JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(11), 26–38
https://doi.org/10.12911/22998993/225930
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.06.29
Accepted: 2026.09.15
Published: 2026.10.01

Occurrence and human health implications of organochlorine pesticides in Nile tilapia from Al Massira Reservoir (Morocco) across consumer groups

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ABSTRACT

Organochlorine pesticides (OCPs) are persistent environmental contaminants that continue to occur in aquatic ecosystems due to their high stability and bioaccumulative properties. This study quantified the OCP residues in the muscle tissue of Nile tilapia (*Oreochromis niloticus*) collected from the Al Massira Reservoir (Morocco) and evaluated the potential human health risks associated with fish consumption. A total of 120 specimens collected between July 2022 and June 2023 were analyzed for eight OCPs (α-HCH, β-HCH, γ-HCH, aldrin, dieldrin, p,p′-DDD, p,p′-DDE, and p,p′-DDT) using gas chromatography–mass spectrometry (GC–MS). Human exposure was assessed through estimated daily intake (EDI) and hazard ratio (HR). All target compounds were detected, with concentrations ranging from below the detection limit to 8.445 ng g^{-1} wet weight. Dieldrin and p,p′-DDT were the predominant residues, whereas p,p′-DDD occurred at the lowest concentrations. No significant temporal variation was observed during the sampling period (ANOVA, $p > 0.05$). OCP concentrations showed no significant relationship with fish total length, whereas dieldrin concentration exhibited a significant positive relationship with fish body weight ($R^2 = 0.238$; $p = 0.016$). All measured residue concentrations remained below the international maximum residue limits, and the estimated daily intake as well as hazard ratio values for all consumer groups were below the recommended safety thresholds, indicating a low health risk associated with Nile tilapia consumption. This study provides one of the first comprehensive assessments of the OCP contamination in Nile tilapia from the Al Massira Reservoir, one of Morocco's largest freshwater reservoirs. The findings establish valuable baseline data for future environmental monitoring, ecological risk assessment, and food safety management of Moroccan freshwater ecosystems.

Keywords: Nile tilapia, organochlorine pesticides, Al Massira Reservoir, human health, consumer groups, bioaccumulation.

INTRODUCTION

Organochlorine pesticides (OCPs) are persistent organic pollutants that remain widely distributed in the environment owing to their high chemical stability, lipophilic nature, and slow degradation. Widely used during the twentieth century in agriculture and vector control, these compounds remain in environmental compartments for decades after application (Chernyak et al., 1996; Li et al., 1998; Taiwo, 2019; Chen et al., 2023). Their persistence led to the inclusion of several OCPs among persistent organic pollutants (POPs) under the Stockholm Convention

(UNEP, 2001). Nevertheless, OCP residues are still detected in soils, sediments, surface waters, and aquatic organisms worldwide.

Freshwater ecosystems receive OCPs from agricultural runoff, contaminated soils, industrial discharges, urban effluents, and atmospheric deposition (Md, 2017; Olisah et al., 2021). Once introduced, these compounds partition between water, sediments, and biota, where their lipophilic nature favors bioaccumulation and biomagnification, increasing contaminant burdens along aquatic food webs and ultimately posing risks to human consumers (Miglioranza et al., 2022; Dione et al., 2023).

Fish are widely used as bioindicators because they integrate contaminant exposure over time and reflect environmental quality. Their capacity to accumulate persistent pollutants also makes them suitable for evaluating the potential risks to consumers (Anyanwu et al., 2011; Al-Busaidi et al., 2011). Among freshwater species, Nile tilapia (*Oreochromis niloticus*) is particularly appropriate for contamination studies because of its wide distribution, ecological adaptability, commercial value, and frequent consumption (Ogbomida et al., 2018; Heshmati et al., 2017).

Although the use of OCPs has been banned or severely restricted in many countries, residues continue to be reported in numerous aquatic ecosystems. In Morocco, previous studies have documented the OCP contamination in rivers, reservoirs, estuaries, marine environments, and aquatic organisms (El Bouraie et al., 2011; El Morhit et al., 2009; Maanan et al., 2014; Kafilzadeh et al., 2012; Ferraj et al., 2024; Ouahb et al., 2025). However, these studies have mainly focused on environmental matrices or a limited number of aquatic species, whereas the information on the OCP contamination in edible freshwater fish from major inland reservoirs, together with the associated human health risks, remains scarce. Consequently, the baseline data for evaluating food safety and supporting long-term environmental monitoring in Moroccan freshwater ecosystems are still lacking.

The Al Massira Reservoir is one of Morocco's largest artificial lakes and plays a key role in water supply, irrigation, fisheries, and recreation. Despite its ecological and socio-economic importance, the information on pesticide contamination in its fish populations is scarce. To bridge this knowledge gap, this study therefore quantified eight organochlorine pesticides (α-HCH, β-HCH, γ-HCH, aldrin, dieldrin, p,p'-DDD, p,p'-DDE, and p,p'-DDT) in the muscle of *Oreochromis niloticus* from the Al Massira Reservoir and assessed the associated human health risks using the estimated daily intake (EDI) and hazard ratio (HR). The results provide the baseline data for future monitoring as well as support freshwater resource management and food safety assessment in Morocco.

