://doi.org/10.1016/j.fct.2012.11.038.

Clottey, C. A. (2018). Assessment of physiochemical parameters and heavy metals contamination in Korle and Kpeshie lagoons. Thesis. *University of Ghana, Legon.*

Coffie, J. (2014). Assessment of Physiochemical Propertiers and Heavy Metals in Water, Sediment and Fish (Oreochromis niloticus) From the Upper Volta Basin (Stratum VII), Ghana. Kwame Krumah University of Science and Technology Kumasi, Ghana.

Copat, C., Bella, F., Castaing, M., Fallico, R., Sciacca, S., & Ferrante, M. (2012). Heavy metals concentrations in fish from Sicily (Mediterranean Sea) and evaluation of possible health risks to consumers. *Bulletin of Environmental Contamination and Toxicology*, *88*(1), 78–83. https://doi.org/10.1007/s00128-011-0433-6

Diop, M., Howsam, M., Diop, C., Cazier, F., Goossens, J. F., Diouf, A., & Amara, R. (2016). Spatial and seasonal variations of trace elements concentrations in liver and muscle of round Sardinelle

(*Sardinella aurita*) and Senegalese sole (*Solea senegalensis*) along the Senegalese coast. *Chemosphere*, *144*, 758–766. https://doi.org/10.1016/j.chemosphere.2015.08.085

Essumang, D. K., Togoh, G. K., & Chokky, L. (2009). Pesticide Residues in the Water and Fish (Lagoon Tilapia) Samples from Lagoons in Ghana. *Bulletin of Chemical Society of Ethiopia*, *23*(1), 19–27.

European Commission (2006). Commission Regulation (Ec) NO 1881/2006 setting maximum levels for certain contaminants in foodstuffs (Vol. L 364/5).

FAO/WHO Codex Alimentarius Commission (2011). Joint FAO/WHO Food Standards Programme Codex Committee on Contaminants in Foods. Fifth Session. The Hague, The Netherlands.

Fosu-Mensah, B. Y., Addae, E., Yirenya-Tawiah, D., & Nyame, F. (2017). Heavy metals concentration and distribution in soils and vegetation at Korle Lagoon area in Accra, Ghana. *Cogent Environmental Science*, *3(1)*, 1–14. https://doi.org/10.1080/23311843.2017.1405887

Gbogbo, F., & Otoo, S. D. (2015). The concentrations of five heavy metals in components of an economically important urban coastal wetland in Ghana : public health and phytoremediation implications. *Environmental Monitoring and Assessment*, *187*. https://doi.org/10.1007/s10661-015-4880-0

Gbogbo, F., Otoo, S. D., Asomaning, O., & Huago, R. Q. (2017). Contamination status of arsenic in fish and shellfish from three river basins in Ghana. *Environmental Monitoring and Assessment*, *189(8)*. https://doi.org/10.1007/s10661-017-6118-9

Gbogbo, F., Arthur-Yartel, A., Bondzie, J. A., Dorleku, W. P., Dadzie, S., Kwansa-Bentum, B., Ewool, J., Maxwell, B.K., Lamptey, A. M. (2018). Risk of heavy metal ingestion from the consumption of two commercially valuable species of fish from the fresh and coastal waters of Ghana. *PLoS ONE*, *13*(3), 1–17. https://doi.org/10.1371/journal.pone.0194682

Gilmour C.C., & Henry, E.A. (1991). Mercury methylation in aquatic systems affected by acid deposition. *Environmental Pollution, 71(2-4)*, 131-69. doi: 10.1016/0269-7491(91)90031-q.

Golden, C. D., Allison, E. H., Cheung, W. W. L., Dey, M. M., Halpern, B. S., McCauley, D. J., Smith, M., Bapu, V., Zeller, D., & Myers, S. (2016). Fall in fish catch threatens human health. *Nature Comment*, *534*, 317–320. https://doi.org/10.1038/534317a

Grant, R. J., & Oteng-Ababio, M. (2016). The global transformation of materials and the emergence of informal urban mining in Accra, Ghana. *Africa Today, 62(4)*, 3-20. https://doi.org/10.2979/africatoday.62.4.01

Ha, N. N., Agusa, T., Ramu, K., Tu, N. P. C., Murata, S., Bulbule, K. A., Parthasaraty, P., Takahashi, S., Subramanian, A. & Tanabe, S. (2009). Contamination by trace elements at e-waste recycling sites in Bangalore, India. *Chemosphere*, 76(1), 9-15. https://doi.org/10.1016/j.chemosphere.2009.02.056

Hammer, O., Harper, D.A.T., & Ryan, P.D. (2001). PAST: Paleontological statistics software package for education and data analysis. *Palaeontological Electronic*, 4(1), 1-9.

