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Pesticide Residue Contamination Levels in Four Fish Species from the Déganobo Lacustrine System (San-Pédro, Côte d'Ivoire)

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Abstract

The study aimed to assess the contamination of four fish species (*Heterotis niloticus*, *Oreochromis niloticus*, *Parachanna obscura*, and *Sarotherodon melanotheron*) by 24 pesticide residues. A total of 120 samples, with 30 samples per species, were collected from August 2021 to July 2022. Pesticide residue analysis was performed on fish muscle using the QuEChERS extraction method. This was followed by quantification of the purified extract using GC-MS, based on the MA. 403-Pest 3.1 standard with minor modifications. Ecotoxicity risks for the four species were evaluated using the bioaccumulation factor (BAF), while human health risks were assessed for adults and children using the hazard index (HI) and short-term carcinogenic risk index (CR_0). Metribuzin exhibited the highest concentrations in the muscle of all four fish species, whereas chlortoluron, imidacloprid, and terbutryn showed the lowest. Bioaccumulation of aldicarb, atrazine, metribuzin, and terbutryn in fish muscle was significant (BAF > 1), indicating substantial ecotoxicological risks to these fish. Regarding human health risks from consuming fish, significant risks were observed only for children, particularly due to the high concentration of chlorfenvinphos in *Parachanna obscura* muscle (HI = 1.0 ± 0.1) and the total detected residues (ΣHI = 1.1 ± 0.1). However, short-term carcinogenic risks were found to be low for humans ($10^{-6} < CR_0$ (ΣCR_0) $\leq 10^{-4}$).

Keywords

Côte d'Ivoire, Fish, Health Risks, Pesticide Pollution, Pesticide Residues

1. Introduction

Pesticides, due to their high lipophilicity, capacity for bioaccumulation, long half-lives, and potential for long-distance transport, pose a heightened risk of contamination to aquatic ecosystems and their biota. Among the species particularly vulnerable to this type of pollution are fish [1] [2]. Fish contamination by pollutants occurs through dermal, respiratory (via gills), and oral pathways [3] [4]. These taxa have the ability to accumulate pollutants in their tissues, reaching concentrations that exceed those in the surrounding environment [5]. This accumulation takes place through absorption across the surface of the gills, as well as the walls of the kidneys, liver, and intestines. Consequently, the level of fish contamination generally reflects the contamination levels of the sediments and waters from which they originate, as well as their exposure time [6] [7]. Contamination levels vary by species and environment. According to Lazartigues [3], dermal contamination of freshwater fish by organic pollutants is low (<5%). Furthermore, Egila *et al.* [8] noted that pollutant accumulation in fish can be passive or selective. Therefore, differences in contamination among species can result from variations in assimilation, ingestion, or both. Contamination through the ingestion of benthos is also significant, given the high concentrations of these pollutants often found in sediments. In the specific case of pesticide residues, the addition of adjuvants or co-formulants to active ingredients to enhance their activity and adsorption onto various target surfaces [9] also contributes to their higher concentration in sediments compared to the water column [7].

The bioaccumulation of organic pollutant residues in fish is dependent on their log Kow. The assimilation of compounds with a log Kow less than 1 is slow and weak. For those with a log Kow between 1 and 3, contaminant assimilation via gill extraction appears to increase with log Kow, occurring through passive diffusion across the membrane. For compounds with a log Kow between 3 and 6, a plateau is observed at approximately 60% assimilation, with the rate dependent on the ventilation rate [3]. The acute toxicity of certain pesticide residues can be lethal, depending on the susceptibility of the exposed biota. The piscivorous and insectivorous dietary habits of fish place them in a toxicologically vulnerable position within the food chain, as they are often the ultimate recipients of pesticide residues [1]. Fish can accumulate substantial quantities of these residues, which in turn can be harmful to humans. Both carcinogenic and genotoxic effects can be observed. Additionally, chronic toxicity can result in a range of health issues, including cancer, brain damage in children, compromised cognitive performance, nephrotoxicity, and congenital malformations [10].

The Déganobo lacustrine system, a notable tourist attraction in the city of

San-Pédro, hosts remarkable biodiversity but faces significant anthropogenic pressures on its catchment area. One of the consequences is the considerable pollution of its waters by pesticide residues, as recently highlighted by the work of Konan and Yao [11] [12]. This situation is all the more concerning as the fish from this lacustrine system are exposed to these chemical compounds. These fish are caught by local populations either for their own consumption or for sale in local markets. Consequently, the health risks to these species and to humans are high. Therefore, there is an urgent need to investigate the level of pesticide residue contamination in the fish of this lacustrine ecosystem and to assess the short-term health risks to humans. It is within this context that this study was conducted. Its primary objective is to assess the level of contamination by 24 pesticide residues in the muscle tissue of four fish species inhabiting this aquatic ecosystem: *Heterotis niloticus* (Cuvier, 1829), *Oreochromis niloticus* (Linnaeus, 1758), *Parachanna obscura* (Günther, 1861), and *Sarotherodon melanotheron* (Rüppell, 1852). The secondary objectives are to assess the health risks of these pesticides for these fish and for two human population groups (children and adults).

2. Materials and Methods

2.1. Presentation of the Study Area

The Déganobo lake system is located in downtown San-Pédro. It comprises two lakes: Lac Ouest and Lac Est. Lac Ouest is the larger of the two, extending between western longitudes 6.637115 and 6.544196 and northern latitudes 4.748951 and 4.755580, with a water surface area of 28.87 hectares. In contrast, Lac Est extends between western longitudes 6.628952 and 6.639512 and northern latitudes 4.749382 and 4.760087 [12] (**Figure 1**).

The hydroclimatic regime of the study area is subequatorial, characterized by two warm seasons (the major hot season (GHS) from December to April and the minor hot season (SHS) from August to September) and two rainy seasons (the major rainy season (GRS) from May to July and the minor rainy season (SRS) from October to November) [11]. Human activities in this ecosystem's catchment area are primarily agricultural, with intensive use of chemical inputs that partially diffuse into the lake system. Additionally, the system receives extensive industrial discharges from two nearby major industrial zones, as well as those from the general hospital and the majority of anthropogenic discharges from the surrounding urban areas. This significant anthropogenic pressure results in visible hypereutrophication [13]. Another consequence is the substantial pollution of its waters by pesticide residues. Indeed, Konan and Yao [11] observed high concentrations of herbicide residues, particularly simazine, in all seasons. Konan and Yao [12] also reported elevated levels of insecticide and dicarboximide fungicide residues, such as aldicarb, bifenthrin, chlorfenvinphos, imidacloprid, methyl parathion, ethyl parathion, and vinclozolin, throughout their study period.

