



Organochlorine Pesticides (OCPs) in Fish Samples from the Iraqi Coast, Northwest Arabian Gulf: Distribution, Sources, and Health Risk Assessment

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ABSTRACT

This study investigated the distribution, probable sources, and food-safety implications of 14 organochlorine pesticides (OCPs) in ten commercially important fish species from the Iraqi coast of the northwest Arabian Gulf. Fish muscle samples ($n = 120$) were collected during spring and autumn 2024 from five coastal stations and analyzed by gas chromatography-electron capture detection (GC-ECD). Total OCP concentrations ranged from 1.44 mg/kg wet weight in *Nematalosa nasus* to 26.13 mg/kg in *Saurida tumbil*, with lindane, δ -lindane, and heptachlor epoxide as the dominant residues. OCP burdens differed significantly among species (Kruskal-Wallis test, $p < 0.001$), reflecting trophic position, feeding habit, habitat preference, and lipid content. A moderate positive relationship occurred between lipid content and total OCPs (Spearman's $\rho = 0.65$, $p = 0.04$), although *Saurida tumbil* remained a marked outlier, indicating an important dietary or benthic-exposure contribution. Diagnostic ratios suggested a mixture of historical residues and possible localized recent inputs. Several residues exceeded international maximum residue limits, and the hazard index was highest for *Saurida tumbil*, indicating potential non-carcinogenic risk for frequent consumers. The findings support regular OCP monitoring and risk-based seafood-consumption guidance for fish from the Iraqi coast.

INTRODUCTION

Organochlorine pesticides (OCPs) are persistent organic pollutants (POPs) characterized by high environmental persistence, resistance to degradation, lipophilicity, and the capacity for bioaccumulation and biomagnification in aquatic food webs (Tanabe, 1988; Jabeen *et al.*, 2016). Despite international restrictions and bans under the Stockholm Convention on Persistent Organic Pollutants, OCP residues remain detectable in marine environments because of historical use, possible illegal application, atmospheric transport, sediment remobilization, and riverine inputs (Gissi *et al.*, 2013; Li *et al.*, 2013).

The northwest Arabian Gulf is a productive marine ecosystem that supports diverse fisheries and provides an important food resource for coastal communities (Al-Shami *et al.*, 2018). However, the region is exposed to anthropogenic pressures from agriculture, industrial activity, oil exploration, and urban expansion. The Shatt Al-Arab River, which drains into the northwest Arabian Gulf, is a major pathway for agricultural runoff and industrial effluents from Iraq and neighboring areas, and may therefore introduce OCPs and other contaminants into the marine environment (DouAbul *et al.*, 1988; Al-Shami *et al.*, 2018).

Recent research on Iraqi aquatic systems has emphasized that bioindicator-based monitoring of persistent organic contaminants is essential for identifying pollution sources and reducing environmental and health risks (Saleh *et al.*, 2025).

Fish consumption is a major route of human exposure to OCPs because these compounds can accumulate in edible tissues and may pose health risks, including endocrine disruption, neurotoxicity, immunotoxicity, and carcinogenicity (Burger & Gochfeld, 2005; Jabeen *et al.*, 2016). Understanding the distribution, sources, and bioaccumulation patterns of OCPs in commercially important fish species is therefore essential for evaluating ecosystem condition, seafood safety, and environmental-management priorities.

Previous studies in the Arabian Gulf region have reported variable OCP concentrations in fish, with relatively low levels in Saudi Arabian waters (0.1-1.5 mg/kg) and moderate levels in parts of the northern Gulf (2.0-15.0 mg/kg) (Al-Majed & Preston, 2000; Al-Shahristani *et al.*, 2005). Nevertheless, comprehensive data from the Iraqi coast remain limited, particularly with respect to species-specific accumulation, diagnostic source ratios, and human health-risk assessment.

This study aims to: (1) determine the levels and distribution of 14 OCPs in ten commercially important fish species from the Iraqi coast; (2) evaluate the influence of lipid content, trophic position, and habitat preference on OCP accumulation; (3) identify probable OCP sources using diagnostic ratios; (4) compare OCP concentrations with international maximum residue limits; and (5) assess potential human health risks associated with consumption of contaminated fish.

The working hypotheses were that OCP concentrations would differ among fish species because of ecological and physiological differences, that predatory and benthic species would generally show higher OCP burdens, and that some residues could exceed international safety guidelines for human consumption.