Harmanescu, M., Alda, L. M., Bordean, D. M., Gogoasa, I., & Gergen, I. (2011). Heavy metals health risk assessment for population via consumption of vegetables grown in old mining area; a case study: Banat County, Romania. *Chemistry Central Journal*, (5) 5:64.

Hepp, L. U., Pratas, J. A. M. S., & Graça, M. A. S. (2017). Arsenic in stream waters is bioaccumulated but neither biomagnified through food webs nor biodispersed to land. *Ecotoxicology and Environmental Safety*, *139*, 132–138. https://doi.org/10.1016/j.ecoenv.2017.01.035

Kang, D.H., Chen, M., & Ogunseitan, O.A. (2013). Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste. *Environmental Science and Technology*, 21, 47(10), 5495-503. doi: 10.1021/es400614y

Karikari, A., Asante, K. A., & Biney, C. A. (2006). Water Quality Characteristics at the Estuary of Korle Lagoon in Ghana. *West African Journal of Applied Ecology*, *10(1)*. https://doi.org/10.4314/wajae.v10i1.45700

Kudo, S., Orleans, M., Hansen, M., & Nyerere, J. (2018). Rural-Urban Linkages and Sustainable Development in Africa.

Kwaansa-Ansah, E. E., Nti, S. O., & Opoku, F. (2019). Heavy metals concentration and human health risk assessment in seven commercial fish species from Asafo Market, Ghana. *Food Science and Biotechnology*, *28*(2), 569–579. https://doi.org/10.1007/s10068-018-0485-z

Kyere, Vincent N, Greve, K., Atiemo, S. M., Amoako, D., Kwame, I. J., & Cheabu, S. (2018). Contamination and Health Risk Assessment of Exposure to Heavy Metals in Soils from Informal E-Waste Recycling Site in Ghana. *Emerging Science Journal*, *2*(6), 428–436.

Kyere, Vincent Nartey, Greve, K., Atiemo, S. M., & Ephraim, J. (2017). Spatial assessment of potential ecological risk of heavy metals in soils from informal e-waste recycling in Ghana. *Environmental Health and Toxicology*, *32*, e2017018. https://doi.org/10.5620/eht.e2017018

Le Croizier, G., Schaal, G., Gallon, R., Fall, M., Le Grand, F., Munaron, J. M., Rouget, M.L., Machu, E., Le Loc'h, F., Lae, R., & De Morais, L. T. (2016). Trophic ecology influence on metal bioaccumulation in marine fish: Inference from stable isotope and fatty acid analyses. *Science of the Total Environment*, *573*, 83–95. https://doi.org/10.1016/j.scitotenv.2016.08.035

Little, P. C., & Akese, G. A. (2019). Centering the Korle Lagoon: exploring blue political ecologies of E-Waste in Ghana. *Journal of Political Ecology*, *26*(1). https://doi.org/10.2458/v26i1.22988

Liu, C., Luo, C., Gao, Y., Li, F., Lin, L., Wu, C., & Li, X. (2010). Arsenic contamination and potential health risk implications at an abandoned tungsten mine, southern China. *Environmental Pollution*, *158(3),* 820–826. https://doi.org/10.1016/j.envpol.2009.09.029

Liu, Q., Liao, Y., Xu, X., & Shi, X. (2020). Heavy metal concentrations in tissues of marine fish and crab collected from the middle coast of Zhejiang. *Environmental Monitoring and Assessment*, 193.

Liu, Q., Xu, X., Zeng, J., Shi, X., Liao, Y., Du, P., & Bay, X. (2019). Heavy metal concentrations in commercial marine organisms from Xiangshan Bay, China, and the potential health risks. *Marine Pollution Bulletin*, *141*(36), 215–226. https://doi.org/10.1016/j.marpolbul.2019.02.058

Makimilua, B., & Ananga Dzifa Afua, M. (2013). Determination of Selected Heavy Metals and Iron Concentration in Two common Fish Species in Densu River at Weija District in Grater Accra Region of Ghana. American International Journal of Biology, 1(1), 45–55. Retrieved from www.aripd.org/aijb

Miri, M., Akbari, E., Amrane, A., Jafari, S. J., Eslami, H., & Taghavi, M. (2017). Health risk assessment of heavy metal intake due to fish consumption in the Sistan region, Iran. *Environmental Monitoring and Assessment*, 189(583).

