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Copper in Commercial Marine Fish: From Biomonitoring to the ESG (Environment, Social, and Governance) Method

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Abstract: The presence of potentially harmful metals in commercially available saltwater fish has been extensively documented in scientific literature. This has demonstrated the significance of monitoring the crucial copper (Cu) levels in fish fillets from a perspective focused on human health risks (HHR). This study aimed to evaluate the human health risk (HHR) associated with the presence of Cu in 40 different species of commercial marine fish purchased from Malaysia. The fish samples were gathered from various sources from April to May 2023. The 40 species of commercial marine fish had concentrations of Cu (0.72–82.3 mg/kg dry weight) that fell below acceptable levels defined by seafood safety recommendations. Therefore, these fish are considered good sources of the essential element. The target hazard quotient values for Cu were below 1, suggesting that the hazards of Cu from fish eating are non-carcinogenic. Furthermore, it was discovered that the computed values for the predicted weekly consumption were lower than the defined provisional tolerated weekly intake of Cu. Consuming fish purchased from Malaysia is unlikely to harm consumers' necessary copper intake. However, it is crucial to consistently monitor the safety of consumers who heavily depend on commercially caught marine fish from Malaysia. This monitoring is an essential aspect of implementing environmental, social, and governance (ESG) practices, which industries are concerned about and report on annually.

Keywords: commercial fish; health risks; fish consumption; Cu

1. Introduction

Throughout the literature concerning metals in palatable fish, copper (Cu) was consistently identified and documented. This phenomenon may be ascribed to the fact that this metal, despite being a common essential element that provides substantial health benefits, is a potentially toxic metal (PTM) when consumed more often than the threshold that poses a risk to human health (HHR) [1]. Dorsey et al. [2] and Roney et al. [3] extensively

documented the toxicological characteristics of Cu. The World Health Organization (WHO) guidelines [4] also specify the environmental health criteria for Cu. This demonstrates that consideration has been given to the environmental and human health dangers associated with Cu [5]. Cu is a cofactor for enzymes involved in glucose metabolism, the synthesis of hemoglobin, connective tissue, and phospholipids [6–10], and is necessary for iron utilization. However, exceedingly high concentrations of Cu have the potential to cause severe toxicity. Cu derived from marine fish is a significant source of human health. While excessive consumption of Cu from marine fish may lead to adverse health effects, such as harm to the liver and kidneys, it does not possess carcinogenic properties in humans and animals [7].

Fish, being an essential provider of animal protein for humans, also contain copper in their tissues. The Cu content in fish indicates their eating patterns since both carnivorous and herbivorous species can have elevated quantities [11]. Nevertheless, it is crucial to acknowledge that although Cu is essential for regular metabolic functions in fish, elevated levels can hurt aquatic creatures. Fish have a tendency to gather Cu from their water environment, and this gathering tends to reach a maximum level as the concentration of Cu increases [12]. In addition, Cu can react with other pollutants, including ammonia, mercury, and zinc, resulting in an increased harmful impact on fish [13]. The excessive accumulation of Cu in fish can harm their well-being and the broader ecology. Therefore, it is vital to comprehend the level of Cu content in fish for environmental management and human consumption [14].

Cu is an inherent trace metal found in the aquatic environment, existing in small amounts that are minor nutrition for plants and animals [15]. Nevertheless, if the concentration of Cu is beyond specific thresholds, it becomes detrimental to the survival of aquatic organisms [16]. It is imperative to meticulously control and supervise copper concentrations in fish to guarantee the aquatic ecosystem's and human consumers' well-being. Cu is a vital metal for plants and animals since it plays a critical role in forming enzymes and physiological functions [17]. Nevertheless, although Cu is indispensable, it needs meticulous regulation in most organisms. Aquatic species, such as fish, have a tendency to collect Cu from their surroundings [12]. The accumulation of Cu in fish is affected by their dietary preferences since both carnivorous and herbivorous species can exhibit elevated levels of copper in their bodily tissues. The consequences of high Cu concentrations in fish are not entirely confirmed; however, data indicate they can cause poisoning [15,16]. Hence, it is crucial to monitor Cu levels in fish to guarantee the well-being of the aquatic environment and safety for human consumption. Ultimately, the level of Cu found in fish is of utmost importance for ecosystem control and human consumption. Elevated levels of Cu in aquatic habitats can cause significant harm to the creatures inhabiting the ecosystem and the general ecological well-being [15]. Moreover, Cu can have comparable effects on invertebrates and amphibians, leading to a decrease in the generation of sperm and eggs [17]. The impact of Cu on aquatic organisms can eventually disturb the equilibrium and operation of the entire ecosystem [17].

Consuming fish that contains elevated amounts of Cu can harm human health. Consuming fish with elevated Cu levels can result in a range of health complications, such as gastrointestinal troubles, liver impairment, and neurological abnormalities. Therefore, monitoring Cu levels in fish consumed by people is crucial for ensuring the safety of their consumption and safeguarding human health [14]. Hence, it is crucial to consistently check the Cu levels in fish and implement suitable measures to avoid excessive accumulation, safeguarding the well-being of both the environment and human consumers. Furthermore, it is crucial to conduct biomonitoring of Cu levels in fish intended for human consumption. Monitoring Cu levels in fish is crucial for guaranteeing safety for human consumption and preserving the general well-being of aquatic ecosystems [12,14]. To mitigate Cu contamination in aquatic ecosystems, it is recommended to adopt effective waste management practices, encourage the utilization of alternative materials and technologies

that do not depend on Cu, and raise public awareness of the detrimental consequences of Cu pollution [18–21].

PTM concentrations in fish from various countries have been thoroughly examined: India [22–24], Pakistan [14,25–28], Malaysia [29], Indonesia [30], the Persian Gulf or Iran [31–35], Bangladesh [36–38], Tanzania [39], and others [40–49]. Pre-2000 studies provide most monitoring data and direct comparisons to PTM food safety regulations. Recently, marine fish HHR evaluations have employed PTM provisional tolerable weekly intake (PTWI) and target hazard quotient (THQ). Babji et al. [50] measured four PTMs (Cu included) in six Peninsular Malaysian marine fish species to food standard MPLs. Kureishy et al. [22] measured six Andaman Sea marine species metals, including Cu. These levels violated seafood safety. In addition to PTM concentrations, Fathi et al. [51] observed that three marine fish species from Mersing, on Peninsular Malaysia's east coast, had estimated daily and weekly intakes of four PTMs (including Cu) well below the PTWI limits. In addition to zinc surpassing food safety norms, Jahangir Sarker et al. [38] found THQ values below 1.0 for all fish species, indicating no public health risks. Alipour et al. [52] revealed high non-carcinogenic metals for Malaysian and Bangladeshi newborns and adults. Malaysians acquire 60–70% of their protein from marine fish [53]. Hence, various PTM monitoring studies have been published [15,16,50,51,54–62]. Agusa et al. [54] tested twenty-one trace elements (including Cu) in twelve Malaysian coastal marine fish species. Peninsular Malaysia's east coast bigeye scads have seven PTMs, including Cu, higher than those of the west coast. Wan Azmi et al. [58] observed that all 46 Peninsular Malaysian coastal marine fish species had THQ values below 1, suggesting minimal non-carcinogenic risk and safe ingestion. According to Salam et al. [59], Kedah and Selangor residents who consume torpedo scad (*Megalaspis cordyla*) have a high chronic risk using the THQ value.