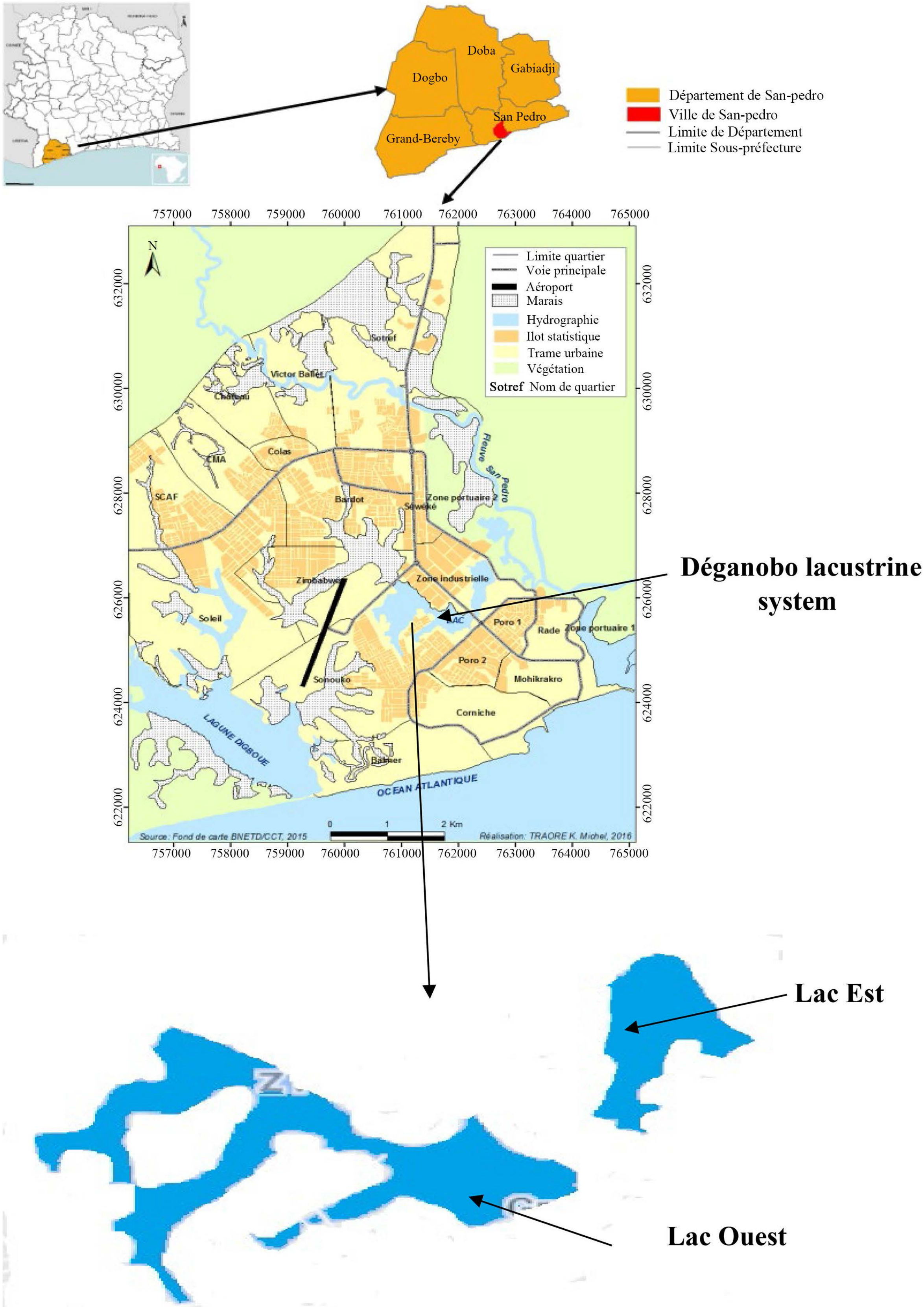

Figure 1. Location of the Deganobo lacustrine system within the city of San-Pédro [12].

2.2. Experimental Techniques

2.2.1. Sample Collection, *In-Situ* Preservation, and Laboratory Storage

This study focused on four fish species: *Heterotis niloticus*, *Oreochromis niloticus*, *Parachanna obscura*, and *Sarotherodon melanotheron*. From August 2021 to July 2022, a total of 120 samples were collected from local fishermen on the lake system, with 30 samples taken for each species.

Immediately after collection, the samples were wrapped in aluminium foil, placed in a polyethylene bag, and stored in a cooler with a significant amount of ice to maintain a temperature of approximately 4˚C, in accordance with the guidelines of Danladi and Akoto [14]. Upon arrival at the laboratory, the fish samples were transferred to a freezer for long-term storage at −6˚C.

2.2.2. Determination of the Concentrations of 24 Pesticide Residues in Fish Muscle Samples

Twenty-four pesticide residues were investigated in the fish samples due to their intensive use in the catchment area of this aquatic ecosystem. These residues are:

- Fourteen herbicides: nine from the triazine family (atrazine (ATZ), cyanazin (CNZ), desethylatrazin (DEA), deisopropylatrazine (DIA), metribuzin (MTZ), propazine (PPZ), terbutryne (TBT), terbuthylazine (TBTL), and simazine (SIZ)), and five from the substituted urea family (buturon (BTR), chlortoluron (CTL), diuron (DRN), fenuron (FEN), and monuron (MNR));
- Nine insecticides: three from the organophosphorus family (chlorfenvinphos (CVP), ethyl parathion (PTE), and methyl parathion (PTM)), two from the carbamate family (aldicarb (ADC) and chloropropham (CPP)), two from the synthetic pyrethroid family (bifenthrin (BFT) and deltamethrin (DMT)), and two from the neonicotinoid family (acetamiprid (AMP) and imidacloprid (IMD));
- One dicarboxamide fungicide: vinclozolin (VCZ).

The determination of pesticide residues in the muscle of the fish samples was performed using the QuEChERS extraction method [15], a technique commonly used for pesticide residue analysis in food due to its simplicity and cost-effectiveness [16] [17]. The procedure involved extracting pesticide residues from the fish muscle with acetonitrile. The organic phase was then separated by salting-out, which was achieved through agitation and centrifugation after the addition of sodium chloride, magnesium sulfate, and a buffer salt (sodium citrate/disodium hydrogen citrate). The crude organic phase was subsequently purified with magnesium sulfate in the presence of Primary and Secondary Amine (PSA) and graphite carbon to remove water and other undesirable substances. After agitation, centrifugation, drying under an argon stream, and reconstitution with isooctane, the purified extract was analyzed by GC-MS.

A standard solution (GB 23200.121-2021 Pesticide Mixture Kit 1, code DRE-K50000720), certified by Dr. Ehrenstorfer Laboratories (GmbH Germany) and of analytical purity, was used to prepare the extraction, control, quantification, injection, and calibration solutions. All other reagents used were also of analytical grade. Experiments were conducted in triplicate to assess the precision of the method.

1) Extraction and Purification

Ten grams of fish muscle were placed in a centrifuge tube and spiked with 10 mL of pure acetonitrile and 100 μL of a control standard solution (an acetonitrile-based solution with a concentration of 200 ng/mL, equivalent to 0.2 μg/g). The mixture was vigorously shaken for 1 minute. Subsequently, 1 g of sodium chloride, 4 g of magnesium sulfate, and a buffer salt (1 g of sodium citrate/0.5 g of disodium hydrogen citrate) were added. After a second vigorous shaking for 1 minute, the resulting solution was centrifuged at 5000 rpm for 5 minutes. The organic phase was collected in a separate centrifuge tube. The remaining residue was then rinsed with an additional 10 mL of acetonitrile under the same conditions, and the supernatant was combined with the first extract to obtain the crude extract.

For purification, 2 mL of the crude extract was transferred to a new centrifuge tube. After adding 150 mg of magnesium sulfate, 50 mg of PSA, and 50 mg of graphite carbon, the mixture was vigorously shaken for 1 minute, followed by centrifugation at 10,000 rpm. The resulting extract was dried under an argon stream, and the residue was reconstituted in 1 mL of isooctane to yield the purified extract. A blank sample, consisting of 10 mL of pure water and omitting the addition of standard solutions, was prepared and processed under the same conditions.