MATERIALS AND METHODS

Study area and fish sampling

The Al Massira Reservoir (32°28′32″ N, 7°32′15″ W) is situated on the Oum Er-Rbia River in central Morocco, approximately 120 km southeast of Casablanca (Figure 1). With a storage capacity exceeding 2.7 billion m^3, it ranks among the country's largest artificial reservoirs and plays an essential role in water supply, irrigation, hydroelectric power production, as well as inland fisheries. The surrounding watershed is dominated by agricultural activities, making the reservoir vulnerable to pesticide inputs through runoff and drainage (Naamane et al., 2020).

Between July 2022 and June 2023, 120 Nile tilapia (*Oreochromis niloticus*) were obtained from local fishermen operating in the reservoir. After capture, the specimens were transported on ice to the Laboratory and stored at −20 °C until analysis.

Before dissection, total length (± 0.1 cm) and body weight (± 0.1 g) were measured for each fish. Dorsal muscle tissue was excised after skin removal and used for chemical analysis. To ensure representative sampling throughout the study period, twenty-four composite samples were prepared by pooling muscle tissues from fish collected during the different sampling campaigns.

Sample preparation

Muscle samples were freeze-dried according to the protocol described by Nowak et al. (2020). Following lyophilization, the dried tissues were homogenized using a stainless-steel grinder and stored in polyethylene containers until extraction. All preparation procedures were carried out under controlled laboratory conditions to minimize the risk of cross-contamination.

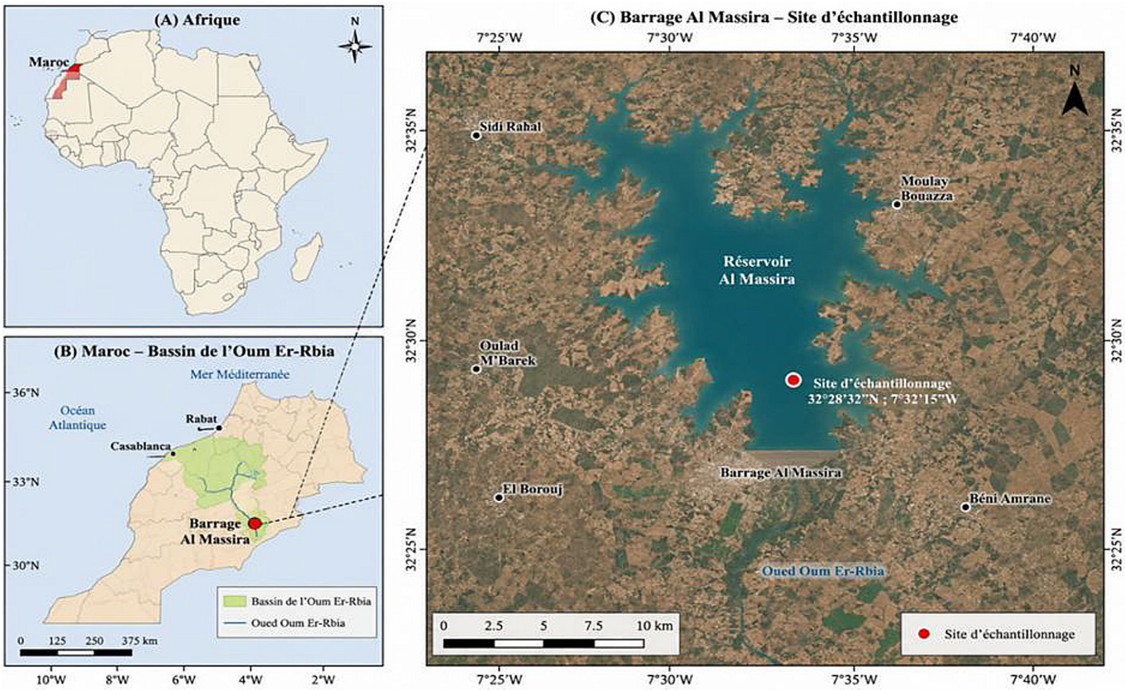

Figure 1. Geographical location of the Al Massira Reservoir, Morocco

Extraction and analysis of organochlorine pesticides

Organochlorine pesticide (OCP) residues were determined using a protocol adapted from the International Atomic Energy Agency guidelines (IAEA-EL/MESL/SOP-002/16-03-2016 REV.#2) and the Moroccan standards NM08.5.266–NM08.5.269 (2009). Target analytes were extracted from 3–8 g of freeze-dried muscle using microwave-assisted extraction with a hexane/acetone mixture (9:1, v/v). PCB-209 was added as an internal standard to evaluate extraction efficiency and analytical performance. The extracts were dried over anhydrous sodium sulfate, concentrated under a gentle stream of nitrogen, treated with concentrated sulfuric acid to remove lipids, and purified using Florisil solid-phase extraction (SPE) cartridges. The target compounds included α-HCH, β-HCH, γ-HCH (lindane), aldrin, dieldrin, and the DDT metabolites p,p′-DDE, p,p′-DDD, and p,p′-DDT. Quantitative analysis was carried out using an Agilent 7890B gas chromatograph coupled with an Agilent 5977B quadrupole mass spectrometer (GC–MS). The compounds were identified based on their retention times and characteristic mass fragments, while quantification was performed using the MassHunter Quantitative Analysis software.