However, there is no current information on the Cu health risk on commercial marine fish purchased from Malaysia. Therefore, this research aimed to determine Cu levels and estimate Cu health risks in 40 marine commercial fish species purchased from Malaysia.

2. Materials and Methods

2.1. Sample Collection

A total of 40 different commercial marine fish samples were purchased and collected from 31 March to 2 May 2023 in random locations of all types of markets in Malaysia (Table S1; Figure S1). The common name, scientific name, exact purchase location, and purchase time were recorded in a table. The edible dorsal muscles of all fish samples were dissected for metal analysis as it is the primary storage site for Cu accumulation [29].

Fish were categorized using www.fishbase.org (accessed as of 1 September 2023), Mohsin and Ambak [63] and Matsunuma et al. [64]. To verify each fish species' name, family, and niche habitat, web data (<https://www.fishbase.in/search.php>; accessed as of 1 September 2023) were used.

2.2. Sample Preparation

Immediately after collection, the samples were stored in a refrigerated ice package to preserve their freshness. Ice was utilized to mitigate tissue degradation and maintain a moist environment throughout transportation. After rinsing the samples with water to remove any foreign particulates, the fish absorbed any remaining water using a paper towel. After weighing each fish with an electronic balance, a ruler determined its length. The fish's length was determined by measuring from the upper mandible's snout to the tail's extremity. Following this, the dorsal musculature of the fish was dissected. In total, 10–20 g of dorsal muscle were excised from each fish. Rahman et al. [36] suggested that the musculature of fish is the principal site for metal storage.

The specimens were preservation-frozen and subsequently transported to the laboratory at the Universiti Putra Malaysia, where they were categorized by species to prevent any potential for cross-contamination. Subsequently, the specimens were placed in a freezer until the time came for metal analysis. In the laboratory, the samples are defrosted at

ambient temperature. The specimens of each species were fragmented and merged in order to create a composite sample. The muscles were then desiccated at 60 °C for 72 h in an oven until their weight remained constant. Drying eliminates surplus water and ascertains the moisture content of the fish, a critical parameter for the conversion to a wet weight (ww) basis. The moisture content could be ascertained by measuring weight reduction after drying. The specimens were homogenized by pulverizing them with mortar and an agate pestle. The sample powder was refrained from further analysis and stored in an impermeable plastic container.

2.3. Cu Analysis

After measuring approximately 0.50 g of the homogenized dried sample, the digestion tube received 5.00 mL of concentrated nitric acid (HNO₃; AnalaR grade, BDH 69%). A hot block digester pre-digested the materials for one hour at 40 °C. Later, samples were digested at 140 °C for three hours [65]. After digestion, the solution settled for 30 min before being diluted with distilled water to 40 mL. After filtering (with Whatman no 1), the acid-digested samples were placed in acid-washed pillboxes.

The Cu concentrations in digested samples were measured using an air–acetylene flame atomic absorption spectrophotometer (FAAS) Model 800. FAAS Cu detection limits were 0.010 mg/L. All plastics and glassware were washed with distilled water, dried, and then placed in 10% nitric acid overnight before use. The quality of procedure blanks and sample triplicates was evaluated. To maintain analytical integrity, each experiment utilized blanks simultaneously. The method accuracy and metal data were verified using dogfish liver certified reference material (CRM) (DOLT-3, National Research Council Canada). The procedure is reproducible: Cu CRM = 31.2 mg/kg, Cu measurement = 32.9 mg/kg, and CV = 1.16%. The recovery was good (106–119%).

2.4. Cu Data Treatment for Human Health Risk Assessment

For human health risk assessment (HHRA), dry weight (dw) two-metal values were translated to ww using a fish species conversion factor (Table S1). To estimate the HHRA from eating fish, three evaluations were made:

(a) Direct MPL comparisons

Three Cu seafood safety recommendations from the FAO [66], Ministry of Agriculture, Fisheries, and Food [67], and Malaysian Food Regulation 1985 (MFR) [68] were utilized in this investigation.

(b) THQ estimation

First, the estimated daily intake (EDI) was determined to calculate THQ. Using body weight (BW) and fish-eating rate, EDI estimates metal intake. It was determined using Equation (1):

$$EDI = (Mc \times CR)/BW. \quad (1)$$

Assuming a ww basis, Mc = metal concentration in fish muscles (mg/kg). Table S1 lists all dorsal muscle fish water contents and conversion factors. It may be 50% of the water content for all fish species studied. Since big catfish have 53.8% water content [69], the conversion factor for all fish samples in this investigation was 0.50.

The fish consumption rate among Malaysian adults is 100g per person per day, based on data collected from 2675 respondents. The respondents were categorized into three ethnic groups: Malay (76.9%), Chinese (14.7%), and Indian (8.4%). The weight used for adult Malaysians was 62 kg, according to Nurul Izzah et al. [70].

Later, Equation (2) computed THQ:

$$THQ = EDI/ORD. \quad (2)$$

ORD stands for oral reference dose. The ORD calculates the maximum amount of a pollutant that may be consumed daily over a lifetime without causing harm to health [71].

The ORD values ($\text{Cu} = 40 \mu\text{g}/\text{kg}/\text{day}$) from the USEPA regional screening level [72] were used in this study.

(c) EWI vs. PTWI comparisons

The provisional tolerable weekly intake (PTWI) was formed by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) [73,74]. An analysis was conducted to assess the health risks associated with consuming fish. This was carried out by estimating the amount of metal exposure weekly and comparing it to the acceptable limits according to the PTWI standards. The PTWI is a calculated quantity of a chemical present in food or water that may be consumed weekly without causing any harm to health. It is expressed in mg/kg of body weight [72].

Hence, computations were conducted to ascertain the number of fish from this study that exceeded the PTWI limits. The JECFA calculated the PTWI for Cu to be $3.50 \text{ mg}/\text{kg}$ body weight per week based on its initial maximum tolerated daily intake of $0.50 \text{ mg}/\text{kg}$ body weight per day. The Cu PTWI for a 62 kg adult is 217 mg/week . The estimated weekly intake (EWI) of fish constituents is used to assess the level of exposure risk. The value of EWI equals EDI times 7.

The EWI is calculated by applying Equation (1) and then multiplied by seven to account for the seven-day week. By comparing the EWI to the established PTWI limits for a 62 kg adult, it may be determined whether the EWI is lower than the Cu level.

3. Results and Discussion

Based on a total of 119 individuals of 37 species (three species were unrecorded) of fish purchased from all different markets or sources from Malaysia, the total body wet weights ranged from 3.00–4.00 g (*Valumugil seheli*) to 245–315g (*Euthynnus affinis*) (Table S1). Based on a total of 113 individuals of 35 species of fish (five species were unrecorded) purchased from all different markets or sources from Malaysia, the maximum body lengths ranged from 14.7–16.4 cm (*Selaroides leptolepis*) to 80.0–93.0 cm (*Trichiurus lepturus*) (Table S1).