Mohd Kusin, F., Azani, N. N. M., Hasan, S. N. M. S., & Sulong, N. A. (2018). Distribution of heavy metals and metalloid in surface sediments of heavily- mined area for bauxite ore in Pengerang , Malaysia and associated risk assessment. *Catena,* 165, 454–464. https://doi.org/10.1016/j.catena.2018.02.029

Ndanu, T. A. (1998). Heavy Metal Pollution of Fish and Fish Oils From Some Coastal and Inland Waters of Ghana. University of Ghana.

Nyarko, E., Foli, B. A. K., Achel, D. G., Botwe, B. O., Adom, T., Fianko, J. R., & Osae, S. D. (2013). Investigation of Selected Trace and Heavy Metals in Two Tropical Fish Species from the Coastal Waters of Ghana. International Journal of Science and Technology, 3(1), 40–47.

Oguchi, M., Sakanakura, H., & Terazono, A. (2013). Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes. *Science of the total environment, 463,* 1124-1132. https://doi.org/10.1016/j.scitotenv.2012.07.078

Onuoha, D. (2016). Economies of Waste: Rethinking Waste Along the Korle Lagoon. *Journal for Undergraduate Ethnography, 6*(1), 1–16. https://doi.org/10.15273/jue.v6i1.8275

Saha, N., Mollah, M. Z. I., Alam, M. F., & Safiur Rahman, M. (2016). Seasonal investigation of heavy metals in marine fishes captured from the Bay of Bengal and the implications for human health risk assessment. *Food Control*, *70*, 110–118. https://doi.org/10.1016/j.foodcont.2016.05.040

Stern, A. H. (2010). A quantitative assessment of the carcinogenicity of hexavalent chromium by the oral route and its relevance to human exposure. *Environmental Research*, 110(8), 798–907. https://doi.org/https://doi.org/10.1016/j.envres.2010.08.002

Storelli, M.M., & Marcotrigiano, G.O. (2000). Organic and inorganic arsenic and lead in fish from the South Adriatic Sea, Italy. *Food Aditives & Contaminants, 17(9),* 763-768. https://doi.org/10.1080/026520300415309

Tay, C., Asmah, R., & Biney, C. (2008). Trace Metal Concentrations in Commercially Important Fishes from some Coastal and Inland Waters in Ghana. West African Journal of Applied Ecology, 13(1). https://doi.org/10.4314/wajae.v13i1.40579

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy Metal Toxicity and the Environment. *Molecular, Clinical and Environmental Toxicology*, *101*, 133–164. https://doi.org/10.1007/978-3-7643-8340-4

Türkmen, M., Türkmen, A., Tepe, Y., Töre, Y., & Ateş, A. (2009). Determination of metals in fish species from Aegean and Mediterranean seas. *Food Chemistry*, *113*(1), 233–237. https://doi.org/10.1016/j.foodchem.2008.06.071

Ullah, A. K. M. A., Maksud, M. A., Khan, S. R., Lutfa, L. N., & Quraishi, S. B. (2017). Dietary intake of heavy metals from eight highly consumed species of cultured fish and possible human health risk implications in Bangladesh. *Toxicology Reports*, 4, 574–579. https://doi.org/10.1016/j.toxrep.2017.10.002

USDA (1998*).* A Dietary Assessment of the US Food Supply. Appendix 2 : Estimation of Serving Weights for Individual Commodities.

USEPA Environmental Protection Agency (1994). Chemical Assessment Summary: Arsenic (Inorganic). Integrated Risk Information System, Iris.

USEPA Environmental Protection Agency (1995). EPA Region III Risk-Based Concentration Table. Background Information.

USEPA Environmental Protection Agency (2019). Advice about eating Fish. Dietary Guidelines for Americans 2015-2020. Retrieved from https://www.fda.gov/media/102331/download

USEPA Environmental Protection Agency(2000). Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories. Volume 2: Risk Assessment and Fish Consumption Limits Third Edition. (EPA, Ed.). U.S. Environmental Protection Agency.

USEPA United States Environmental Protection Agency (2007). Framework for Metals Risk Assessment.

Vaccari, M., Vinti, G., Cesaro, A., Belgiorno, V., Salhofer, S., Dias, M. I., & Jandric, A. (2019). WEEE treatment in developing countries: Environmental pollution and health consequences—An overview. *International journal of environmental research and public health, 16(9),* 1595. https://doi.org/10.3390/ijerph16091595

Vandermeersch, G., Lourenço, H. M., Alvarez-Muñoz, D., Cunha, S., Diogène, J., Cano-Sancho, G., Sloth, J.J., Kwadijk, C., Barcelo, D., Allegaert, W., Bekaert, K., Fernandes, J.O., Marques, A., & Robbens, J. (2015). Environmental contaminants of emerging concern in seafood - European database on contaminant levels. *Environmental Research,* 143, 29–45. https://doi.org/10.1016/j.envres.2015.06.011