Human health risk assessment

The potential health risks associated with the consumption of Nile tilapia contaminated with organochlorine pesticides were assessed following the guidelines established by the United States Environmental Protection Agency (US EPA, 2000; US EPA, 2006).

Concentrations below the limit of detection (LOD) were treated as zero, in accordance with the approach recommended by the US EPA (2006). To account for the variability of contaminant levels observed among samples, the risk assessment was performed using both mean concentrations and the 95th percentile (P95) concentrations.

Estimated daily intake (EDI)

Human dietary exposure to organochlorine pesticides through fish consumption was estimated using the following equation:

$$EDI = (C \times IR) / BW \quad (1)$$

where: C is the concentration of the contaminant in fish muscle (ng g^{-1} wet weight), IR is the daily fish ingestion rate (g day^{-1}), and BW is the body weight (kg).

Exposure parameters were adopted from Kasmi et al. (2023). Average body weights of 73.3

kg for Moroccan adults and 30 kg for 10-year-old children were considered. Daily fish consumption rates were set at 38 g day^{-1} for average consumers and 56.16 g day^{-1} for high consumers.

Cancer benchmark concentration (CBC)

The Cancer Benchmark Concentration (*CBC*) was estimated according to:

$$CBC = (RL / OSF) \times (BW / IR) \quad (2)$$

where: *RL* is the acceptable risk level (10^{-6}), *OSF* is the oral slope factor, *BW* is the body weight (kg), and *IR* is the daily fish ingestion rate (g day^{-1}). The oral slope factor values were obtained from the integrated risk information system (IRIS) database of the United States Environmental Protection Agency (US EPA).

Hazard ratio (HR)

Potential carcinogenic risk was assessed using the HR:

$$HR = EDI / CBC \quad (3)$$

where: *EDI* is the estimated daily intake and *CBC* is the cancer benchmark concentration. *HR* values below 1 indicate negligible carcinogenic risk, whereas values ≥ 1 suggest a potential health concern.

Statistical analysis

The concentrations measured on a dry-weight basis were converted to wet-weight concentrations using the equation proposed by Cresson et al. (2017):

$$Cww = Cdw / FC \quad (4)$$

where: *Cww* is the concentration expressed on a wet-weight basis, *Cdw* is the concentration expressed on a dry-weight basis, and *FC* is the conversion factor.

Descriptive statistical analyses were performed using the R software version 4.4.0 (R Core Team, 2024). Summary statistics, including mean, median, standard deviation, percentiles, and concentration ranges, were calculated for all investigated organochlorine pesticides.

RESULTS

Distribution of organochlorine pesticides in Nile tilapia muscle

All target organochlorine pesticides were detected in the muscle of *Oreochromis niloticus*, although their concentrations varied considerably among compounds (Figure 2). Dieldrin showed