Carangidae (six species), Sciaenidae (three species), Stromateidae (one species), Clupeidae (one species), Chirocentridae (one species), Scrombidae (two species), Dasyatidae (one species), Nemipteridae (one species), Lactariidae (one species), Trichiuridae (one species), and Ariidae (one species) were among the 40 marine fish species analyzed. These families have specialized environments, including amphibious, demersal, potamodromous, anadromous, oceanodromous, catadromous, reef-associated, pelagic, neritic, tropical, and benthopelagic (Table S1).

3.1. Comparison of Cu Food Safety Recommendations and Reported Cu Amounts in Fish Species

In 40 fish species, Cu concentrations varied from 0.06–16.9 mg/kg ww (0.72–82.3 mg/kg dw) (Figure 1; Table 1). This Cu range exceeds the 0.29–1.80 mg/kg ww; 1.50–7.83 mg/kg dw were reported for the 19 Setiu commercial fish species from the east coast of the Malaysian Peninsular [29]. The present Cu range (0.06–16.9 mg/kg ww) was significantly below the MPLs proposed by FAO [66] of 20–70 mg/kg ww, MAFF (20 mg/kg ww) [67], and MFR (30 mg/kg ww) [68]. Thus, eating fish purchased from Malaysian does not pose a Cu danger. Similarly, even though the skin parts of some selected fish species have higher levels of Cu than those in the dorsal muscle, their levels are well below the three MPLs (Figure 2).

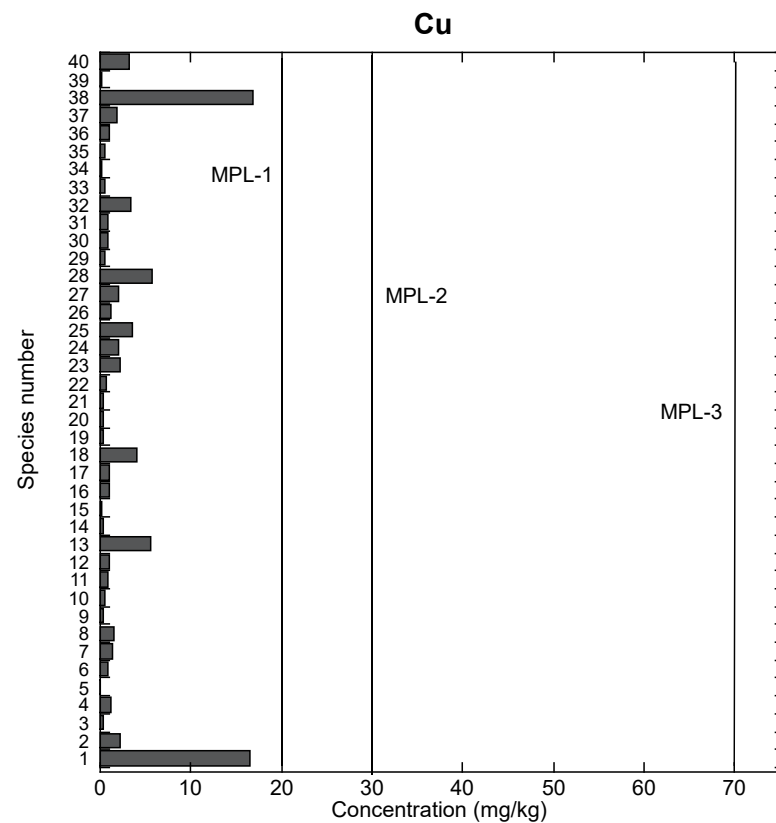


Figure 1. Mean concentrations (mean, mg/kg wet weight) of Cu in the dorsal muscles of 40 commercial marine fish purchased from Malaysia. Note: MPL = maximum permissible limit; MPL-1 = MAFF [67]; MPL-2 = MFR [68]; MPL-3 = FAO [66]. Note: 1 = *Abalistes stellaris*; 2 = *Alectis indicus*; 3 = *Alepes melanoptera*; 4 = *Anabas testudineus*; 5 = *Arius arius*; 6 = *Atule mate*; 7 = *Carangoides armatus*; 8 = *Decapterus macrosoma*; 9 = *Drepana punctata*; 10 = *Elagatis bipinnulata*; 11 = *Eleutheronema tetradactylum*; 12 = *Epinephelus tauvina*; 13 = *Escualosa thoracata*; 14 = *Euthynnus affinis*; 15 = *Lates calcarifer*; 16 = *Leptomelanosoma indicum*; 17 = *Megalaspis cordyla*; 18 = *Nemipterus tumbuloides*; 19 = *Parastromateus niger*; 20 = *Pennahia argentata*; 21 = *Plectorhinchus flavomaculatus*; 22 = *Pomadasys kakaan*; 23 = *Rastrelliger brancy soma*; 24 = *Rastrelliger kanagurta*; 25 = *Sardinella fimbriata*; 26 = *Scomberoides lysan*; 27 = *Scomberomorus commerson*; 28 = *Scomberomorus guttatus*; 29 = *Selar boops*; 30 = *Selar crumenophthalmus*; 31 = *Selaroides leptolepis*; 32 = *Siganus javus*; 33 = *Sphyaera putnamae*; 34 = *Sphyaera obtusata*; 35 = *Tenualosa toli*; 36 = *Thunnus tonggol*; 37 = *Trichiurus lepturus*; 38 = *Tylosurus crocodilus*; 39 = *Upeneus sulphureus*; 40 = *Valumugil seheli*.

Table 1. Overall statistics of Cu concentrations (mg/kg wet weight), estimated daily intake (EDI), target hazard quotient (THQ), and estimated weekly intake (EWI) in the 40 commercial marine fish species purchased from Malaysia (N = 40).

	DW	WW	EDI	High EDI	THQ	High THQ	EWI	High EWI	PTWI%	High PTWI%
Minimum	0.72	0.06	0.10	0.20	0.00	0.01	0.70	1.41	0.00	0.00
Maximum	82.3	16.9	27.3	54.6	0.68	1.37	191	382	0.09	0.18
Mean	10.2	2.17	3.50	6.89	0.09	0.17	24.1	48.2	0.01	0.02
Median	4.66	0.98	1.58	2.57	0.04	0.07	9.01	18.0	0.00	0.01
SD	17.7	3.65	5.89	11.82	0.15	0.29	41.4	82.8	0.02	0.04
Variance	313	13.3	34.7	139	0.02	0.09	1712	6848	0.00	0.00
SE	2.80	0.58	0.93	1.87	0.02	0.05	6.54	13.1	0.00	0.01
Skewness	3.36	3.26	3.26	3.25	3.25	3.25	3.25	3.25	3.25	3.25
Kurtosis	10.7	10.3	10.3	10.2	10.2	10.2	10.2	10.2	10.2	10.2

Note: SD = standard deviation; SE = standard error.