2) Quantification

For quantification and control, a series of standard solutions were prepared by mixing the following components: 250 μL of a calibration solution (containing all target pesticides in pure isooctane at varying concentrations of 10, 50, 100, and 200 ng/mL); 50 μL of an extraction standard solution; 50 μL of an injection standard solution; and 150 μL of pure isooctane.

The purified extract and the blank were then reconstituted in 15 μL of an injection standard solution (containing all target pesticides in pure isooctane at two concentrations: 100 ng/mL for some compounds and 600 ng/mL for others). Finally, these reconstituted solutions were transferred to glass conical vials for analysis by GC-MS.

The quantification of pesticide residues was performed using a Shimadzu GC-MS system (Japan). High-purity helium (99.999%) served as the carrier gas, with the flow rate maintained at 1 mL/min. The injection volume was 1 μL. The GC oven temperature program began with an initial hold at 70˚C for 2 minutes. The temperature was then ramped at a rate of 20˚C/min to a final temperature of 320˚C, which was held for 5 minutes. Both the injector and ion source temperatures were maintained at 250˚C. The injector operated in "splitless" mode for 2 minutes, followed by "split" mode with a 50:1 ratio. The electron energy was set to 70 eV, and the transfer line temperature was 250˚C. Pesticide residue concentrations were determined by comparing the peak areas of the purified extracts with those of the standards. The concentrations were then normalized to the initial sample mass.

3) Control Quality

The quality control procedures for the analysis followed the methodology described by Konan and Yao [11] [12]. The determined Limits of Detection (LOD), Limits of Quantification (LOQ), and recovery percentage (R) for these chemical compounds were identical to those previously reported by the same authors, namely:

ATZ (LOD = 0.02 ng/L, LOQ = 0.5 ng/L, R = 83.6%); CNZ (LOD = 0.05 ng/L, LOQ = 0.5 ng/L, R = 101%); DEA (LOD = 0.03 ng/L, LOQ = 0.4 ng/L, R = 93.8%); DIA (LOD = 0.03 ng/L, LOQ = 0.4 ng/L, R = 88.6%); MTZ (LOD = 0.02 ng/L, LOQ = 0.5 ng/L, R = 95.3%); PPZ (LOD = 0.03 ng/L, LOQ = 0.4 ng/L, R = 99.4%); TBT (LOD = 0.03 ng/L, LOQ = 0.4 ng/L, R = 108%); TBTL (LOD= 0.03 ng/L, LOQ = 0.5 ng/L, R = 118.2%); SIZ (LOD = 0.02 ng/L, LOQ = 0.4 ng/L, R = 118%); BTR (LOD = 0.18 ng/L, LOQ = 1.5 ng/L, R = 100.5%); CTL (LOD = 0.13 ng/L, LOQ = 1.0, R = 90.7%); DRN (LOD = 0.28 ng/L, LOQ = 2.5 ng/L, R = 94.8%); FEN (LOD = 0.02 ng/L, LOQ = 0.9 ng/L, R = 113.7%); MNR (LOD = 0.06 ng/L, LOQ = 0.9 ng/L, R = 95%); CVP (LOD = 0.05 ng/L, LOQ = 0.7 ng/L, R = 119.5%); PTE (LOD = 0.02 ng/L, LOQ = 0.8 ng/L, R = 92.8%); PTM (LOD = 0.03 ng/L, LOQ = 0.4 ng/L, R = 99.6%); ADC (LOD = 0.05 ng/L, LOQ = 0.7 ng/L, R = 96.3%); CPP (LOD = 0.03 ng/L, LOQ = 0.5 ng/L, R = 91.9%); BFT (LOD = 0.04 ng/L, LOQ = 1.5 ng/L, R = 97.9%); DMT (LOD = 0.08 ng/L, LOQ = 1.0 ng/L; R = 100%); AMP (LOD = 0.02 ng/L, LOQ = 0.5 ng/L, R = 102.5%); IMD (LOD = 0.06 ng/L, LOQ = 0.9 ng/L, R = 111%); and VCZ (LOD = 0.03 ng/L, LOQ = 0.5 ng/L, R = 118%).

2.2.3. Health Risk Assessment

Two approaches were adopted for the health risk assessment: the ecotoxicity of pesticide residues to the fish species, and the health risks to two population groups (children and adults) from the consumption of fish muscle tissue.

1) Fish Health Risks Assessment

The ecotoxicity of the detected pesticide residues to the four fish species was assessed using the bioaccumulation factor (BAF). This dimensionless index is commonly used to evaluate the ecotoxicity of pollutants in biota, as it compares the concentration of a pollutant in an organism relative to its concentration in the surrounding environment. In this study, the BAF was calculated using the following equation:

$$\text{BAF} = \frac{C_{\text{fish}}}{C_{\text{water}}} \tag{1}$$

where:

- C_{fish} is the concentration of the pesticide residue in the muscle of the target fish (in µg/L);
- C_{water} is the concentration of the pesticide residue in the water (in µg/L).

If the BAF is less than or equal to 1 (BAF ≤ 1), the ecotoxicity of the pesticide residue to the target fish is considered low. Conversely, if the BAF is greater than

1 (BAF > 1), the ecotoxicity is considered high for that taxon [18].

The seasonal mean concentrations of these 24 active substances in this lacustrine system waters, used for BAF calculation, were provided by Konan and Yao [11] [12] (**Table 1** and **Table 2**).

Table 1. Mean seasonal concentrations of herbicide residues in waters from Deganobo Lake System in the study period reported by Konan and Yao [11].

Seasons	DIA	DEA	SIZ	ATZ	PPZ	CNZ	TBT	TBTL	MTZ
SHS	0.407 ± 0.107	0.578 ± 0.013	23.323 ± 0.673	0.011 ± 0.003	0.706 ± 0.007	0.624 ± 0.034	0.012 ± 0.004	<LOD	0.216 ± 0.010
SRS	0.289 ± 0.053	0.524 ± 0.009	24.364 ± 0.201	0.026 ± 0.010	0.774 ± 0.040	0.673 ± 0.004	0.018 ± 0.015	<LOD	0.138 ± 0.009
GHS	0.563 ± 0.028	0.621 ± 0.015	29.912 ± 0.025	0.044 ± 0.005	0.904 ± 0.001	0.841 ± 0.006	0.037 ± 0.002	<LOD	0.196 ± 0.001
GRS	0.549 ± 0.056	0.605 ± 0.054	29.299 ± 3.965	0.045 ± 0.001	0.883 ± 0.008	0.822 ± 0.071	0.037 ± 0.002	<LOD	0.197 ± 0.019
Annual	0.452 ± 0.066	0.582 ± 0.048	26.725 ± 3.046	0.031 ± 0.011	0.817 ± 0.069	0.740 ± 0.070	0.026 ± 0.002	<LOD	0.187 ± 0.014

Table 2. Mean seasonal concentrations of insecticide residues in waters from Deganobo Lake System in the study period reported by Konan and Yao [12].