Voegborlo, R. B., Adimado, A. A., & Ephraim, J. H. (2007). Total Mercury Distribution in Different Tissues of Frigate Tuna (*Auxis thazard thazard*) from the Atlantic Coastal Waters of Ghana, Gulf of Guinea, *Environmental Monitoring and Assessment,* 503–508. https://doi.org/10.1007/s10661-006-9552-7

Wang, X., Sato, T., Xing, B., & Tao, S. (2005). Health risks of heavy metals to the general public in Tianjin, China via consumption of vegetables and fish. *Science of the total environment, 350(1-3)*, 28-37. https://doi.org/10.1016/j.scitotenv.2004.09.044

WHO World Health Organization (2018). Fact Sheet Arsenic. Retrieved May 2, 2020, from https://www.who.int/news-room/fact-sheets/detail/arsenic

WHO World Health Organization Europe (2007). Exposure of children to chemical hazards in food. Fact Sheet No. 4.4, Code: RPG4_Food_Ex1

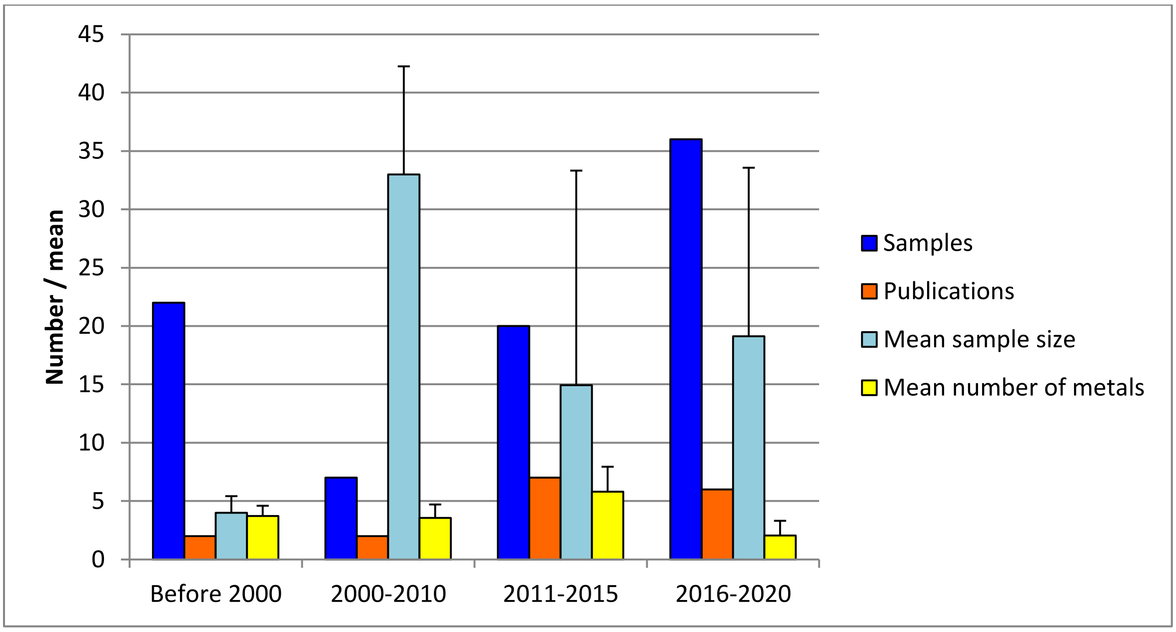
Wong, C. S., Duzgoren-Aydin, N. S., Aydin, A., & Wong, M. H. (2007). Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. *Environmental Pollution,* 148(1), 62-72. https://doi.org/10.1016/j.envpol.2006.11.006

Yang, J., Bertram, J., Schettgen, T., Heitland, P., Fischer, D., Seidu, F., Felten, M., Kraus, T., Fobil, J.N., Kaifie, A. (2020). Arsenic burden in e-waste recycling workers e A cross-sectional study at the Agbogbloshie e-waste recycling site , Ghana. *Chemosphere*, 261, 1–9. ISSN 0045-6535, https://doi.org/10.1016/j.chemosphere.2020.127712

Zhao, R., Yan, S., Liu, M., Wang, B., Hu, D., Guo, D., Wang, J., Xu, W.,& Fan, C. (2016). Seafood consumption among Chinese coastal residents and health risk assessment of heavy metals in seafood. *Environmental Science and Pollution Research*, 23(16), 16834–16844. https://doi.org/10.1007/s11356-016-6817-8

Zieliński, E., Wielgus, A., Sas, K., & Zukow, W. (2018). Health hazards resulting from the WEEE combustion at illegal e-waste yards in developing countries on the example of Agbogbloshie. *Journal of Education, Health and Sport, 8(12)*, 363-369.