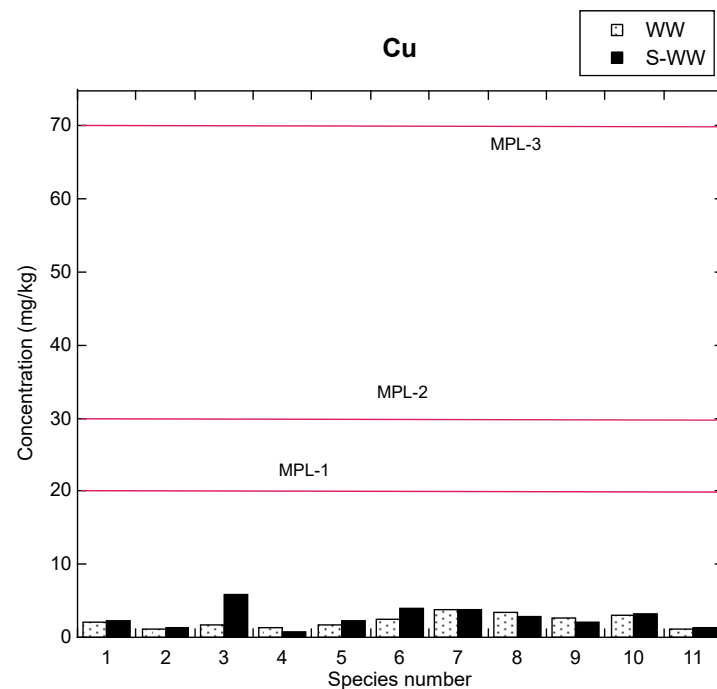


Figure 2. Mean concentrations (mean, mg/kg wet weight) of Cu in the dorsal muscles and skins of 10 commercial marine fish purchased from Malaysia. Note: MPL = maximum permissible limit; MPL-1 = MAFF [67]; MPL-2 = MFR [68]; MPL-3 = FAO [66]. Note: 1 = *Drepana punctata*; 2 = *Elagatis bipinnulata*; 3 = *Selar crumenophthalmus*; 4 = *Eleutheronema tetradactylum*; 5 = *Pomadasys kakaan*; 6 = *Megalaspis cordyla*; 7 = *Trichiurus lepturus*; 8 = *Siganus javus*; 9 = *Leptomelanosoma indicum*; 10 = *Scomberoides lysan*; 11 = *Tenualosa toli*.

3.2. Comparison to Reported Studies

Marine fish Cu concentrations from 99 studies (28 citations) are presented in Table S4. The lowest and highest Cu concentrations among 40 fish species were found in *Arius arius* (0.06 mg/kg ww) and *Tylosurus crocodilus* (16.9 mg/kg ww). Yap and Al-Mutairi [29] found the highest and lowest Cu concentrations in *Atule mate* (1.80 mg/kg ww) and *Pampus chinensis* (0.29 mg/kg ww) among 19 Setiu commercial fish. Table S3 and Figure 1 reveal that 40 commercial marine fish species exhibit Cu ranges of 0.06–16.9 mg/kg ww, like 99 reports from 24 citations (Tables 2 and S4). In 46 marine fish from selected main fish landing ports of the Fisheries Development Authority of Malaysia and wholesale markets in the Peninsular of Malaysia, Wan Azmi et al. [58] discovered that *M. cordyla* had the highest Cu content (1.61 mg/kg ww) and *Otolithoides biauritus* the lowest (0.039 mg/kg).

Table 2. Overall statistics of Cu concentrations (mg/kg wet weight) (WW) with recalculation of estimated daily intake (EDI), target hazard quotient (THQ), and estimated weekly intake (EWI) in the 24 marine fish species cited from the literature (99 reports of 24papers) (N = 99).

	DW	WW	EDI	High EDI	THQ	High THQ	EWI	High EWI	PTWI%	High PTWI%
Minimum	0.05	0.01	0.01	0.03	0.00	0.00	0.10	0.20	0.00	0.00
Maximum	42.8	11.2	18.1	36.1	0.45	0.90	126	253	0.06	0.12
Mean	4.24	0.94	1.51	3.02	0.04	0.08	10.6	21.2	0.00	0.01
Median	2.50	0.58	0.94	1.87	0.02	0.05	6.55	13.1	0.00	0.01
SD	5.45	1.33	2.15	4.30	0.05	0.11	15.05	30.1	0.01	0.01
Variance	29.7	1.78	4.62	18.5	0.00	0.01	226	906	0.00	0.00
SE	0.55	0.13	0.22	0.43	0.01	0.01	1.51	3.03	0.00	0.00
Skewness	4.42	5.35	5.35	5.36	5.36	5.36	5.36	5.36	5.36	5.36
Kurtosis	25.5	35.5	35.5	35.6	35.6	35.6	35.6	35.6	35.6	35.6

Note: SD = standard deviation; SE = standard error.

Yap and Al-Mutairi [29] observed that *A. mate* contained the most Cu (1.80 mg/kg ww), followed by *Decapterus macrosoma*, *Rastrelliger kanagurta*, *M. cordyla*, and others. Figure 1 and Table S3 show that *A. mate*'s Cu level (0.81 mg/kg ww) was reported on within the three literature studies (1.53 mg/kg ww) (0.82–1.90 mg/kg ww) (Table S4). *D. macrosoma* contains 1.53 mg/kg ww Cu, consistent with five investigations (0.70–11.20 mg/kg ww) (Table S4). *D. macrosoma* had a higher Cu content than Yap and Al-Mutairi [29] (1.42 mg/kg ww) but lower than Kuala Terengganu (11.2 mg/kg ww) (Table S4). *R. kanagurta* possesses 2.08 mg/kg ww Cu, similar to 16 investigations (0.27–3.30 mg/kg ww) (Table S4). *R. kanagurta* contains 1.45 mg/kg ww more Cu than Yap and Al-Mutairi [29]. Compared to Mersing (east coast of Peninsular Malaysia), Indonesia, Thailand, Saint Martin Island, Andaman Sea, Peninsular Malaysia, Port Dickson, Pahang coastal waters, Co-chin coast, Palk Bay, Kochi coast, Langkawi Island, and Kunduchi fish market in Dar es Salaam, Cu levels were higher.

The present Cu level in *M. cordyla* (0.95 mg/kg ww) matches 19 studies (1.40–25.7 mg/kg ww) (Table S4), including Yap and Al-Mutairi [29]'s (1.03 mg/kg ww). The Cu level was higher than Langkawi, Port Dickson, Kelantan, Cambodia, Thailand, Kuala Kedah, Pahang coastal waters, Mersing, and Cochin coast. It was below Tanjung Sepat (Selangor), Peninsular Malaysia marine fish, and the west coast. Nurnadia et al. [75] found 1.56 mg/kg ww of Cu in *M. cordyla*, more than the previous study (0.95 mg/kg ww).

S. leptolepis possesses 0.97 mg/kg ww Cu, which is comparable with five investigations (0.05–1.41 mg/kg ww) (Table S4), including Setiu's 0.89 mg/kg [29]. *S. leptolepis* had more Cu than Peninsular Malaysian marine fish, Port Dickson, and Pahang coastal waters but less than the West coast. This was below Nurnadia et al.'s 1.41 mg/kg ww [75]. Table S4 shows that *S. commerson*'s Cu level (2.02 mg/kg ww) matches that of six literature studies (0.30–2.90 mg/kg ww). Cu levels exceeded those of Setiu (0.43 mg/kg ww), Koh Kong (Cambodia), Marine fish Peninsular Malaysia, and Zhongsha. *T. lepturus* had 1.78 mg/kg ww Cu in four literature investigations (0.46–1.98 mg/kg ww) (Table S4). The Cu level was greater than Setiu [29], Kutubdia Island, and Mumbai Harbor (India) (0.66 mg/kg ww).