Seasons	ADC	AMP	BFT	CVP	DMT	IMD	PTM	PTE	VCZ
SHS	0.020 ± 0.011	<LOD	0.653 ± 0.016	0.798 ± 0.071	<LOD	0.024 ± 0.006	0.044 ± 0.004	1.433 ± 0.006	0.745 ± 0.060
SRS	0.018 ± 0.001	<LOD	0.552 ± 0.014	0.586 ± 0.005	<LOD	0.064 ± 0.052	0.046 ± 0.001	1.258 ± 0.033	0.721 ± 0.008
GHS	0.031 ± 0.003	<LOD	0.573 ± 0.026	0.676 ± 0.007	<LOD	0.138 ± 0.005	0.071 ± 0.002	1.359 ± 0.005	0.774 ± 0.037
GRS	0.031 ± 0.006	<LOD	0.556 ± 0.013	0.660 ± 0.055	<LOD	0.136 ± 0.007	0.069 ± 0.001	1.327 ± 0.028	0.754 ± 0.042
Annual	0.025 ± 0.006	<LOD	0.583 ± 0.043	0.680 ± 0.074	<LOD	0.090 ± 0.027	0.057 ± 0.005	1.344 ± 0.108	0.749 ± 0.076

2) Human Health Risk Assessment

To assess the human health risks associated with the consumption of fish muscle contaminated with certain pesticide residues, two metrics were employed: the Hazard Index (HI) and the Carcinogenic Risk Index (CR_0).

a) Hazard Index (HI)

The HI is used to estimate the toxicity of a pollutant to humans and, consequently, the potential for adverse health effects. This index is calculated by comparing the Estimated Daily Dose (EDD) of a pollutant to the Reference Dose (RfD) of that pollutant. The RfD, expressed in mg/(kg·day), is the daily dose at or below which adverse health effects are unlikely to occur.

The EDD can be expressed in various ways. The most common approach involves estimating the daily amount of a pollutant to which an individual is exposed through the ingestion of a contaminated organism, based on the individual's body weight, the daily ingestion rate of the organism, and the concentration of the pollutant within its tissue.

In this study, the EDD, expressed in mg/(kg·day), was calculated using the following formula:

$$\mathrm{DED} = \frac{\mathrm{C_{fish}} \times \mathrm{Tij_{individual}}}{\mathrm{m_{individual}}} \quad (2)$$

where:

- C_{fish} is the concentration of pesticide residues in the fish muscle (in μg/kg);
- Tij is the daily ingestion rate of fish muscle (in kg/day) for a given individual;
- $m_{individual}$ is the body weight of the individual (in kg) [14].

The HI is a dimensionless value calculated as follows:

$$HI = \frac{DED}{RfD} \quad (3)$$

When the HI is less than 1, the probability of adverse health risks to humans is considered low. Conversely, if the HI exceeds 1, the probability of health risks—whether carcinogenic or non-carcinogenic—is considered high. This interpretation also applies to the sum of the hazard indices (ΣHI) [14] [16].

For this study, two population groups were considered: children (aged 6 to 9 years) and adults. The body weights used were 42.6 kg for children and 65.9 kg for adults [19]. The daily ingestion rate (Tij) of fish muscle was 0.069 kg/day for both groups [20].

The RfD values (in mg/kg/day) for the pesticide residues used in the HI calculation were provided by the WHO [21] as follows: ADC (0.001), ATZ (0.05), BFT (0.015), CPP (0.2), CVP (0.0007), IMD (0.057), MTB (0.025), PTM (0.00025), SIZ (0.005), TBT (0.001), and VCZ (0.025).

b) Short-term Carcinogenic Risk Index (CR_0)

The CR_0 is used to assess the likelihood of developing cancer in humans following exposure to a pollutant through ingestion. This dimensionless index, as defined by the US-EPA [22], is calculated as follows:

$$CR_0 = DED \times SFO \quad (4)$$

with SFO, the Slope Factor Oral.

The CR_0 was assessed for ADC, ATZ, CPP, and SIZ, which are all likely to cause carcinogenic effects in humans. The SFO values for these chemical compounds, in units of $(mg/kg \cdot day)^{-1}$, are:

ADC (0.056), ATZ (0.23), CPP (0.024), and SIZ (0.12).

Based on these assessments, carcinogenic risks are classified according to the following scale:

negligible, $CR_0 \leq 10^{-6}$; low: $10^{-6} < CR_0 \leq 10^{-4}$; moderate, $10^{-4} < CR_0 \leq 10^{-3}$; high, $10^{-3} < CR_0 \leq 10^{-1}$; and very High: $CR_0 > 10^{-1}$ [23].

2.2.4. Statistical Analysis

In addition to descriptive statistics, including the mean (m), standard deviation (s), coefficient of variation (CV), minimum (Min), and maximum (Max), both univariate and multivariate analyses were performed. These analyses included a one-way ANOVA and Student's t-test.

A one-way ANOVA was used to determine if there were statistically significant differences between the mean concentrations of a pesticide residue in the muscle of different fish species. When a significant difference was observed, three post-hoc tests were performed to identify which mean concentrations differed and to group homogeneous subgroups. These tests included Fisher's LSD test, Tukey's HSD test, and Dunnett's test. For the one-way ANOVA and post-hoc tests, results were considered statistically significant at a $p < 0.05$.

A Student's t-test was applied to assess whether the measured results were statistically significant in relation to the health risk thresholds defined by the various health risk indexes. For this test, results were considered statistically significant at a $p < 0.05$.

All statistical analyses were performed using Statistica version 7 software.

3. Results and Discussion

3.1. Results

3.1.1. Concentrations of Pesticide Residues in Fish Muscle

Table 3 presents the concentrations of pesticide residues in the muscles of the four fish species examined.

Concentrations of AMP, CNZ, DMT, DRN, FEN, MNR, PTE, and TBTL in the fish muscle were below their respective Limits of Detection (LOD). This was also true for ADC, BFT, IMD, and TBT concentrations in the muscle of *Parachanna obscura*. Only DEA and PTM were exclusively detected in the muscle of *Parachanna obscura*.

With the exception of *Parachanna obscura*, the muscles of all fish species showed the highest mean concentrations of MTB. In the muscle of *Parachanna obscura*, the highest mean concentration was for BTR. The mean concentrations of CVP and SIZ were also notable in these fish, as were the concentrations of BTR in the muscles of *Heterotis niloticus* and *Oreochromis niloticus*.

The lowest mean concentrations of pesticide residues were observed as follows: IMD in *Heterotis niloticus*; BTR and IMD in *Sarotherodon melanotheron*; CTL and TBT in *Oreochromis niloticus*; and CTL, DEA, and PTM in *Parachanna obscura*.

The variations in the mean concentrations of pesticide residues across these fish species were minimal.

A one-way ANOVA revealed significant differences in the mean concentrations of pesticide residues among the fish species ($p < 0.05$), with the exception of TBT ($p > 0.05$). Post-hoc tests showed statistically significant differences in the mean concentrations of herbicide residues between the muscle of *Parachanna obscura* and the other three fish species ($p < 0.05$). Similar differences were observed for the mean concentrations of CPP, CVP, and VCZ in the muscle of *Parachanna obscura* compared to those in *Heterotis niloticus* ($p < 0.05$).

Furthermore, significant differences were found between the mean concentrations of BFT, BTR, CVP, SIZ, and VCZ in the muscle of *Heterotis niloticus* and those in the muscle of *Sarotherodon melanotheron* ($p < 0.05$). Post-hoc tests also revealed that the mean concentrations of ADC, BFT, CPP, CVP, and IMD in *Heterotis niloticus* were statistically different from those in *Oreochromis niloticus* ($p < 0.05$). Additionally, the mean concentrations of ADC, DIA, CPP, CVP, DEA, and IMD in *Oreochromis niloticus* were significantly different from those in *Sa-*

rotherodon melanotheron ($p < 0.05$).