Supplementary Figure 1. Evolution of published studies about trace metals in Ghanaian fish in the last decades. Number of samples and publications per considered period (before 2000, decade 2000-2010, 2011-2015, 2016-2020).



Supplementary Table 1. ICP-MS settings. Scandium, Rhodium, Iridium isotopes (^{45}Sc, ^{103}Rh, ^{193}Ir) were used as internal standards: ^{45}Sc for Cr, Co, Ni, Cu and Zn, ^{103}Rh for As and Cd and ^{193}Ir for Hg and Pb.

Inductively Coupled Plasma Mass Spectrometer			
Rf power (W)	1550	Sampling cone	Nickel
Carrier gas (L/min)	1.07	Skimmer cone	Nickel
Plasma gas (L/min)	15	Peak Pattern	1 points
Auxiliary gas (L/min)	0.9	Replicates	3
Sample depth (mm)	10	Sweeps/Replicate	100
Solution uptake rate (mL/min)	0.1	Integration time/Mass	0.2s / Cr, Co, Ni, Cu, Zn, Pb 0.6s /As, Cd, Hg
Nebulizer	MicroMist	Analytical masses	^{45}Sc, ^{52}Cr, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{75}As, ^{103}Rh, ^{193}Ir, ^{202}Hg, ^{208}Pb

Supplementary Table 2. Mean metal concentrations of heavy metals in Ghanaian fish from different studies [mg kg^{-1}]; 0 = below level of detection; N/A = not available. A, article; T, thesis. In bold, samples caught from the estuary near Korle lagoon.

Authors	Sampling year	Type	Study area	Fish common name	Scientific name	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn	Tissue status	Sample size
Amonoo-Neizer & Amekor 1993	N/A	A	Kumasi market	Tilapia	*Tilapia spp.*	3,30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	N/A
Amonoo-Neizer & Amekor 1993	N/A	A	Obuasi (mining)	Tilapia	*Tilapia spp.*	2,60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	N/A
Ndanu 1998	N/A	T	Apam	Mackerel	- not specfied -	3,30	1,20	N/A	N/A	N/A	68,00	N/A	2,40	N/A	Dry	N/A
Ndanu 1998	N/A	T	Apam	Herring	*Sardinella spp*	9,30	1,20	N/A	N/A	N/A	92,00	N/A	8,00	N/A	Dry	N/A
Ndanu 1998	N/A	T	Apam	Emule	- not specfied -	1,90	1,00	N/A	N/A	N/A	68,00	N/A	5,20	N/A	Dry	N/A
Ndanu 1998	N/A	T	Elmina landing beach	Red mullet/Redfish	- not specfied -	10,10	0,60	N/A	N/A	N/A	144,00	N/A	7,00	N/A	Dry	N/A
Ndanu 1998	N/A	T	Elmina landing beach	Tuna	*Thunnus spp.*	19,80	0,60	N/A	N/A	N/A	50,00	N/A	5,20	N/A	Dry	N/A
Ndanu 1998	N/A	T	Elmina landing beach	Herring	- not specified -	8,40	1,20	N/A	N/A	N/A	25,00	N/A	14,10	N/A	Dry	N/A
Ndanu 1998	N/A	T	Jamestown fishing market	Red mullet/Redfish	- not specified -	6,50	0,60	N/A	N/A	N/A	20,00	N/A	9,80	N/A	Dry	N/A
Ndanu 1998	N/A	T	Jamestown fishing market	Tuna	*Thunnus spp.*	19,10	0,60	N/A	N/A	N/A	58,00	N/A	4,30	N/A	Dry	N/A
Ndanu 1998	N/A	T	Jamestown fishing market	Herring	*Sardinella spp*	9,30	0,60	N/A	N/A	N/A	70,00	N/A	6,10	N/A	Dry	N/A
Ndanu 1998	N/A	T	Tema fishing harbour	Red mullet/Redfish	- not specified -	14,80	0,80	N/A	N/A	N/A	74,00	N/A	3,40	N/A	Dry	N/A