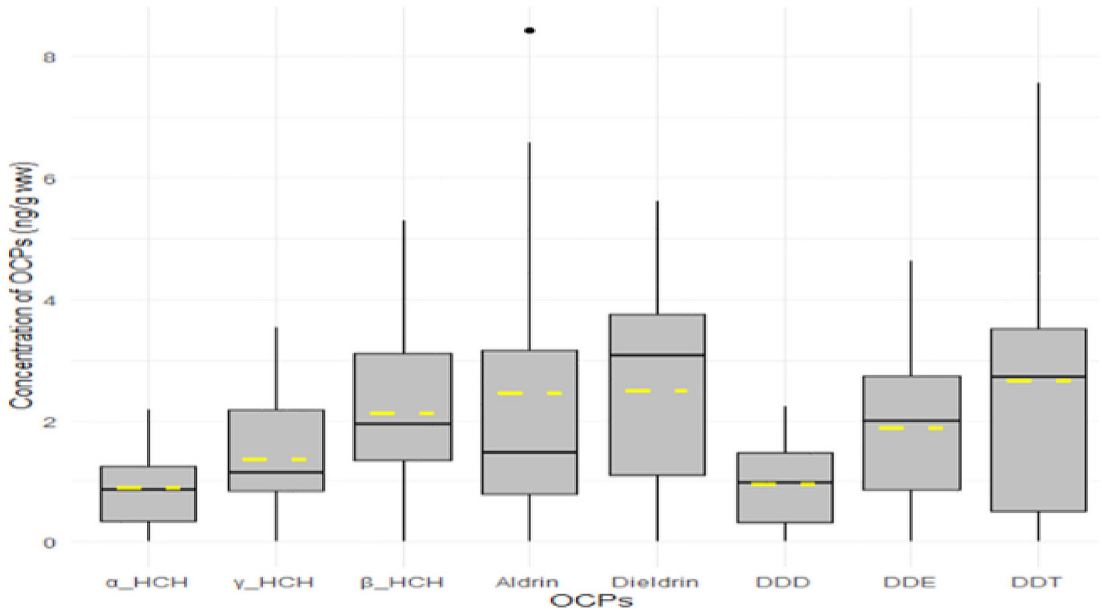

Figure 2. Distribution of organochlorine pesticide (OCP) concentrations (ng g^{-1} ww) in the muscle tissues of Nile tilapia (*Oreochromis niloticus*). Central solid lines indicate median values, whereas dashed lines represent mean concentrations

the highest residue levels, with median and maximum concentrations of 3.06 and 5.61 ng g^{-1} ww, respectively. Conversely, p,p′-DDD was consistently the least abundant compound, with median and maximum concentrations of 0.97 and 2.23 ng g^{-1} ww, respectively.

Relationships among organochlorine pesticides

The relationships among organochlorine pesticide residues varied considerably (Table 1; Figure 3). As shown in Table 1, β-HCH and γ-HCH exhibited the strongest positive correlation (r = 0.60), whereas the strongest negative correlation was observed between p,p′-DDD and γ-HCH (r = −0.26). The correlation matrix presented in Figure 3 provides a graphical representation of these association patterns, highlighting the heterogeneous relationships among the OCP residues detected in *Oreochromis niloticus* muscle.

Temporal variations in OCP concentrations

Total OCP concentrations varied among sampling months but showed no significant temporal differences (one-way ANOVA, p = 0.0647; p > 0.05) (Figure 4). The highest mean concentration was recorded in September (2.81 ± 1.45 ng g^{-1} ww), whereas the lowest occurred in June (1.04 ± 0.69 ng g^{-1} ww).

Table 1. Pearson correlation coefficients among organochlorine pesticide (OCP) concentrations detected in the muscle tissues of *Oreochromis niloticus*

Parameter	α-HCH	γ-HCH	β-HCH	Aldrin	Dieldrin	DDD	DDE	DDT
α-HCH	1.0000	0.4921	0.5000	-0.0109	0.2746	-0.1323	0.0404	-0.1181
γ-HCH	0.4921	1.0000	0.6008	0.3643	0.1911	-0.2640	-0.0129	-0.1122
β-HCH	0.5000	0.6008	1.0000	0.5216	0.0487	-0.0872	0.3696	0.0274
Aldrin	-0.0109	0.3643	0.5216	1.0000	0.0993	0.1012	0.4410	0.0540
Dieldrin	0.2746	0.1911	0.0487	0.0993	1.0000	-0.1995	-0.0070	0.1334
DDD	-0.1323	-0.2640	-0.0872	0.1012	-0.1995	1.0000	-0.1871	0.1070
DDE	0.0404	-0.0129	0.3696	0.4410	-0.0070	-0.1871	1.0000	-0.0119
DDT	-0.1181	-0.1122	0.0274	0.0540	0.1334	0.1070	-0.0119	1.0000

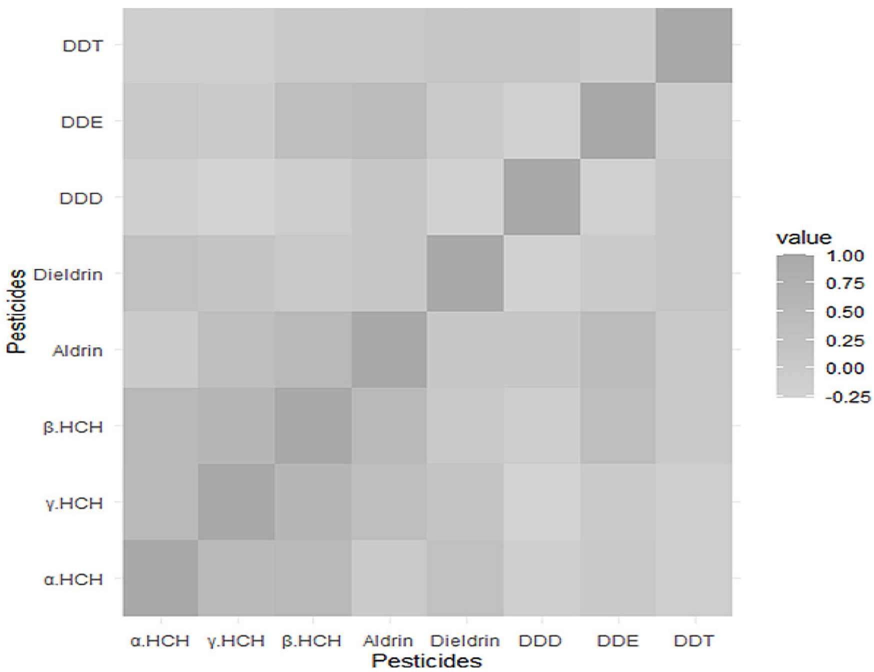

Figure 3. Correlation matrix of organochlorine pesticide (OCP) concentrations detected in the muscle tissues of *Oreochromis niloticus*. Color gradients indicate the strength and direction of the correlations among the investigated compounds