Table 3. Mean concentrations of pesticide residues (µg/g fresh weight) in the muscle of the four fish species.

Pesticide residues	Statistical parameters	Fish species			
		Hétérotis niloticus	*Sarotherodon melanotheron*	*Oreochromis niloticus*	*Parachanna obscura*
ADC	m ± s	0.02 ± 0.03	0.024 ± 0.005	0.025 ± 0.005	<LOD
	VC	0.18	21.101	20.889	
	Min-Max	0.020 - 0.030	0.020 - 0.030	0.020 - 0.030	
ATZ	m ± s	0.025 ± 0.005	0.03 ± 0.03	0.04 ± 0.01	0.09 ± 0.02
	VC	20.889	92.32	26.11	18.43
	Min-Max	0.020 - 0.030	0.01 - 0.06	0.03 - 0.05	0.07 - 0.10
BFT	m ± s	0.07 ± 0.04	0.09 ± 0.01	0.025 ± 0.005	<LOD
	VC	56.24	15.03	20.889	
	Min-Max	0.03 - 0.10	0.07 - 0.10	0.020 - 0.030	
BTR	m ± s	0.175 ± 0.005	0.013 ± 0.005	0.255 ± 0.005	0.67 ± 0.03
	VC	2.984	36.927	2.048	3.93
	Min-Max	0.170 - 0.180	0.010 - 0.020	0.250 - 0.260	0.64 - 0.69
CPP	m ± s	0.105 ± 0.005	0.09 ± 0.02	0.04 ± 0.03	0.02 ± 0.04
	VC	4.974	22.20	74.61	0.18
	Min-Max	0.100 - 0.110	0.07 - 0.12	0.01 - 0.06	0.01 - 0.011
CTL	m ± s	0.015 ± 0.005	0.017 ± 0.005	0.015 ± 0.005	0.01 ± 0.02
	VC	34.816	29.542	34.816	0.18
	Min-Max	0.010 - 0.020	0.010 - 0.020	0.010 - 0.020	0.01 - 0.02
CVP	m ± s	0.23 ± 0.05	0.14 ± 0.04	0.11 ± 0.01	0.16 ± 0.02
	VC	20.89	28.14	9.50	10.11
	Min-Max	0.18 - 0.27	0.09 - 0.18	0.10 - 0.12	0.14 - 0.17
DEA	m ± s	<LOD	<LOD	<LOD	0.01 ± 0.01
	VC				0.18
	Min-Max				0.01 - 0.02
DIA	m ± s	0.105 ± 0.005	0.08 ± 0.02	0.08 ± 0.02	0.02 ± 0.03
	VC	4.974	23.16	26.11	0.18
	Min-Max	0.100 - 0.110	0.06 - 0.10	0.06 - 0.10	0.01 - 0.02
IMD	m ± s	0.01 ± 0.02	0.014 ± 0.005	0.021 ± 0.005	<LOD
	VC	0.18	36.927	2.547	
	Min-Max	0.010 - 0.011	0.01 - 0.02	0.020 - 0.021	
MTB	m ± s	0.3 ± 0.1	0.3 ± 0.1	0.28 ± 0.06	0.5 ± 0.1
	VC	36.9	40.1	22.38	1.9
	Min-Max	0.2 - 0.4	0.2 - 0.5	0.22 - 0.34	0.2 - 0.4

Continued

PTM	m ± s	<LOD	<LOD	<LOD	0.11 ± 0.01
	VC				474
	Min-Max				0.010 - 0.011
SIZ	m ± s	0.23 ± 0.05	0.14 ± 0.04	0.11 ± 0.01	0.16 ± 0.02
	VC	20.89	28.14	9.50	10.11
	Min-Max	0.18 - 0.27	0.09 - 0.18	0.10 - 0.12	0.14 - 0.17
TBT	m ± s	0.015 ± 0.005	0.017 ± 0.005	0.015 ± 0.005	<LOD
	VC	34.816	29.542	34.816	
	Min-Max	0.010 - 0.020	0.010 - 0.020	0.010 - 0.020	
VCZ	m ± s	0.025 ± 0.005	0.09 ± 0.02	0.04 ± 0.01	0.06 ± 0.05
	VC	20.889	22.73	26.11	85.46
	Min-Max	0.020 - 0.030	0.06 - 0.10	0.03 - 0.05	0.01 - 0.10

LOD: Limit of Detection.

3.1.2. Health Risks

1) Ecotoxicological Risks of Pesticide Residues for these Fish

Table 4 and Table 5 present the seasonal mean BAF values for some pesticide residues in the muscle of the fish examined. The results indicate that the ecotoxicological risks of MTB for these fish are high across all seasons. This also applies to the elevated health risks for *Parachanna obscura* due to ATZ, regardless of the season.

Heterotis niloticus showed high health risks linked to significant accumulations of ATZ and TBT in its muscle during the PSC, as well as ADC during the PSP. Both *Oreochromis niloticus* and *Sarotherodon melanotheron* simultaneously exhibited high health risks due to substantial accumulations of ATZ and ADC in their muscles during the PSC and PSP. Additionally, *Sarotherodon melanotheron* showed significant potential health risks in the PSC, attributed to the high ecotoxicological risks of TBT for this fish during that season. These observations are supported by the results of a Student's t-test ($p < 0.05$).

Table 4. Seasonal and annual mean values of the BAF for some herbicide residues in the muscle of the four fish species during the study period.

Pesticide residues	Seasons et annual	*Hétérotis niloticus*	*Sarotherodon melanotheron*	*Oreochromis niloticus*	*Parachanna obscura*
ATZ	SHS	**2.3 ± 0.5**	**2.4 ± 2.2**	**3.6 ± 0.9**	**7.7 ± 1.4**
	SRS	*0.9 ± 0.2	**1.1 ± 0.9**	**1.5 ± 0.4**	**3.2 ± 0.6**
	GHS	0.6 ± 0.1	0.6 ± 0.5	*0.9 ± 0.2	**1.9 ± 0.4**
	GRS	0.6 ± 0.1	0.6 ± 0.5	0.9 ± 0.2	**1.9 ± 0.3**
	Annual	0.8 ± 0.2	0.8 ± 0.7	*1.3 ± 0.3	**2.7 ± 0.5**