The Cu ranges (0.06–16.9 mg/kg ww) of 40 commercial marine fish species (Table S3; Figure 1) were mostly consistent and greater than reported values. Celik and Oehlen-schläger [76] discovered Cu concentrations of 0.12 to 1.14 mg/kg ww in 49 eastern Mediterranean Sea commercial fish species (Izmir Outer Bay, Homa Lagoon/Izmir, and Mersin Bay). Simanjuntak et al. [77] detected 0.09–0.35 mg/kg ww Cu in eight North Sumatra marine species. Tuzen [78] found 0.65–2.78 mg/kg ww Cu in eleven Black Sea fish species. El-Moselhy et al. [19] reported Cu in fourteen benthic and pelagic fish species from three key Red Sea landing sites (Shalateen, Hurghada, and Suez) at 0.17 to 0.77 mg/g ww. Blevins and Pancorbo [79] observed that 17 species from nine sites had muscle Cu levels of 0.12 to 2.20 mg/kg ww after five years in different surface water systems in eastern Tennessee.

Ong et al. [16] observed five Setiu marine species with Cu levels of 0.69–3.04 mg/kg dw, while Yap and Al-Mutairi [29] recorded 19 species with 1.50–7.83 mg/kg dw. Fish muscle Cu in Malaysian coastal waters was 0.86–3.48 mg/kg dw [54]. Rejomon et al. [80] found that *Caranx melampygus* had the greatest Cu levels in its muscle tissues off Mangalore and Kochi. Seven marine fish species from the Miri coast had Cu concentrations in their muscles between 8.50 and 13.3 mg/kg dw [81], which was higher than those from the Mediterranean Sea (3.40–5.88 mg/kg dw) [82], Mumbai Harbor (0.87 to 6.51 mg/kg dw) [27], the Turkish Sea (0.16–10.7 mg/kg dw) [83], the Palk Bay of India (0.90–8.68 mg/kg dw) [84], and Langkawi Island, Malaysia (11.5–13.9 mg/kg dw; [57]). Similar findings were reported by Prasath and Khan [85]. Jahangir Sarker et al. [38] detected 4.63–73.6 mg/kg dw Cu in Bangladeshi Meghna River estuary fish. Nine Turkish Black and Aegean Sea fish showed Cu levels of 0.73–1.83 mg/kg dw [46]. According to Dural Eken et al. [86], three marine fish species from Turkey's Tuzla Lagoon had Cu concentrations of 0.26–0.82 mg/kg dw. Off Newfoundland, Hellou et al. [87] detected 1.00 mg/kg dw Cu in northwest Atlantic bluefin tuna muscle tissue. The researchers discovered <1.2–1.5 mg/kg dw Cu levels in Newfoundland cod muscle [87].

3.3. Cu Health Risk Assessment

Tables S3 and S4 provide Cu values for EDI, THQ, and EWI in marine fish from our research and published data. In Table 1 and Figure 3, Cu (mg/kg ww), EDI, THQ, and EWI are shown for 40 marine fish species. Table 2 indicates Cu concentrations (mg/kg ww) and the recalculation of EDI, THQ, and EWI in 28 marine fish species from 99 literature reports of 24 papers. EDI and THQ are comparable to Setiu fish values of 0.46–2.90 and Cu THQ of 0.01–0.07 [29] (Table S3).

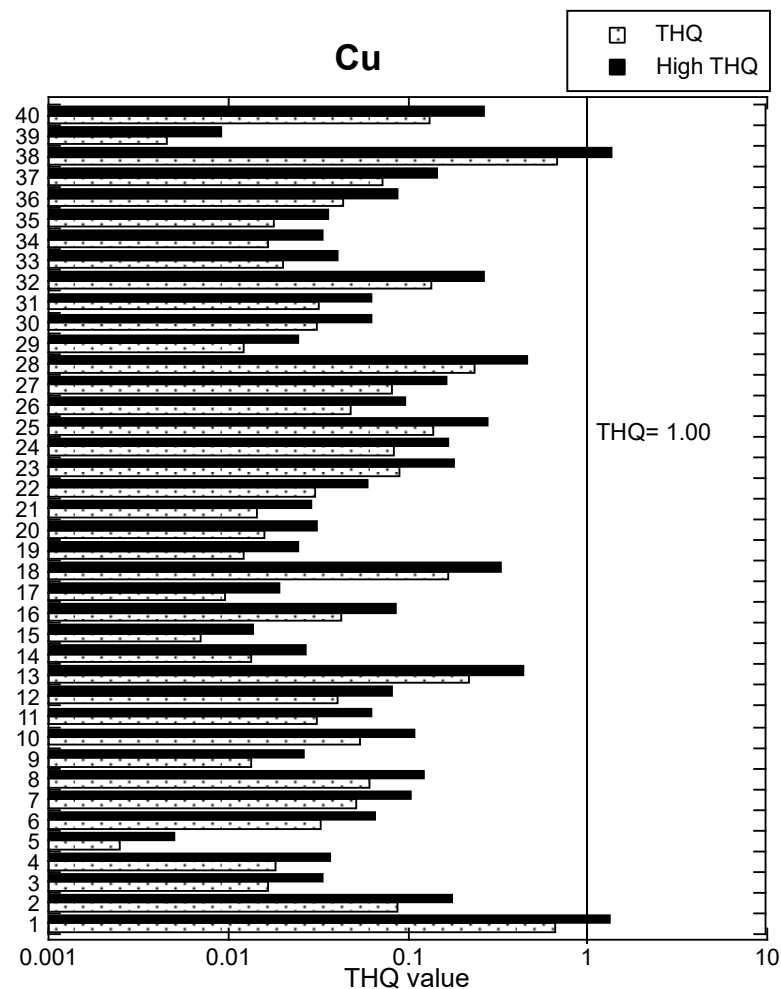


Figure 3. Target hazard quotient (THQ) values of Cu in 40 commercial marine fish purchased from Malaysia. Note: High THQ values indicate two times the consumption of the average consumption rate. Note: 1 = *Abalistes stellaris*; 2 = *Alectis indicus*; 3 = *Alepes melanoptera*; 4 = *Anabas testudineus*; 5 = *Arius arius*; 6 = *Atule mate*; 7 = *Carangoides armatus*; 8 = *Decapterus macrosoma*; 9 = *Drepana punctata*; 10 = *Elagatis bipinnulata*; 11 = *Eleutheronema tetradactylum*; 12 = *Epinephelus tauvina*; 13 = *Escualosa thoracata*; 14 = *Euthynnus affinis*; 15 = *Lates calcarifer*; 16 = *Leptomelanosoma indicum*; 17 = *Megalaspis cordyla*; 18 = *Nemipterus tumbuloides*; 19 = *Parastromateus niger*; 20 = *Pennahia argentata*; 21 = *Plectorhinchus flavomaculatus*; 22 = *Pomadasys kakaan*; 23 = *Rastrelliger brancysoma*; 24 = *Rastrelliger kanagurta*; 25 = *Sardinella fimbriata*; 26 = *Scomberoides lysan*; 27 = *Scomberomorus commerson*; 28 = *Scomberomorus guttatus*; 29 = *Selar boops*; 30 = *Selar crumenophthalmus*; 31 = *Selaroides leptolepis*; 32 = *Siganus javus*; 33 = *Sphyaera putnamae*; 34 = *Sphyaera obtusata*; 35 = *Tenualosa toli*; 36 = *Thunnus tonggol*; 37 = *Trichiurus lepturus*; 38 = *Tylosurus crocodilus*; 39 = *Upeneus sulphureus*; 40 = *Valamugil seheli*.