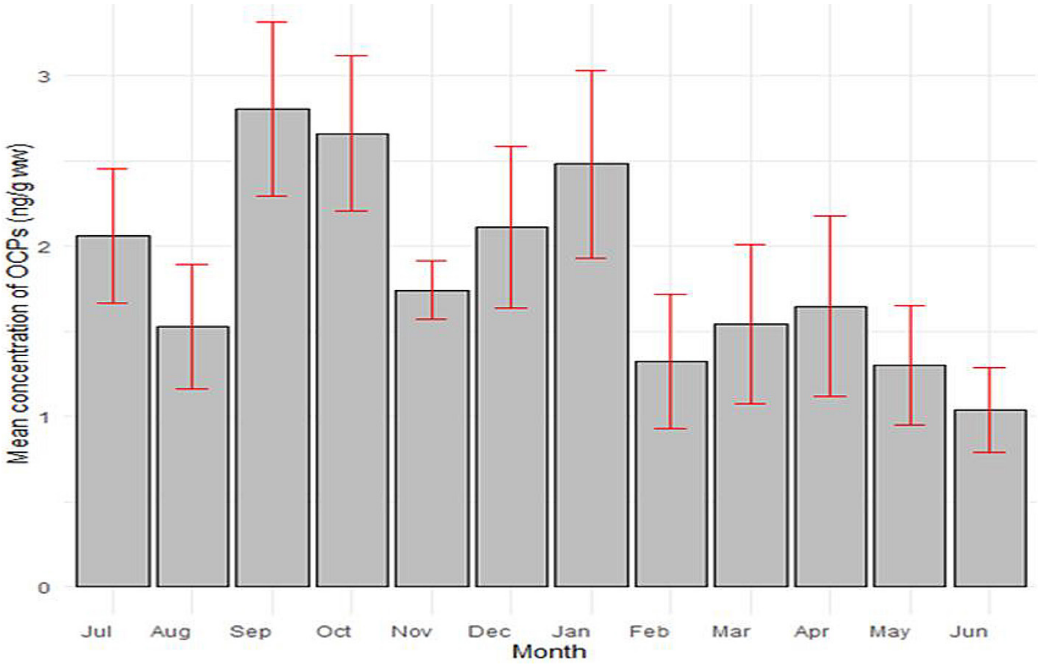

Figure 4. Monthly variation in mean total OCP concentrations (± SE) in the muscle tissues of *Oreochromis niloticus* from Al Massira Reservoir between July 2022 and June 2023

Influence of morphometric characteristics on OCP concentrations

Linear regression analysis showed no significant relationship between total length and the concentrations of the investigated organochlorine pesticides ($p > 0.05$; Table 1). Likewise, body weight was not significantly associated with the concentrations of most compounds. The only exception was dieldrin, which showed a significant positive relationship with body weight ($R^2 = 0.238$; $p = 0.016$; Table 2).

Human health risk assessment associated with the consumption of Nile tilapia

The concentrations of organochlorine pesticides detected in the *Oreochromis niloticus* muscle were compared with the maximum residue limits (MRLs) established by the European Union, the United States Food and Drug Administration (FDA), and Health Canada. All measured concentrations remained below the corresponding regulatory limits (Table 3).

Table 2. Relationships between the morphometric characteristics of *Oreochromis niloticus* and organochlorine pesticide concentrations in muscle tissues

Compound	Total length			Total weight		
	b	*R²* (%)	*p*	*b*	*R²* (%)	*p*
α-HCH	-0.410	8.9	> 0.05	-0.226	11.74	0.101
γ-HCH	-0.175	1.1	> 0.05	-0.148	3.55	0.378
β-HCH	-0.070	0.1	> 0.05	-0.093	1.02	0.638
Aldrin	0.141	0.28	> 0.05	-0.574	0.03	0.941
Dieldrin	-0.981	16.0	> 0.05	**0.574**	**23.81**	**0.016***
p,p'-DDD	0.106	0.56	> 0.05	0.081	1.43	0.578
p,p'-DDE	0.264	1.67	> 0.05	0.142	2.08	0.501
p,p'-DDT	-0.732	7.0	> 0.05	-0.315	5.60	0.266

Note: *b*: slope coefficient of the linear regression, R^2: coefficient of determination, * indicates a statistically significant relationship ($p < 0.05$).