Ndanu 1998	N/A	T	Tema fishing harbour	Tuna	*Thunnus spp.*	4,20	1,40	N/A	N/A	N/A	98,00	N/A	8,80	N/A	Dry	N/A
Ndanu 1998	N/A	T	Tema fishing harbour	Mackerel	- not specified -	9,30	1,80	N/A	N/A	N/A	124,00	N/A	4,30	N/A	Dry	N/A
Ndanu 1998	N/A	T	Tema fishing harbour	Herring	- not specified -	9,30	1,60	N/A	N/A	N/A	118,00	N/A	6,10	N/A	Dry	N/A
Ndanu 1998	N/A	T	Wejia Dam	Tilapia	*Tilapia spp.*	9,80	0,40	N/A	N/A	N/A	50,00	N/A	12,70	N/A	Dry	3-5
Ndanu 1998	N/A	T	Kpong	Blolo	*Chrysichthys nigrodigitatus*	6,10	0,80	N/A	N/A	N/A	50,00	N/A	22,70	N/A	Dry	3-5
Ndanu 1998	N/A	T	Kpong	Tilapia	*Tilapia spp.*	4,80	0,70	N/A	N/A	N/A	50,00	N/A	3,40	N/A	Dry	3-5
Ndanu 1998	N/A	T	Obuasi (mining)	Tilapia	*Tilapia spp.*	18,5	1,7	N/A	N/A	N/A	150	N/A	20,8	N/A	Dry	3-5
Ndanu 1998	N/A	T	Dunkwa (mining)	Tilapia	*Tilapia spp.*	6,2	0,6	N/A	N/A	N/A	75	N/A	6,1	N/A	Dry	3-5
Ndanu 1998	N/A	T	Dunkwa (mining)	Catfish	- not specified -	1,3	0,3	N/A	N/A	N/A	50	N/A	8	N/A	Dry	3-5
Ndanu 1998	N/A	T	Dunkwa (mining)	Blolo	*Chrysichthys nigrodigitatus*	5,7	1	N/A	N/A	N/A	50	N/A	9,3	N/A	Dry	3-5
Voegborlo et al 2007	2004	A	Tema fishing harbour	Frigate tuna	*Auxis thazard thazard*	N/A	N/A	N/A	N/A	N/A	0,11	N/A	N/A	N/A	Wet	21
Tay et al 2008	2003-2004	A	Jamestown, Salaha, Tema	Ghanaian tonguesole	*Cynoglossus cadenati*	N/A	0	N/A	N/A	0,10	N/A	N/A	0,76	6,63	Wet	28
Tay et al 2008	2003-2004	A	Jamestown, Salaha, Tema	Congo dentex	*Dentex congoensis*	N/A	0	N/A	N/A	1,22	N/A	N/A	0,90	6,20	Wet	39
Tay et al 2008	2003-2004	A	Jamestown, Salaha, Tema	Pompano	*Trachinotus ovatus*	N/A	0,002	N/A	N/A	0,35	N/A	N/A	0,90	1,05	Wet	26
Tay et al 2008	2003-2004	A	Jamestown, Salaha, Tema	Atlantic horse mackerel	*Trachurus trachurus*	N/A	0	N/A	N/A	7,68	N/A	N/A	1,09	19,19	Wet	33
Tay et al 2008	2003-2004	A	Jamestown, Salaha, Tema	Flat sardine	*Sardinella eba*	N/A	0	N/A	N/A	13,23	N/A	N/A	0,74	18,08	Wet	49