MATERIALS AND METHODS

1. Study Area and Sampling Design

Fish specimens were collected from Iraqi coastal waters of the northwest Arabian Gulf (Fig. 1) during two sampling campaigns: March-April 2024 (spring) and September-October 2024 (autumn). Five sampling stations were selected along the Iraqi coastline according to proximity to potential pollution sources and accessibility:

- Station 1: 29°59'15"N, 48°28'30"E (Khor Al-Zubair)
- Station 2: 30°05'22"N, 48°20'15"E (Shatt Al-Arab mouth, north)
- Station 3: 30°10'45"N, 48°15'30"E (Shatt Al-Arab mouth, south)
- Station 4: 30°20'10"N, 48°10'20"E (Fao region)
- Station 5: 30°30'05"N, 48°05'15"E (Bubian Island vicinity)



Fig. 1. Sampling locations along the Iraqi coast, northwest Arabian Gulf.

Ten commercially important fish species were targeted, representing diverse ecological niches and feeding habits: *Nematalosa nasus* (Bloch, 1795) (pelagic filter-feeder), *Cynoglossus arel* (Bloch & Schneider, 1801) (benthic predator), *Johnieops sina* (Cuvier, 1830) (demersal predator), *Liza subviridis* (Cuvier & Valenciennes, 1836) (pelagic omnivore), *Synaptura orientalis* (Bloch & Schneider, 1801) (benthic predator), *Otolithes ruber* (Bloch & Schneider, 1801) (pelagic predator), *Acanthopagrus latus* (Houttuyn, 1782) (demersal omnivore), *Tenualosa ilisha* (Hamilton, 1822) (pelagic filter-feeder), *Epinephelus coioides* (Hamilton, 1822) (reef-associated predator), and *Saurida tumbil* (Bloch, 1795) (benthic predator).

For each species, 10-15 individuals were collected (total $n = 120$) using gill nets and trawling. Fish were measured for total length (± 0.1 cm) and wet weight (± 0.1 g). Muscle tissue from each fish was analyzed separately as an individual biological replicate to capture intraspecies variability.

2. Sample Processing

Collected fish were transported on ice to the laboratory, identified using standard taxonomic keys (Carpenter *et al.*, 1997), measured, and dissected. Edible dorsal muscle tissue was separated, homogenized using a stainless-steel blender, and stored at -20°C in pre-cleaned glass jars with Teflon-lined lids until chemical analysis.

Muscle lipid content (% fat) was determined gravimetrically by Soxhlet extraction using petroleum ether (boiling range $40\text{--}60^{\circ}\text{C}$), following Bligh and Dyer (1959) with minor modifications. Briefly, 5 g of homogenized tissue was extracted with 100 mL petroleum ether for 6 h. The extract was evaporated to dryness under reduced pressure at 40°C , and lipid content was calculated gravimetrically.

3. Chemicals and Standards

Analytical-grade standards of 14 OCP compounds (α -lindane, lindane (γ -HCH), δ -lindane, heptachlor, aldrin, heptachlor epoxide, p,p'-DDE, dieldrin, p,p'-DDD, endrin aldehyde, endrin ketone,

methoxychlor, endrin, and endosulfan) were purchased from Sigma-Aldrich (St. Louis, MO, USA). 2,4,5,6-tetrachloro-m-xylene (TCMX) was used as the surrogate standard. All solvents were pesticide-residue-analysis grade.

4. Extraction and Cleanup

OCP extraction from fish muscle followed a modified version of EPA Method 8081B (USEPA, 1996) and the protocol of Murphy and Lader (1974). Approximately 25 g of wet homogenized muscle tissue was mixed with 30 g of anhydrous sodium sulfate to remove moisture, transferred to a Soxhlet thimble, and extracted with 200 mL hexane-acetone (1:1, v/v) for 16 h at a minimum of eight cycles per hour. The crude extract was concentrated to approximately 5 mL by rotary evaporation at 40 °C.

Cleanup was performed using a Florisil column (1 cm i.d. × 30 cm) packed with 10 g activated Florisil topped with 2 g anhydrous sodium sulfate. The column was pre-eluted with 50 mL hexane. The concentrated extract was applied to the column and eluted with 200 mL hexane-diethyl ether (95:5, v/v) at a flow rate of 2 mL/min. The eluate was concentrated to 1 mL under a gentle stream of nitrogen and stored in amber vials at -20 °C until GC analysis.

5. GC-ECD Analysis

The 14 target OCPs were quantified using an Agilent 7890B gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) equipped with a 63Ni electron capture detector (GC-ECD). Separation was performed on a DB-5 capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness; Agilent Technologies). Nitrogen was used as carrier gas at 1.0 mL/min and as make-up gas at 30 mL/min. Injection volume was 1 µL in splitless mode, with injector and detector temperatures maintained at 250 °C and 300 °C, respectively.