Table 3. Concentrations of organochlorine pesticides (OCPs) in the muscle tissues of *Oreochromis niloticus* and comparison with international regulatory limits

OCPs	EU MRL (ng g⁻¹)	FDA MRL (ng g⁻¹)	Health Canada MRL (ng g⁻¹)	Mean ± SE (ng g⁻¹ ww)	Range (ng g⁻¹ ww)
α-HCH	200	–	–	0.887 ± 0.65	BDL–2.171
γ-HCH (Lindane)	200	–	–	1.364 ± 0.97	BDL–3.535
β-HCH	–	–	–	2.130 ± 1.37	BDL–5.305
ΣHCHs	–	–	–	1.460 ± 1.14	BDL–5.305
Aldrin	200	300	–	2.416 ± 2.65	BDL–8.445
Dieldrin	200	300	–	2.500 ± 1.75	BDL–5.611
ΣDrins	–	–	–	2.409 ± 2.18	BDL–8.445
p,p'-DDD	1000	5000	5000	0.957 ± 0.69	BDL–2.226
p,p'-DDE	1000	5000	5000	1.870 ± 1.33	BDL–4.634
p,p'-DDT	1000	5000	5000	2.730 ± 2.26	BDL–7.571
ΣDDTs	–	–	–	1.830 ± 1.72	BDL–7.571

Note: EU – European Union, FDA – United States Food and Drug Administration.

Mean OCP concentrations ranged from 0.89 ng g^{-1} ww for α-HCH to 2.73 ng g^{-1} ww for p,p′-DDT. Among the investigated compounds, DDTs showed the highest concentrations, followed by drins and HCHs.

Estimated Daily Intake (*EDI*)

EDI values were calculated for adults, high fish consumers, and children. For all exposure scenarios, the EDI values based on both the 50th and 95th percentile concentrations remained below the corresponding Acceptable Daily Intake (ADI) values established by the US EPA. Among the investigated compounds, p,p′-DDT and dieldrin produced the highest EDI values, whereas α-HCH and p,p′-DDD showed the lowest. Children exhibited the highest estimated dietary exposure, while adults had the lowest (Table 4).

Carcinogenic risk assessment

HR values calculated for all investigated organochlorine pesticides remained below 1 for adults, high fish consumers, and children. Aldrin and dieldrin exhibited the highest HR values, particularly in children. Even under the most conservative exposure scenario based on the 95th percentile concentrations, all HR values remained below unity (Table 5).

DISCUSSION

Patterns of OCP contamination in Nile tilapia from the Al Massira Reservoir

Organochlorine pesticide residues were detected in the muscle of *Oreochromis niloticus*,

Table 4. Estimated daily intake (EDI; ng kg^{-1} bw day^{-1}) associated with the consumption of *Oreochromis niloticus*

OCPs	ADI (ng kg⁻¹ day⁻¹)	Adults (Mean)	Adults (*P95*)	High consumers (Mean)	High consumers (*P95*)	Children (Mean)	Children (P95)
α-HCH	5000	0.45	1.04	0.67	1.56	1.10	2.57
β-HCH	5000	1.10	2.17	1.63	3.21	2.68	5.29
γ-HCH	5000	0.70	1.47	1.04	2.17	1.71	3.57
Aldrin	100	1.24	4.22	1.84	6.25	3.03	10.28
Dieldrin	100	1.29	2.60	1.91	3.84	3.15	6.32
p,p'-DDD	10000	0.49	1.12	0.72	1.66	1.19	2.74
p,p'-DDE	10000	0.96	2.09	1.43	3.10	2.35	5.10
p,p'-DDT	10000	1.41	3.44	2.09	5.09	3.43	8.37

Table 5. Carcinogenic risk ratios (HRs) associated with the consumption of *Oreochromis niloticus*

OCPs	Adults (Mean)	Adults (*P95*)	High consumers (Mean)	High consumers (*P95*)	Children (Mean)	Children (*P95*)
α-HCH	2.6×10^{-4}	5.9×10^{-4}	5.6×10^{-4}	8.5×10^{-4}	1.0×10^{-3}	3.5×10^{-3}
β-HCH	6.3×10^{-4}	1.6×10^{-3}	1.3×10^{-3}	2.7×10^{-3}	3.7×10^{-3}	7.3×10^{-3}
γ-HCH	4.0×10^{-4}	8.4×10^{-4}	8.0×10^{-4}	1.8×10^{-3}	2.3×10^{-3}	4.9×10^{-3}
Aldrin	1.0×10^{-2}	3.2×10^{-2}	2.2×10^{-2}	7.6×10^{-2}	6.1×10^{-2}	2.08×10^{-1}
Dieldrin	1.0×10^{-2}	2.1×10^{-2}	2.3×10^{-2}	4.7×10^{-2}	6.3×10^{-2}	1.28×10^{-1}
p,p'-DDD	8.6×10^{-5}	2.0×10^{-4}	2.0×10^{-4}	4.0×10^{-4}	5.1×10^{-4}	1.1×10^{-3}
p,p'-DDE	1.7×10^{-4}	3.7×10^{-4}	4.0×10^{-4}	9.0×10^{-4}	1.0×10^{-3}	2.1×10^{-3}
p,p'-DDT	2.5×10^{-4}	6.0×10^{-4}	6.0×10^{-4}	1.5×10^{-3}	1.4×10^{-3}	3.6×10^{-3}

Note: *HR* < 1 indicates an acceptable carcinogenic risk level.

although all measured concentrations remained below the maximum residue limits established by international regulatory agencies. These findings indicate a relatively low contamination status of Nile tilapia from the Al Massira Reservoir compared with the values reported for several freshwater ecosystems (Eqani et al., 2013; Van Ael et al., 2013).