Continued

	SHS	<LOD	<LOD	<LOD	$0.02 \pm 3.62 \times 10^{-4}$
	SRS	<LOD	<LOD	<LOD	$0.02 \pm 3.62 \times 10^{-4}$
DEA	GHS	<LOD	<LOD	<LOD	$0.02 \pm 3.62 \times 10^{-4}$
	GRS	<LOD	<LOD	<LOD	0.017 ± 0.001
	Annual	<LOD	<LOD	<LOD	0.017 ± 0.001
	SHS	0.26 ± 0.01	0.19 ± 0.04	0.2 ± 0.5	$0.05 \pm 7.25 \times 10^{-4}$
	SRS	0.36 ± 0.02	0.27 ± 0.06	0.28 ± 0.07	0.069 ± 0.001
DIA	GHS	0.186 ± 0.009	0.14 ± 0.03	0.14 ± 0.04	$0.04 \pm 7.25 \times 10^{-14}$
	GRS	0.19 ± 0.01	0.14 ± 0.03	0.15 ± 0.04	0.036 ± 0.001
	Annual	0.23 ± 0.01	0.17 ± 0.04	0.18 ± 0.04	$0.044 \pm 7.247 \times 10^{-4}$
	SHS	**1.5 ± 0.6**	**1.6 ± 0.6**	**1.3 ± 0.3**	**2.46 ± 0.05**
	SRS	**2.4 ± 0.6**	**2.5 ± 0.9**	**2.1 ± 0.5**	**3.86 ± 0.08**
MTB	GHS	**1.7 ± 0.6**	**1.7 ± 0.7**	**1.4 ± 0.3**	**2.70 ± 0.05**
	GRS	**1.7 ± 0.6**	**1.7 ± 0.7**	**1.4 ± 0.3**	**2.69 ± 0.05**
	Annual	**1.7 ± 0.6**	**1.8 ± 0.8**	**1.5 ± 0.3**	**2.84 ± 0.06**
	SHS	0.010 ± 0.002	0.006 ± 0.002	0.0047 ± 0.0004	0.240 ± 0.007
	SRS	0.009 ± 0.002	0.006 ± 0.002	0.0050 ± 0.0004	0.227 ± 0.006
SIZ	GHS	0.008 ± 0.002	0.005 ± 0.001	0.0040 ± 0.0003	0.005 ± 0.0005
	GRS	0.008 ± 0.002	0.005 ± 0.001	0.0040 ± 0.0003	0.153 ± 0.0005
	Annual	0.008 ± 0.002	0.005 ± 0.001	0.0040 ± 0.0004	0.183 ± 0.0006
	SHS	**1.3 ± 0.4**	**1.4 ± 0.4**	*1.3 ± 0.5	<LOD
	SRS	*0.9 ± 0.3	*0.9 ± 0.3	0.9 ± 0.3	<LOD
TBT	GHS	0.4 ± 0.1	0.5 ± 0.1	0.4 ± 0.1	<LOD
	GRS	0.4 ± 0.1	0.5 ± 0.1	0.4 ± 0.1	<LOD
	Annual	0.6 ± 0.2	0.6 ± 0.2	0.6 ± 0.2	<LOD
	SHS	0.157 ± 0.005	0.012 ± 0.004	0.229 ± 0.005	0.59 ± 0.06
	SRS	0.117 ± 0.003	0.009 ± 0.003	0.170 ± 0.003	0.44 ± 0.02
BTR	GHS	0.104 ± 0.003	0.008 ± 0.003	0.152 ± 0.003	0.37 ± 0.02
	GRS	0.107 ± 0.003	0.008 ± 0.003	0.155 ± 0.003	0.41 ± 0.02
	Annual	0.118 ± 0.004	0.009 ± 0.003	0.229 ± 0.004	0.45 ± 0.02
	SHS	0.8 ± 0.3	0.8 ± 0.2	0.8 ± 0.3	0.500 ± 0.001
	SRS	<LOD	<LOD	<LOD	<LOD
CTL	GHS	<LOD	<LOD	<LOD	<LOD
	GRS	<LOD	<LOD	<LOD	<LOD
	Annual	0.8 ± 0.3	0.8 ± 0.2	0.8 ± 0.3	0.500 ± 0.001

LOD: Limit of Detection; In bold, the high ecotoxicity risks; *statistically equivalent to 1 according to Student's t-test.

Table 5. Seasonal and annual mean values of the BAF for some residues of insecticides and dicarboxamide fungicides in the muscle of the four fish species examined during the study period.

Pesticides residues	Seasons et annual	*Hétérotis niloticus*	*Sarotherodon melanotheron*	*Oreochromis niloticus*	*Parachanna obscura*
ADC	SHS	0.9 ± 1.2 × 10^{-4}	**1.2 ± 0.2**	**1.2 ± 0.3**	<LOD
	SRS	**1.105 ± 0.001**	**1.3 ± 0.3**	**1.4 ± 0.3**	<LOD
	GHS	0.65 ± 1.16 × 10^{-4}	0.8 ± 0.2	0.8 ± 0.1	<LOD
	GRS	0.64 ± 1.16 × 10^{-4}	0.7 ± 0.2	0.8 ± 0.2	<LOD
	Annual	0.799 ± 0.001	*0.9 ± 0.2	*0.9 ± 0.2	<LOD
BFT	SHS	0.01 ± 0.06	0.13 ± 0.02	0.038 ± 0.008	<LOD
	SRS	0.12 ± 0.07	0.16 ± 0.02	0.045 ± 0.009	<LOD
	GHS	0.11 ± 0.06	0.15 ± 0.02	0.044 ± 0.009	<LOD
	GRS	0.12 ± 0.07	0.16 ± 0.02	0.045 ± 0.009	<LOD
	Annual	0.11 ± 0.06	0.15 ± 0.02	0.043 ± 0.009	<LOD
CPP	SHS	0.25 ± 0.01	0.23 ± 0.05	0.08 ± 0.06	0.047 ± 7.2 × 10^{-18}
	SRS	0.31 ± 0.02	0.28 ± 0.06	0.10 ± 0.08	0.058 ± 7.2 × 10^{-18}
	GHS	0.24 ± 0.01	0.22 ± 0.05	0.08 ± 0.06	0.046 ± 7.2 × 10^{-18}
	GRS	0.25 ± 0.01	0.23 ± 0.05	0.08 ± 0.06	0.048 ± 7.2 × 10^{-18}
	Annual	0.26 ± 0.01	0.24 ± 0.05	0.09 ± 0.07	0.050 ± 7.2 × 10^{-18}
CVP	SHS	0.282 ± 0.060	0.171 ± 0.048	0.138 ± 0.013	0.19 ± 0.02
	SRS	0.384 ± 0.080	0.233 ± 0.066	0.188 ± 0.018	0.26 ± 0.03
	GHS	0.333 ± 0.070	0.202 ± 0.057	0.163 ± 0.015	0.23 ± 0.02
	GRS	0.341 ± 0.071	0.207 ± 0.058	0.167 ± 0.016	0.24 ± 0.02
	Annual	0.331 ± 0.069	0.201 ± 0.057	0.162 ± 0.015	0.23 ± 0.02
PTM	SHS	<LOD	<LOD	<LOD	0.24 ± 0.01
	SRS	<LOD	<LOD	<LOD	0.23 ± 0.01
	GHS	<LOD	<LOD	<LOD	0.149 ± 0.007
	GRS	<LOD	<LOD	<LOD	0.153 ± 0.008
	Annual	<LOD	<LOD	<LOD	0.183 ± 0.009
IMD	SHS	0.43 ± 5.80 × 10^{-4}	0.6 ± 0.2	0.87 ± 0.02	<LOD
	SRS	0.16 ± 2.90 × 10^{-4}	0.21 ± 0.07	0.322 ± 0.008	<LOD
	GHS	0.072 ± 1.45 × 10^{-4}	0.09 ± 0.04	0.148 ± 0.004	<LOD
	GRS	0.073 ± 0.001	0.09 ± 0.04	0.150 ± 0.004	<LOD
	Annual	0.11 ± 2.9 × 10^{-4}	0.15 ± 0.05	0.227 ± 0.006	<LOD
VCZ	SHS	0.034 ± 0.007	0.12 ± 0.03	0.05 ± 0.01	0.07 ± 0.06
	SRS	0.035 ± 0.007	0.12 ± 0.03	0.06 ± 0.01	0.08 ± 0.07
	GHS	0.032 ± 0.007	0.11 ± 0.03	0.05 ± 0.01	0.07 ± 0.06
	GRS	0.033 ± 0.007	0.12 ± 0.03	0.05 ± 0.01	0.07 ± 0.06
	Annual	0.033 ± 0.007	0.12 ± 0.03	0.053 ± 0.001	0.07 ± 0.06

In bold, the high ecotoxicity risks.