Tay et al 2008	2003-2004	A	Jamestown, Salaha, Tema	Bigeye scad	*Solar crumophthalmus*	N/A	0,14	N/A	N/A	11,91	N/A	N/A	0,00	16,73	Wet	35
Aboagye 2012	**N/A**	**T**	**Korle Lagoon**	**Boe drum**	***Pteroscion peli***	**N/A**	**2,17**	**N/A**	**N/A**	**5,11**	**N/A**	**N/A**	**2,73**	**16,41**	**Wet**	**32**
Aboagye 2012	**N/A**	**T**	**Korle Lagoon**	**Amberjack**	***Seriola dumerili***	**N/A**	**2,03**	**N/A**	**N/A**	**4,43**	**N/A**	**N/A**	**2,54**	**13,9**	**Wet**	**32**
Anim-Gyampo et al 2013	N/A	A	Tono dam, Navrongo	Tilapia	*Sarotherodon gallelacus*	N/A	0.035	N/A	N/A	0.045	N/A	N/A	0.38	0.004	Wet	N/A
Anim-Gyampo et al 2013	N/A	A	Tono dam, Navrongo	African giraffe bagrid	*Auchenoglanis occidestalis*	N/A	0.035	N/A	N/A	0.045	N/A	N/A	0.38	0.035	Wet	N/A
Makimula & Afua 2013	2012	A	Weja Dam, Densu river	Catfish	- not specified -	0	0,808	N/A	N/A	N/A	0	N/A	0	N/A	Wet	50
Makimula & Afua 2013	2012	A	Weja Dam, Densu river	Tilapia	*Tilapia spp.*	0	0,129	N/A	N/A	N/A	0	N/A	0	N/A	Wet	50
Nyarko et al 2013	2008-2009	A	Half-Assini	Atlantic bumper	*Chloroscrombus chrysurus*	N/A	0	N/A	N/A	66,30	N/A	N/A	0	N/A	Dry	N/A
Nyarko et al 2013	2008-2009	A	Elmina landing beach	Atlantic bumper	*Chloroscrombus chrysurus*	N/A	0	N/A	N/A	51,90	N/A	N/A	0	N/A	Dry	N/A
Nyarko et al 2013	2008-2009	A	Aboadze	Madeiran sardinella	*Sardinella maderensis*	N/A	0	N/A	N/A	35,70	N/A	N/A	0	N/A	Dry	N/A
Akoto et al 2014	2011	A	Fosu lagoon	Blackchin tilapia	*Sarotherodon melanotheron*	N/A	0,275	N/A	0	0,22	N/A	0,36	6,82	20,66	Wet	20
Bandowe et al 2014	2010	A	Tema fishing harbour	African sicklefish	*Drapane africana*	2	0	0	9	1,00	N/A	0	0,28	17	Dry	3
Bandowe et al 2014	2010	A	Tema fishing harbour	Senegalese tonguesole	*Cynoglossus senegalensis*	25	0,7	0	9	0,90	N/A	0	0,7	27	Dry	3
Bandowe et al 2014	2010	A	Tema fishing harbour	Parrot grunt	*Pomadasys peroteti*	4	0	0	12	1,00	N/A	0	0	17	Dry	1
Bandowe et al 2014	2010	A	Takoradi fishing harbour	African sicklefish	*Drapane africana*	3	0,1	0	12	1,00	N/A	0	0	24	Dry	3
Bandowe et al 2014	2010	A	Takoradi fishing harbour	Senegalese tonguesole	*Cynoglossus senegalensis*	20	0,2	0	9	1,00	N/A	1	0	34	Dry	3

Bandowe et al 2014	2010	A	Takoradi fishing harbour	Parrot grunt	*Pomadasys perotaei*	6	0	0	7	2,00	N/A	0	0	28	Dry	3
Bandowe et al 2014	2010	A	Elmina landing beach	African sicklefish	*Drapane africana*	2	0,1	0	4	0,80	N/A	0	0	19	Dry	3
Bandowe et al 2014	2010	A	Elmina landing beach	Senegalese tonguesole	*Cynoglossus senegalensis*	18	0,1	0	17	0,50	N/A	0	NA	29	Dry	3
Bandowe et al 2014	2010	A	Elmina landing beach	Parrot grunt	*Pomadasys perotaei*	27	0,1	0	15	0,60	N/A	0	0,2	30	Dry	3
Coffie 2014	2012	T	Volta River Basin	Nile tilapia	*Oreochromis niloticus*	0,23	0,71	N/A	N/A	4,06	0,001	N/A	0,389	10,58	Wet	N/A
Awuah 2016	N/A	T	Tano	Tailspot ctenopoma	*Ctenopoma kingsleyae*	1,28	N/A	N/A	N/A	N/A	2,51	N/A	N/A	N/A	Wet	53
Awuah 2016	N/A	T	Tano	Mango tilapia	*Sarotherodon galilaeus*	1,14	N/A	N/A	N/A	N/A	1,73	N/A	N/A	N/A	Wet	
Awuah 2016	N/A	T	Tano	North African catfish	*Clarias gariepinus*	1,02	N/A	N/A	N/A	N/A	2,66	N/A	N/A	N/A	Wet	
Awuah 2016	N/A	T	Tano	African obscure snakehead	*Parachanna obscura*	0,80	N/A	N/A	N/A	N/A	2,96	N/A	N/A	N/A	Wet	
Awuah 2016	N/A	T	Tano	Black chin tilapia	*Sarotherodon melanotheron*	2,01	N/A	N/A	N/A	N/A	3,71	N/A	N/A	N/A	Wet	
Awuah 2016	N/A	T	Ankobra	Sompat grunt	*Pomadasys jubelini*	0,48	N/A	N/A	N/A	N/A	1,24	N/A	N/A	N/A	Wet	
Awuah 2016	N/A	T	Ankobra	North African catfish	*Clarias gariepinus*	0,69	N/A	N/A	N/A	N/A	1,08	N/A	N/A	N/A	Wet	
Awuah 2016	N/A	T	Ankobra	African obscure snakehead	*Parachanna obscura*	0,86	N/A	N/A	N/A	N/A	0,98	N/A	N/A	N/A	Wet	
Gbogbo et al 2015	N/A	A	Sakumo II Lagoon	Blackchin tilapia	*Sarotherodon melanotheron*	0	0,039	N/A	N/A	0,00	0,001	N/A	0	N/A	Wet	15
Gbogbo et al 2017	2015	A	Ankobra Basin	Redbelly tilapia	*Tilapia zilii*	0,80	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	14
Gbogbo et al 2017	2015	A	Densu Basin	Redbelly tilapia	*Tilapia zilii*	0,20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	16