HCH isomers were detected at concentrations ranging from below the detection limit to 5.305 ng g^{-1} ww, remaining lower than those reported for *Clarias gariepinus* and *Oreochromis mossambicus* from African aquatic ecosystems (Table 6). The predominance of γ-HCH over α-HCH, reflected by an α-HCH/γ-HCH ratio of 0.65 ± 0.67, suggests recent inputs of lindane. Likewise, a β-HCH/γ-HCH ratio above unity (1.56 ± 1.41) is consistent with the greater environmental persistence of β-HCH, the most stable HCH isomer (Yang et al., 2015; Eqani et al., 2013; Kumari et al., 2014; Chakraborty et al., 2017).

The ΣDDT concentrations observed in *O. niloticus* were comparable to those reported in several African aquatic ecosystems, including the same species from Lake Edward, Uganda (BDL–51 ng g^{-1} ww) (Ssebugere et al., 2009), and Lake Ziway, Ethiopia (0.9–5.1 ng g^{-1} ww) (Yohannes et al., 2014). However, they were considerably lower than the concentrations reported from heavily contaminated environments in Nigeria and South Africa (Williams et al., 2013; Govaerts et al., 2018). The simultaneous

Table 6. Comparison of organochlorine pesticide (OCP) concentrations (ng g^{-1} ww) in the fish muscle tissues reported from different aquatic ecosystems worldwide

Species	ΣHCHs (ng g^{-1} ww)	ΣDDTs (ng g^{-1} ww)	ΣDrins (ng g^{-1} ww)	ΣOCPs (ng g^{-1} ww)	Reference
Oreochromis niloticus	BDL–5.305	BDL–7.571	BDL–8.445	BDL–5.6264	This study
Clarias gariepinus	6–179	11–264	–	2–267	Buah-Kwofie et al. (2018)
Clarias gariepinus	BDL–515	BDL–601	BDL–315	BDL–601	Buah-Kwofie et al. (2018)
Oreochromis mossambicus	0.8–132.6	3.7–111.7	2.4–23.3	0.8–132.6	Buah-Kwofie et al. (2018)
Oreochromis niloticus	–	20–30	–	–	Buah-Kwofie et al. (2018)
Oreochromis mossambicus	0.7–1.4	3.4–11.9	0.3–0.6	–	Buah-Kwofie et al. (2018)
Oreochromis niloticus	–	BDL–51	–	–	Buah-Kwofie et al. (2018)
Prochilodus lineatus	0.1–18.0	220–380	–	–	Colombo et al. (2011)
Odontesthes bonariensis	1.14–13.81	1.01–3.00	BDL–0.11	–	Menone et al. (2000)
Mixed fish species	1.82–8.38	0.05–10.3	–	–	Fair et al. (2018)
Three-species assemblage	–	–	BDL–18.00	–	Granados-Galván et al. (2015)
Oreochromis niloticus	5.81–8.17	6.81–9.31	–	–	Abbassy (2018)
Pomadasys commersonnii	BDL–191.1	BDL–27.1	BDL–232.2	–	Olisah et al. (2019a)
Mugil cephalus	0.6–57.8	BDL–6.8	3.9–186	–	Olisah et al. (2019a)

Note: BDL – below detection limit.

occurrence of DDT and its major metabolites (DDE and DDD) reflects the historical persistence of these compounds in the environment. Due to their high chemical stability and elevated octanol–water partition coefficients (*Kow*), DDT residues can remain in aquatic ecosystems for several decades after their application (Fisk et al., 2001). Previous studies have demonstrated that DDT is progressively transformed into DDE and DDD in both organisms and environmental matrices (Sericano et al., 1990; Newsome and Andrews, 1993), suggesting that the residues detected in the Al Massira Reservoir are primarily associated with historical inputs, rather than recent contamination events.

The ΣDrin concentrations measured in *O. niloticus* ranged from BDL to 8.445 ng g^{-1} ww. These levels are comparable to those reported in several studies conducted in Mexico and Vietnam (Redondo-López et al., 2022). Variations among studies may be attributed to differences in environmental conditions, local contamination levels, and species-specific biological characteristics, including metabolic activity, detoxification capacity, feeding behavior, and body composition (Redondo-López et al., 2022).