3.1.3. Levels of Human Health Risks

1) Hazard Index (HI)

The highest mean HI values for human consumption were for SIZ residues in all four fish species, while those for CPP and IMD were the lowest. The mean HI values for pesticide residues in the muscle of *Parachanna obscura* were higher than those in the other three fish species. Health risks for children due to CVP in the muscle of *Parachanna obscura* were significant (Table 6 and Table 7). The health risks for children from the total pesticide residues (ΣHI) in the muscle of *Parachanna obscura* were also high during this period (Table 8). All these observations were confirmed by a Student's t-test ($p < 0.05$).

Table 6. Mean HI values for individuals due to herbicide residues found in the muscle of the four fish species during the study period.

Fish species	Individuals	ATZ	MTB	SIZ	TBT
Hétérotis niloticus	Adults	0.0005 ± 0.0001	0.014 ± 0.005	0.05 ± 0.01	0.016 ± 0.005
	Children	0.0008 ± 0.0002	0.021 ± 0.008	0.07 ± 0.02	0.024 ± 0.008
Oreochromis niloticus	Adults	0.0008 ± 0.0002	0.012 ± 0.003	0.023 ± 0.002	0.016 ± 0.005
	Children	0.0010 ± 0.0003	0.0180 ± 0.0004	0.036 ± 0.003	0.024 ± 0.008
Parachanna obscura	Adults	0.0020 ± 0.0003	0.0220 ± 0.0004	0.032 ± 0.003	-
	Children	0.0030 ± 0.0005	0.0340 ± 0.0007	0.050 ± 0.005	-
Sarotherodon melanotheron	Adults	0.0006 ± 0.0005	0.014 ± 0.006	0.029 ± 0.008	0.017 ± 0.005
	Children	0.0009 ± 0.0008	0.022 ± 0.009	0.044 ± 0.012	0.027 ± 0.008

Table 7. Mean HI values for individuals related to residues of insecticides and dicarboximide fungicides found in the muscle of the four fish species during the study period.

Fish species	Individuals	ADC	BFT	CPP	CVP	IMD (*PTM)	VCZ
Hétérotis niloticus	Adults	0.02 ± 7.25 × 10^{-5}	0.005 ± 0.003	0.0005 ± 2.73 × 10^{-6}	0.34 ± 0.07	0.002 ± 0.001	0.0010 ± 0.0002
	Children	0.03 ± 7.25 × 10^{-5}	0.007 ± 0.004	0.0009 ± 4.23 × 10^{-6}	0.5 ± 0.1	0.0003 ± 5.66 × 10^{-6}	0.0020 ± 0.0003
Oreochromis niloticus	Adults	0.026 ± 0.005	0.0020 ± 0.0004	0.0002 ± 0.0001	0.17 ± 0.02	0.0004 ± 9.59 × 10^{-6}	0.0020 ± 0.0004
	Children	0.040 ± 0.008	0.0030 ± 0.0006	0.0003 ± 0.0002	0.26 ± 0.02	0.0006 ± 1.48 × 10^{-5}	0.0030 ± 0.0007
Parachanna obscura	Adults	–	–	0.0001 ± 2.83 × 10^{-6}	0.65 ± 0.07	*0.0440 ± 0.0002	0.002 ± 0.002
	Children	–	–	0.0002 ± 2.83 × 10^{-6}	**1.00 ± 0.10**	*0.068 ± 0.003	0.004 ± 0.003
Sarotherodon melanotheron	Adults	0.024 ± 0.005	0.0060 ± 0.0009	0.0005 ± 0.0001	0.20 ± 0.06	0.0002 ± 9.04 × 10^{-5}	0.0040 ± 0.0008
	Children	0.038 ± 0.008	0.009 ± 0.001	0.0008 ± 0.0002	0.32 ± 0.09	0.0004 ± 0.0001	0.006 ± 0.001

In bold significant value of HI. *statistically equivalent to 1 according to Student's t-test.

Table 8. Mean ΣHI values for individuals related to the total pesticide residues found in the muscle of the four fish species during the study period.

Fish species	Individual	ΣHI
Hétérotis niloticus	Adults	0.44 ± 0.08
	Children	0.7 ± 0.1

Continued

Oreochromis niloticus	Adults	0.25 ± 0.02
	Children	0.38 ± 0.03
Parachanna obscura	Adults	0.75 ± 0.07
	Children	**1.2 ± 0.1**
Sarotherodon melanotheron	Adult	0.30 ± 0.07
	Children	0.5 ± 0.1

In bold significant value of ΣHI.

2) Short-term Carcinogenic Risk Index (CR_0)

All mean CR_0 values for ADC, ATZ, CPP, and SIZ in the muscle of the four fish species were low, with mean values ranging between 10^{-6} and 10^{-4}. Furthermore, the highest mean CR_0 values were for SIZ, whereas those for ADC and CPP were the lowest.

The mean sum of the carcinogenic risks (ΣCR_0) for these four pesticide residues was high in the muscle of *Heterotis niloticus* and *Parachanna obscura*, but low in the muscle of *Oreochromis niloticus* and *Sarotherodon melanotheron* (Table 9). All these results were confirmed by a Student's t-test ($p < 0.05$).

Table 9. Mean CR_0 and ΣCR_0 values for individuals related to ADC, ATZ, CPP, and SIZ in the muscle of the four fish species during the study period.