Gbogbo et al 2017	2015	A	Volta River Basin	Redbelly tilapia	*Tilapia zilii*	2,00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	12
Gbogbo et al 2017	2015	A	Ankobra	Bagrid catfish	*Chrysichthys nigrodigitatus*	2,00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	13
Gbogbo et al 2017	2015	A	Densu river	Bagrid catfish	*Chrysichthys nigrodigitatus*	0,40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	12
Gbogbo et al 2017	2015	A	Volta River Basin	Bagrid catfish	*Chrysichthys nigrodigitatus*	1,00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	12
Gbogbo et al 2017	2015	A	Densu river	Blackchin tilapia	*Sarotherodon melanotheron*	0,60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	31
Gbogbo et al 2017	2015	A	Volta River Basin	Blackchin tilapia	*Sarotherodon melanotheron*	2,20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	12
Gbogbo et al 2017	2015	A	Densu river	Grey mullet	*Mugil cephalus*	0,60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	13
Gbogbo et al 2017	2015	A	Volta River Basin	Grey mullet	*Mugil cephalus*	1,00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	11
Gbogbo et al 2017	2015	A	Densu river	Bonga shad	*Ethmolosa frimbriata*	0,40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	13
Gbogbo et al 2017	2015	A	Volta River Basin	Bonga shad	*Ethmolosa frimbriata*	2,00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	14
Gbogbo et al 2017	2015	A	Ankobra	Nile tilapia	*Oreochromis niloticus*	0,80	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	1
Gbogbo et al 2017	2015	A	Densu river	Banded jewfish	*Hemichromis fasciatus*	0,20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	16
Gbogbo et al 2017	2015	A	Densu river	African sharptooth catfish	*Clarias gariepinus*	0,80	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	1
Gbogbo et al 2017	2015	A	Ankobra	Tongue sole	*Cynoglossus senegalensis*	2,00	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	12
Gbogbo et al 2017	2015	A	Densu river	Tongue sole	*Cynoglossus senegalensis*	0,2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Dry	13
Clottey 2018	2017-2018	T	Kpeshie lagoon	Blackchin tilapia	*Sarotherodon melanotheron*	0,423	0,683	N/A	9,321	4,06	N/A	N/A	2,404	17,81	Dry	24

Gbogbo et al 2018	2016	A	Tema Fishing Habour	Bigeye grunt	*Brachydeuterus auritus*	0,21	0	N/A	N/A	0,42	0,31	N/A	N/A	2,28	Wet	45
Gbogbo et al 2018	2016	A	Weja Dam, Densu river	Bagrid catfish	*Chrysichthys nigrodigitatus*	0,37	N/A	N/A	N/A	0,59	0,19	N/A	N/A	2,34	Wet	45
Kwaansa-Ansah et al 2019	2017	A	Asafo markets	Atlantic horse mackerel	*Trachurus trachurus*	N/A	0,008	0,058	N/A	N/A	N/A	N/A	0,085	N/A	Wet	42
Kwaansa-Ansah et al 2019	2017	A	Asafo markets	Golden African snapper	*Lutjanus fulgens*	N/A	0,015	0,156	N/A	N/A	N/A	N/A	0,06	N/A	Wet	
Kwaansa-Ansah et al 2019	2017	A	Asafo markets	Gorean snapper	*Lutjanus goreensis*	N/A	0,012	0,093	N/A	N/A	N/A	N/A	0,077	N/A	Wet	
Kwaansa-Ansah et al 2019	2017	A	Asafo markets	Wahoo	*Acanthocybium solandri*	N/A	0,007	0,118	N/A	N/A	N/A	N/A	0,054	N/A	Wet	
Kwaansa-Ansah et al 2019	2017	A	Asafo markets	Red pandora	*Pagellus bellottii*	N/A	0,015	0,076	N/A	N/A	N/A	N/A	0,074	N/A	Wet	
Kwaansa-Ansah et al 2019	2017	A	Asafo markets	Atlantic chub mackerel	*Scomber colias*	N/A	0,01	0,02	N/A	N/A	N/A	N/A	0,069	N/A	Wet	
Kwaansa-Ansah et al 2019	2017	A	Asafo markets	Congo dentex	*Dentex congoensis*	N/A	0.019	0.083	N/A	N/A	N/A	N/A	0,071	N/A	Wet	