Cu THQ levels were below 1 in all 40 commercial fish species (Figure 3) and selected fish species' skin portions (Figure 4), indicating low non-carcinogenic risk and safe human intake. The absence of Cu health risks was also established. Consuming contaminated

seafood may raise Cu levels. In comparison to worldwide recommendations, this study found Cu concentration acceptable. Yabanli and Alparslan [88] also discovered lower EDIs. Adult Cu has an EDI of 0.07, and 12-year-olds 0.04. Yabanli and Alparslan [88] reported lower THQ in kids and adults. Children and adults had THQs below 1.00. Praveena and Lin [89] observed that marine fishes from Port Dickson (west coast of Peninsular Malaysia) had Cu THQ values below 1, suggesting no Cu adverse effects from eating.

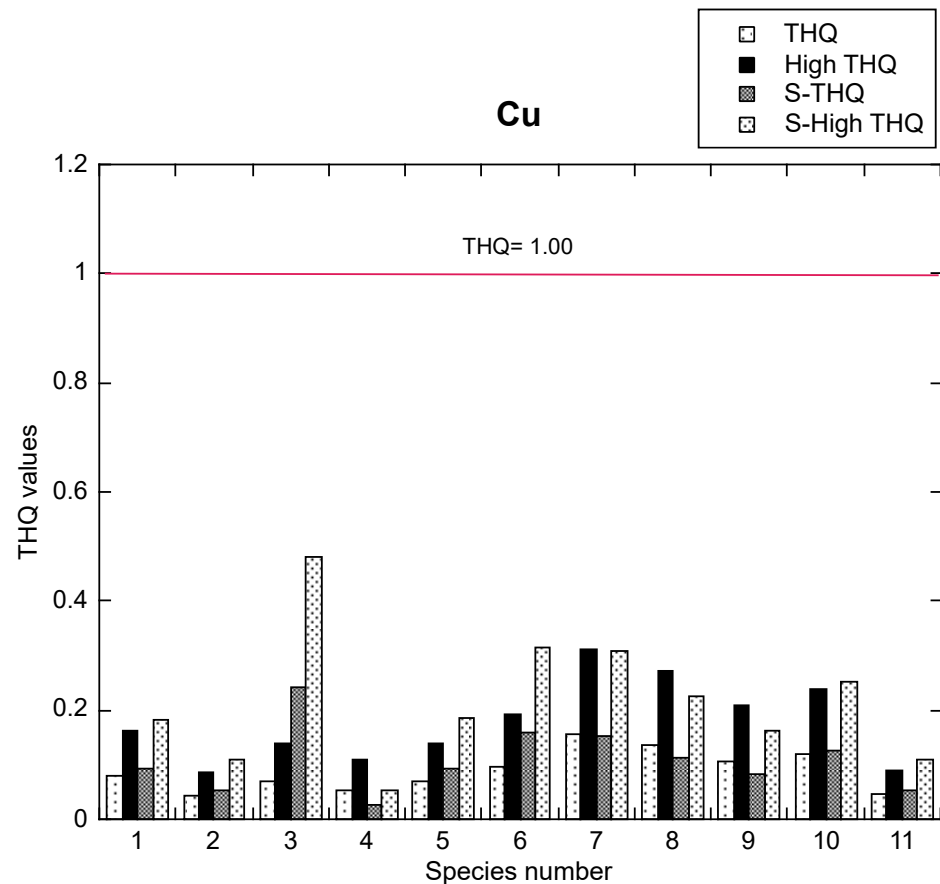


Figure 4. Target hazard quotient (THQ) values of Cu in the dorsal muscles and skins of 10 commercial marine fish purchased from Malaysia. Note: High THQ values indicate two times the consumption of the average consumption rate. Note: 1 = *Drepana punctata*; 2 = *Elagatis bipinnulata*; 3 = *Selar crumenophthalmus*; 4 = *Eleutheronema tetradactylum*; 5 = *Pomadasys kakaan*; 6 = *Megalaspis cordyla*; 7 = *Trichiurus lepturus*; 8 = *Siganus javus*; 9 = *Leptomelanosoma indicum*; 10 = *Scomberoides lysan*; 11 = *Tenualosa toli*.

According to Table 1 and Figure 5, Cu EWI ranged from 0.10 to 27.3 $\mu\text{g}/\text{kg BW}/\text{week}$, with *Arius arius* and *Tylosurus crocodilus* having the lowest and greatest concentrations. Figures 5 and 6 show reduced EWI in 40 fish species' dorsal muscles and 10 fish species' skin parts compared to the Cu (3500 $\mu\text{g}/\text{kg BW}/\text{week}$) determined PTWI. The FAO/WHO JECFA guideline states that eating fish does not cause Cu toxicity. Wan Azmi et al. [58] reported Cu EWI ranged from 0.69 to 27.65 ($\mu\text{g}/\text{kg BW}/\text{week}$) in 46 marine fish species from Peninsular Malaysia's coastal waters, using nine heavy metals. From 99 Cu data in marine fish, EWI ranged from 0.20 to 253 ($\mu\text{g}/\text{kg BW}/\text{week}$). In Bulgaria, Peycheva et al. [90] observed Cu EWI 0.48–1.28 g/kg BW/week.