Influence of morphometric characteristics on OCP accumulation

No significant relationship was found between fish total length and OCP concentrations, while body weight was unrelated to the concentrations of most compounds. Similar observations have been reported in previous studies, indicating that contaminant accumulation is influenced more by environmental conditions, feeding behavior, trophic ecology, and the physicochemical properties of pollutants than by fish size alone (McIntyre et al., 2007; Le Croizier et al., 2016; Anzalone et al., 2024; Dey et al., 2024; Jamil Emon et al., 2024).

In contrast, dieldrin concentration increased significantly with body weight. This relationship may reflect greater accumulation in larger individuals as a result of prolonged exposure and increased lipid storage capacity. However, the moderate coefficient of determination (R^2 = 0.238) suggests that body weight explains only part of the observed variability, with additional biological and environmental factors likely contributing to dieldrin accumulation (Borgå et al., 2002; Burreau et al., 2004; Nowell et al., 2009).

Human health risk assessment associated with the consumption of Nile tilapia

Fish consumption is a major route of human exposure to persistent organic pollutants (Paiano et al., 2013). The measured OCP concentrations in *Oreochromis niloticus* remained below the maximum residue limits established by international regulatory agencies, indicating limited contamination of edible muscle tissues.

EDI was evaluated for adults, high fish consumers, and children. In all exposure scenarios, EDI values remained below the corresponding acceptable daily intake (ADI) thresholds recommended by the US Environmental Protection Agency (US EPA). For adults, EDI values ranged from 0.45 to 1.41 ng kg^{-1} bw day^{-1} based on mean concentrations and from 1.04 to 4.22 ng kg^{-1} bw day^{-1} using the 95th percentile concentrations. Collectively, these results support the conclusion that dietary exposure to OCPs through the consumption of *Oreochromis niloticus* from Al Massira Reservoir is unlikely to pose a significant health concern.

Similar observations have been reported for *Oreochromis niloticus* from Ethiopia, where the EDI values associated with HCHs and DDTs remained substantially below the corresponding ADI thresholds (Yohannes et al., 2014). Comparable results have also been documented for several freshwater fish species from South Africa exposed to organochlorine pesticides (Buah-Kwofie et al., 2018; Volschenk et al., 2019). In contrast, Ogbeide et al. (2016) reported EDI values exceeding recommended limits for aldrin and dieldrin in certain African fish species, highlighting the influence of local environmental conditions on contamination levels and human exposure.

HR values remained below 1 for adults, high fish consumers, and children under both average and high-exposure scenarios. HR values ranged from 8.6×10^{-5} to 1.0×10^{-2} based on mean concentrations, from 8.8×10^{-5} to 1.3×10^{-2} using the 50th percentile concentrations, and from 8.4×10^{-4} to 2.1×10^{-2} using the 95th percentile concentrations. Overall, the calculated HR values indicate a negligible carcinogenic risk associated with the consumption of *Oreochromis niloticus* from the Al Massira Reservoir.

These findings differ from those reported by Yohannes et al. (2014), who observed HR values exceeding 1 for HCHs in *O. niloticus* under certain exposure scenarios. Such discrepancies among studies may be attributed to differences in environmental contamination levels, fish consumption patterns, and population-specific characteristics used in risk assessment models (Hussein et al., 2022; Sarrazin et al., 2022; KV et al., 2024). The relatively low OCP concentrations observed in *Oreochromis niloticus* from the Al Massira Reservoir may reflect the long-term ban and restriction of organochlorine pesticides under the Stockholm Convention and Moroccan regulations, which have contributed to a gradual decline in environmental contamination (UNEP, 2001). In addition, environmental processes, such as sedimentation and natural degradation, may have reduced the bioavailability of these compounds, while legacy residues stored in soils and sediments could explain the low concentrations still detected in fish tissues (Taiwo, 2019; Olisah et al., 2020).

Although the current findings suggest a low health risk associated with the consumption of *Oreochromis niloticus* from the Al Massira Reservoir, the continued occurrence of OCP residues in edible tissues supports the need for regular environmental monitoring. Continued surveillance is particularly important for vulnerable population groups, especially children and frequent fish consumers, to ensure long-term food safety and effective public health protection.

CONCLUSIONS

This study presented the first assessment of organochlorine pesticide contamination in *Oreochromis niloticus* from the Al Massira Reservoir, Morocco. All investigated compounds were detected, with dieldrin and DDTs occurring at the highest concentrations, whereas HCH isomers were comparatively less abundant. OCP concentrations showed no significant temporal variation, and fish size had little influence on residue levels, except for a positive relationship between body weight and dieldrin concentration.

All measured concentrations remained below international maximum residue limits, while EDI values and HRs indicated low dietary exposure and negligible carcinogenic risk for adults, high fish consumers, and children.

Although the current contamination levels do not represent an immediate public health concern, the persistence of OCP residues highlights the importance of continued environmental monitoring. Overall, the results contribute to a better understanding of organochlorine pesticide occurrence in Moroccan freshwater ecosystems and their implications for food safety.

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