Fish species	Individuals	RC_0				ΣCR_0
		ADC	ATZ	CPP	SIZ	
Hétérotis niloticus	Adults	$1.2 \times 10^{-6} \pm 2.1 \times 10^{-8}$	$6.1 \times 10^{-6} \pm 1.3 \times 10^{-6}$	$2.6 \times 10^{-6} \pm 1.3 \times 10^{-7}$	$2.8 \times 10^{-5} \pm 5.9 \times 10^{-6}$	$3.2 \times 10^{-5} \pm 7.0 \times 10^{-6}$
	Children	$1.8 \times 10^{-6} \pm 10^{-8}$	$9.3 \times 10^{-6} \pm 1.9 \times 10^{-6}$	$4.1 \times 10^{-6} \pm 2.0 \times 10^{-7}$	$4.4 \times 10^{-5} \pm 9.1 \times 10^{-6}$	$5.9 \times 10^{-5} \pm 1.1 \times 10^{-5}$
Oreochromis niloticus	Adults	$1.5 \times 10^{-6} \pm 3.1 \times 10^{-7}$	$9.6 \times 10^{-6} \pm 2.5 \times 10^{-6}$	***$8.8 \times 10^{-7} \pm 6.6 \times 10^{-7}$**	$1.4 \times 10^{-5} \pm 1.3 \times 10^{-6}$	$2.6 \times 10^{-5} \pm 4.2 \times 10^{-6}$
	Children	$2.7 \times 10^{-6} \pm 4.7 \times 10^{-7}$	$1.5 \times 10^{-5} \pm 3.9 \times 10^{-6}$	***$1.4 \times 10^{-6} \pm 1.1 \times 10^{-6}$**	$2.1 \times 10^{-5} \pm 2 \times 10^{-6}$	$3.9 \times 10^{-5} \pm 6.5 \times 10^{-6}$
Parachanna obscura	Adults	-	$2.1 \times 10^{-5} \pm 3.8 \times 10^{-6}$	$5.1 \times 10^{-7} \pm 10^{-9}$	$1.9 \times 10^{-5} \pm 1.9 \times 10^{-6}$	$4.1 \times 10^{-5} \pm 5.7 \times 10^{-6}$
	Children	-	$3.2 \times 10^{-5} \pm 5.8 \times 10^{-6}$	$7.8 \times 10^{-7} \pm 1.1 \times 10^{-9}$	$3.1 \times 10^{-5} \pm 3.1 \times 10^{-9}$	$6.4 \times 10^{-5} \pm 8.9 \times 10^{-6}$
Sarotherodon melanotheron	Adults	$1.4 \times 10^{-6} \pm 2.9 \times 10^{-7}$	$6.4 \times 10^{-6} \pm 5.9 \times 10^{-6}$	$2.4 \times 10^{-6} \pm 5.4 \times 10^{-7}$	$1.7 \times 10^{-5} \pm 4.8 \times 10^{-6}$	$2.7 \times 10^{-5} \pm 3.3 \times 10^{-6}$
	Children	$2.0 \times 10^{-6} \pm 4.5 \times 10^{-7}$	$9.9 \times 10^{-6} \pm 9.2 \times 10^{-6}$	$3.8 \times 10^{-6} \pm 8.3 \times 10^{-7}$	$2.7 \times 10^{-5} \pm 7.5 \times 10^{-6}$	$4.2 \times 10^{-5} \pm 5.1 \times 10^{-6}$

In bold significant value of CR_0. *statistically equivalent to 1 according to Student's t-test.

3.2. Discussion

The contamination of fish by organic pollutants occurs through dermal, respiratory (gill), and oral pathways [3] [4]. However, for freshwater fish, dermal absorption of pollutants is negligible, accounting for less than 5% of total uptake compared to oral and branchial absorption [3]. This is especially true for the four fish species examined in this study, as their integument and scales provide significant protection against external exposure to pollutants [3] [24].

Although these fish species inhabit the same ecological environment, the accumulation of pesticide residues in their bodies varies based on their feeding habits, trophic levels, and physiologies. This explains the observed differences in the mean concentrations of pesticide residues in their muscle tissue. Similar observations have been reported in recent studies by Siddique *et al.* [6] and Zafarani *et al.* [7].

Most of the detected pesticide residues exhibit low bioaccumulation and low persistence in organisms, indicated by a low log K_{ow} (<6), with the exception of bifenthrin (log K_{ow} = 6.6) [25] [26]. However, these compounds are still relatively well assimilated through branchial pathways, except for imidacloprid (log K_{ow} = 1) [27]. According to Lazartigues [3], the assimilation of compounds with a log Kow below 1 is slow and weak. For those with a log Kow between 1 and 3, gill absorption and contaminant assimilation increase with log K_{ow} via passive diffusion across the membrane. For compounds with a log Kow between 3 and 6, a plateau is observed, with an assimilation rate of approximately 60%, depending on the ventilation rate. Thus, pesticide residues in the waters of the Déganobo system contributed to the contamination of *Heterotis niloticus*, *Oreochromis niloticus*, and *Sarotherodon melanotheron* through branchial pathways [28] [29] [30]. In contrast, contamination in *Parachanna obscura* likely occurred through a combination of both branchial and oral pathways. Oral contamination was also notable in all species, particularly from the consumption of benthic fauna and flora. Adjuvants added to pesticide active ingredients to enhance their activity and adsorption on various surfaces [9] also promote their presence in sediments, where their concentrations are often more significant than in open waters [7].

The carnivorous diet of *Parachanna obscura* [31] [32] contributed to significant contamination of its muscle by several detected pesticide residues, particularly ATZ, BTR, and MTB, whose concentrations in this fish were higher than in the other three species. Microfauna, primarily benthic, constitutes the majority of its diet [32] and can bioaccumulate these substances when they are in excess in the environment [33] [34]. This study confirmed the contribution of diet to the contamination of *Parachanna obscura* muscle by pesticides, as demonstrated by the high BAF values for ATZ and MTB. ATZ is known to potentially affect the endocrine, reproductive, neurological, and immune systems of fish [35], while MTB may cause respiratory and renal issues, similar to those observed in *Oncorhynchus mykiss*.

The omnivorous diets of *Heterotis niloticus*, *Oreochromis niloticus*, and *Sarotherodon melanotheron* also facilitated the contamination of their muscles through oral intake. However, this was to a lesser extent for certain residues compared to *Parachanna obscura*, likely due to differences in habitat [36]-[38]. The contribution of ingestion to muscle contamination in these omnivorous species was particularly evident for MTB across all seasons, with high seasonal BAF values for this residue. Oral contamination was also observed for other pesticides:

- in *Heterotis niloticus*: ATZ and TBT during the PSC, and ADC during the PSP;
- in *Oreochromis niloticus*: ATZ during both the PSC and PSP, TBT during the

PSC, and ADC during the PSP;

- in *Sarotherodon melanotheron*: ATZ during both the PSC and PSP, and ADC during the PSP.

The differences observed in pesticide residue concentrations among the various fish species can also be explained by variations in their physiology, anatomy, and diet [3]. These variations account for the significant differences in concentrations for certain residues, as revealed by post-hoc tests. Conversely, the non-statistically significant differences for other residues may result from a common food source.

The higher contamination of fish muscle by herbicides compared to insecticides confirms the significant presence of herbicides in this lacustrine system, particularly in its waters. This finding reflects the predominance of agricultural activities in the San-Pedro region [13], where the use of herbicides is widespread, as it is throughout Côte d'Ivoire [11] [12]. The high concentration of herbicide residues and low concentration of insecticide residues in *Parachanna obscura* muscle, in comparison to the other three species, suggests significant contamination of the benthic fauna by herbicides. This could be explained by the mortality effects of insecticides on this faunal community. A similar observation was reported by Choung *et al.* [39] in experiments on invertebrates using a mixture of terbufos and atrazine. Additionally, the high total insecticide residue concentration in the muscles of the other three species can be attributed to their omnivorous diet. The consumption of animal detritus, which includes invertebrates killed by insecticides in the water [40], provides a clear pathway for contamination. This is especially true for *Heterotis niloticus*, whose muscle showed the highest total insecticide concentration during the study period. The high concentrations of both total herbicide and insecticide residues in the muscles of these fish highlight the significant health risks to which these organisms are exposed [41].

Based on mean HI values, the health risks for adults associated with consuming these fish were low. According to US-EPA criteria [22], the short-term carcinogenic risks for both adults and children, linked to the presence of ADC, ATZ, CPP, SIZ, and their cumulative total, were low during the study period. However, the health risks for children from consuming the muscle of *Parachanna obscura* were high, primarily due to the concentration of CVP. For children, the potential health risks include adverse effects on their nervous systems [42]. In conclusion, although the detected pesticide residues could potentially impact the health of the fish themselves, they pose a very low health risk to adults. The primary concern is the high health risk to children from consuming the contaminated fish.

Author Contributions

K.F.A. Konan: Data curation; Formal analysis; Investigation; Software; Roles/Writing—original draft.

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T. Diarrassouba: Writing—review & editing; Resources.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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