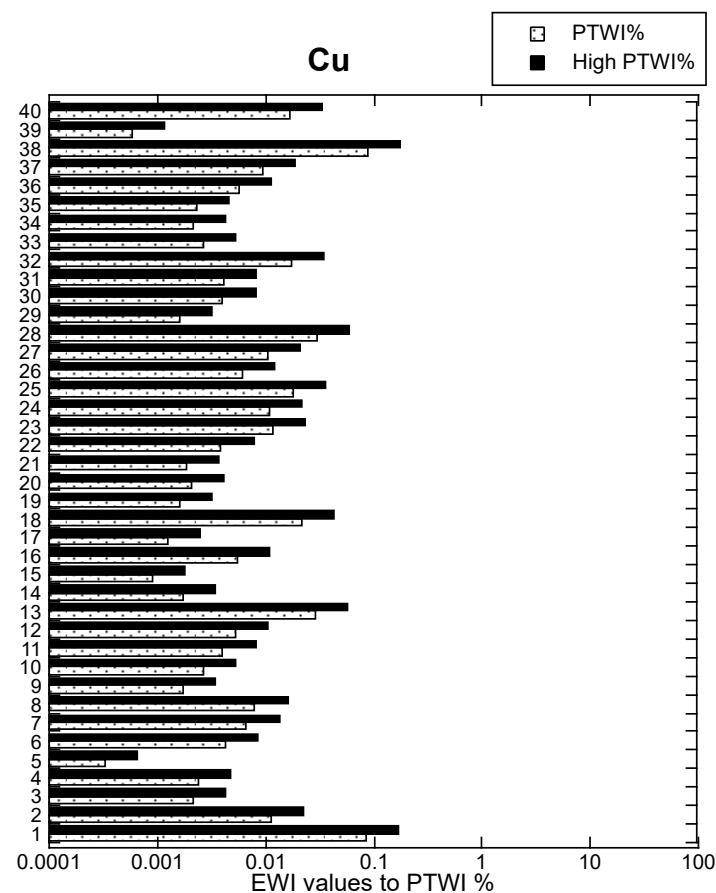


Figure 5. Percentages (%) of estimated weekly intake (EWI) to provisional tolerable weekly intake (PTWI) of Cu in 40 commercial marine fish purchased from Malaysia. Note: High PTWI values indicate two times the consumption of the average consumption rate. Note: 1 = *Abalistes stellaris*, 2 = *Alectis indicus*; 3 = *Alepes melanoptera*; 4 = *Anabas testudineus*; 5 = *Arius arius*; 6 = *Atule mate*; 7 = *Carangoides armatus*; 8 = *Decapterus macrosoma*; 9 = *Drepana punctata*; 10 = *Elagatis bipinnulata*; 11 = *Eleutheronema tetradactylum*; 12 = *Epinephelus tauvina*; 13 = *Escualosa thoracata*; 14 = *Euthynnus affinis*; 15 = *Lates calcarifer*; 16 = *Leptomelanosoma indicum*; 17 = *Megalaspis cordyla*; 18 = *Nemipterus tambuloides*; 19 = *Parastromateus niger*; 20 = *Pennahia argentata*; 21 = *Plectorhinchus flavomaculatus*; 22 = *Pomadasys kakaan*; 23 = *Rastrelliger brancysoma*; 24 = *Rastrelliger kanagurta*; 25 = *Sardinella fimbriata*; 26 = *Scomberoides lysan*; 27 = *Scomberomorus commerson*; 28 = *Scomberomorus guttatus*; 29 = *Selar boops*; 30 = *Selar crumenophthalmus*; 31 = *Selaroides leptolepis*; 32 = *Siganus javus*; 33 = *Sphyaera putnamae*; 34 = *Sphyaera obtusata*; 35 = *Tenuulosa toli*; 36 = *Thunnus tonggol*; 37 = *Trichiurus lepturus*; 38 = *Tylosurus crocodilus*; 39 = *Upeneus sulphureus*; 40 = *Valamugil seheli*.

Ates et al. [83] found Cu EDI and EWI values for Turkish adults' economically relevant fish consumption. These values were determined by assuming a 70 kg individual consumes 20 g fish/day or 140 g/week. Eight commercially relevant fish species from the Aegean and Mediterranean seas had EWI levels of 165–987 $\mu\text{g}/70 \text{ kg BW/week}$, well below the necessary PTWI values of 3500 $\mu\text{g}/\text{kg BW/week}$ and 245,000 $\mu\text{g}/70 \text{ kg BW/week}$ for 70 kg adults.

Adults take 0.9–2.2 mg Cu daily. Children are estimated to eat 0.6–0.8 mg/day (0.07–0.1 mg/kg BW/day) [4]. The lowest permitted oral consumption is 20 $\mu\text{g Cu/kg BW/day}$. In babies, this is 50 $\mu\text{g Cu/kg BW/day}$ [4]. Estimated daily human Cu intake is 1.0–1.3 mg (0.014–0.019 mg/kg) [2]. In the US, adults consume 0.93–1.3 mg Cu/day (0.013–0.019 mg Cu/kg BW/day using a 70 kg reference BW) [2].

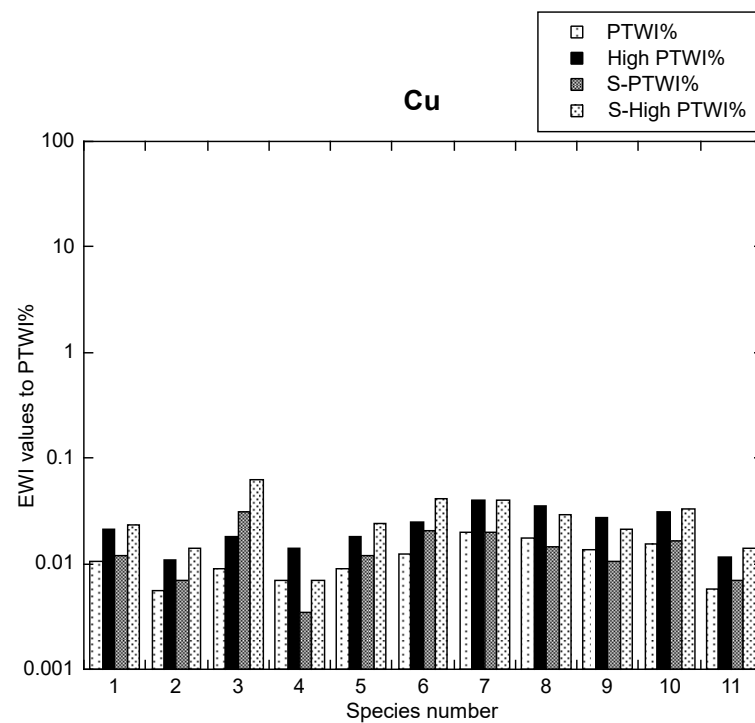


Figure 6. Percentages (%) of estimated weekly intake (EWI) to provisional tolerable weekly intake (PTWI) of Cu in the dorsal muscles and skins of 10 commercial marine fish purchased from Malaysia. Note: High THQ values indicate two times the consumption of the average consumption rate. Note: 1 = *Drepana punctata*; 2 = *Elagatis bipinnulata*; 3 = *Selar crumenophthalmus*; 4 = *Eleutheronema tetradactylum*; 5 = *Pomadasys kakaan*; 6 = *Megalaspis cordyla*; 7 = *Trichiurus lepturus*; 8 = *Siganus javus*; 9 = *Leptomelanosoma indicum*; 10 = *Scomberoides lysan*; 11 = *Tenualosa toli*.

3.4. Correlations of Cu Concentrations and Body Size of Fish

Figure 7 compares Cu concentrations to body lengths and wet weights in 36 Malaysian commercial marine fish species. Overall, Cu levels and body size (length and weight) are similar ($p > 0.05$). The literature suggests contradictory relationships [58,91–96]. Wan Azmi et al. [58] found no significant Cu–body length relationship in 46 marine fish species from Peninsular Malaysia’s coastal waters ($p > 0.05$). Bashir et al. [91] discovered a significant ($p < 0.05$) association between fish length, weight, and heavy metal levels.

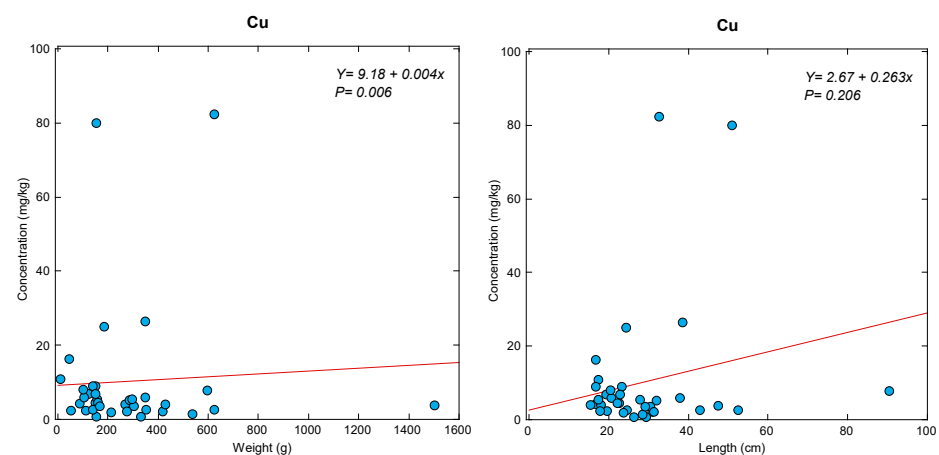


Figure 7. Relationships between Cu concentrations (mg/kg dry weight) and body lengths (g) (and body wet weight (g)) in the 36 species of commercial marine fish purchased from Malaysia.

Using linear regression, Yi and Zhang [97] evaluated the relationships between fish size (length and weight) and metal concentrations in seven Yangtze River fish species. Metal levels were associated favorably with most fish sizes except catfish and yellow-head catfish, which correlated negatively. Fish size (length and weight) and metal concentrations in six northeast Mediterranean Sea fish species' tissues were studied by Canli and Atli [98]. Only a few studies linked metal concentration to fish size.

3.5. Monitoring of Cu as an ESG Requirement to Safeguard Consumers' Health

Heavy metals in seafood are becoming more concerning owing to their potential to damage humans and the environment [99]. Preventing population contamination requires precise heavy metal monitoring and management in fish and water. Toxic metals in the food chain, especially in fish, pose a serious health risk. This entails using appropriate fishing and farming techniques to reduce harmful Cu in fish products [100].

In addition, industrial academia can cooperate with regulatory bodies and industry partners to develop protocols and benchmarks for the permissible concentrations of Cu in fish. Industries are now dedicated to adhering to environmental, social, and governance (ESG) principles, which motivates industries to actively address the concerns linked to heavy metal pollution in fish. Through proactive measures and responsible research innovation, the issue of Cu pollution in fish products can be addressed, guaranteeing our consumers' safety and welfare while safeguarding the aquatic ecosystem. It is essential to implement efficient ESG strategies to tackle the issue of Cu pollution in fish to safeguard human health and the environment.

Nevertheless, the implementation of ESG may encounter obstacles. The problems encompass the absence of standardized norms and standards about Cu levels in fish, the limited accessibility and high expenses associated with dependable testing methods, and the necessity for ongoing staff education and training to guarantee the appropriate execution of ESG practices. In order to surmount these obstacles, the industry is dedicated to being informed about the most recent legislation and recommendations about the amounts of Cu found in fish.

Research and development investments are necessary to enhance testing methodologies and guarantee their dependability. It is crucial to prioritize personnel training and education to foster a comprehensive comprehension of ESG practices and their significance in reducing Cu pollution. This approach can effectively address the obstacles and efficiently execute ESG strategies to mitigate heavy metal pollution in our fish products (Figure 8).

By implementing these measures, the firm may showcase its dedication to environmental sustainability and the ethical treatment of our customers. ESG practices are closely linked to the United Nations Sustainable Development Goals (UNSDGs). Using ESG (environmental, social, and governance) practices to mitigate heavy metal contamination in fish, we can significantly contribute to achieving several United Nations Sustainable Development Goals. These objectives encompass Goal 3: Ensuring good health and well-being, Goal 14: Preserving life below water, and Goal 17: Establishing partnerships for achieving the goals, among others. Incorporating ESG practices to tackle the Cu contamination in fish is consistent with the industry's dedication to environmental sustainability and the welfare of our customers.

Through the surveillance and mitigation of elevated concentrations of Cu in fish, the well-being and security of the customers are put at the forefront. This showcases the industries' commitment to ethical business practices. Hence, using ESG measures to mitigate heavy metal pollution in fish is imperative, as it is vital for safeguarding human well-being and ecological integrity. Ultimately, adopting ESG practices to tackle the issue of heavy metal pollution in fish is crucial for safeguarding human well-being and the environment and guaranteeing consumer safety and health.



Figure 8. The importance of Cu monitoring in commercial marine fish about environment, social, and governance (ESG) method.

4. Conclusions

Overall, Malaysian commercial marine fish Cu concentrations were below MPLs and THQs for all species were below 1. It showed no non-carcinogenic dangers of Cu for consumers. EWI values were similarly lower than Cu PTWI. Even though the population's EWI was lower than PTWI, excessive fish eating might harm health. More physiological and ecological study is needed to understand how fish species accumulate Cu. A continuous monitoring programme should be conducted to determine local fish species consumption rates using a validated questionnaire. This information is vital for predicting the likelihood of non-carcinogenic/chronic systemic Cu effects after ingesting each species. To guarantee safe fish eating, Cu contamination of commercial marine fish species should be evaluated routinely.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/pollutants4010008/s1>, Figure S1: The purchase sites for 40 species of fish. Some sites were not shown due to similar purchase locations and distance settings. The sites were plotted via QGIS software, Table S1: Purchased commercial fish from different purchase sites and dates, Table S2: Description of the purchased commercial fish, biometric features, water content and conversion factors of dorsal parts of the fish samples, Table S3: Values of estimated daily intake (EDI) (mg/kg bw), target hazard quotient (THQ), and estimated weekly intake (EWI; mg/kg bw) to the provisional tolerable weekly intake (PTWI; mg/kg bw) of Cu in fish (n = 40) from the present study, Table S4: Values of estimated daily intake (EDI) (mg/kg bw), target hazard quotient (THQ), and estimated weekly intake (EWI; mg/kg bw) to the provisional tolerable weekly intake (PTWI; mg/kg bw) of Cu in fish (N = 99), based on Cu cited data in the literature, Table S5: Values of high estimated daily intake (EDI) (mg/kg bw), high target hazard quotient (THQ), and high estimated weekly intake (EWI) (mg/kg bw) to provisional tolerable weekly intake (PTWI) and high PTWI of Cu in selected fish species from the present study.

Author Contributions: Conceptualization, C.K.Y.; methodology, C.K.Y. and T.Y.A.H.; software, W.M.S.; validation, C.K.Y., R.N. and M.C.O.; formal analysis, C.K.Y. and T.Y.A.H.; investigation, C.K.Y., T.Y.A.H., W.M.S. and H.O.; resources, H.O., M.C.O. and Y.H.; data curation, T.Y.A.H., M.S.I., H.M.H.Z. and K.K.; writing—original draft preparation, C.K.Y. and T.Y.A.H.; writing—review and editing, R.N., M.C.O., M.S.I., K.K., H.M.H.Z. and W.H.C.; visualization, K.K. and M.C.O.; supervision, C.K.Y.; project administration, C.K.Y. and H.O.; funding acquisition, C.K.Y. All authors have read and agreed to the published version of the manuscript.

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