6. Quality Assurance and Quality Control

Calibration curves were prepared using six concentration levels (0.01, 0.05, 0.1, 0.5, 1.0, and 5.0 µg/mL) for each target compound, with linearity (r^2) > 0.995 for all analytes. TCMX was added to all samples as a surrogate standard to monitor extraction efficiency; surrogate recoveries ranged from 85 to 103%. Method blanks ($n = 5$) were processed with each batch of samples and showed no detectable contamination.

Method detection limits (MDLs) and limits of quantification (LOQs) were calculated using signal-to-noise ratios of 3:1 and 10:1, respectively, from the lowest calibration standards. MDLs ranged from 0.001 to 0.005 mg/kg, and LOQs ranged from 0.003 to 0.015 mg/kg. Recovery studies were performed by spiking homogenized fish samples ($n = 6$) at two concentration levels (0.5 and 2.0 µg/g). Mean recoveries ranged from 78 to 112% (Table 1), with relative standard deviations (RSDs) < 15% for all compounds. Matrix-matched calibration was used to correct for matrix effects, and values below the MDL were reported as <MDL and replaced with MDL/√2 for statistical calculations.

Table 1: Method validation parameters for target OCPs.

Compound	MDL (mg/kg)	LOQ (mg/kg)	Mean Recovery (%)	RSD (%)	r^2
α -Lindane	0.001	0.003	89	8.2	0.998
Lindane	0.001	0.004	95	6.5	0.999
δ -Lindane	0.002	0.006	88	10.1	0.997
Heptachlor	0.001	0.004	92	7.4	0.998
Aldrin	0.002	0.005	85	9.8	0.996
heptachlor epoxide	0.003	0.009	82	12.3	0.996
p,p'-DDE	0.001	0.003	96	5.9	0.999
Dieldrin	0.002	0.006	90	8.7	0.998

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p,p'-DDD	0.002	0.005	91	7.3	0.998
Endrin Aldehyde	0.003	0.010	79	13.5	0.995
Endrin Ketone	0.004	0.012	78	14.2	0.995
Methoxychlor	0.005	0.015	84	11.8	0.996
Endrin	0.002	0.006	87	9.1	0.997
Endosulfan	0.003	0.008	83	10.5	0.997

RESULTS

1. Fish Biometric Data

Biometric data for the ten fish species are presented in Table (2) and Fig. (2). Fish length ranged from 15.2 ± 2.1 cm in *Liza subviridis* to 45.8 ± 5.3 cm in *Epinephelus coioides*, and body weight ranged from 45.3 ± 8.2 g to 845.6 ± 95.4 g in the same species. Lipid content varied substantially among species, with the highest values in *Cynoglossus arel* ($19.84 \pm 2.15\%$) and *Acanthopagrus latus* ($16.54 \pm 1.88\%$), and the lowest values in *Synaptura orientalis* ($1.49 \pm 0.21\%$) and *Nematalosa nasus* ($1.91 \pm 0.25\%$).

Table 2: Biometric data and lipid content of fish species (mean $\pm$ SD).

Species	n	Total Length (cm)	Wet Weight (g)	Lipid Content (%)
<i>Nematalosa nasus</i>	12	22.4 ± 3.1	125.3 ± 18.6	1.91 ± 0.25
<i>Cynoglossus arel</i>	10	28.6 ± 4.2	215.8 ± 32.4	19.84 ± 2.15
<i>Johnieops sina</i>	12	35.2 ± 4.8	342.5 ± 45.7	6.53 ± 0.87
<i>Liza subviridis</i>	15	15.2 ± 2.1	45.3 ± 8.2	3.36 ± 0.42
<i>Synaptura orientalis</i>	12	25.8 ± 3.5	168.4 ± 22.6	1.49 ± 0.21
<i>Otolithes ruber</i>	12	32.4 ± 4.1	285.6 ± 38.4	13.67 ± 1.54
<i>Acanthopagrus latus</i>	10	28.2 ± 3.8	198.5 ± 28.7	16.54 ± 1.88
<i>Tenualosa ilisha</i>	12	38.5 ± 4.9	456.7 ± 56.8	12.01 ± 1.43
<i>Epinephelus coioides</i>	10	45.8 ± 5.3	845.6 ± 95.4	3.59 ± 0.48
<i>Saurida tumbil</i>	15	32.6 ± 4.2	298.4 ± 42.3	2.01 ± 0.28

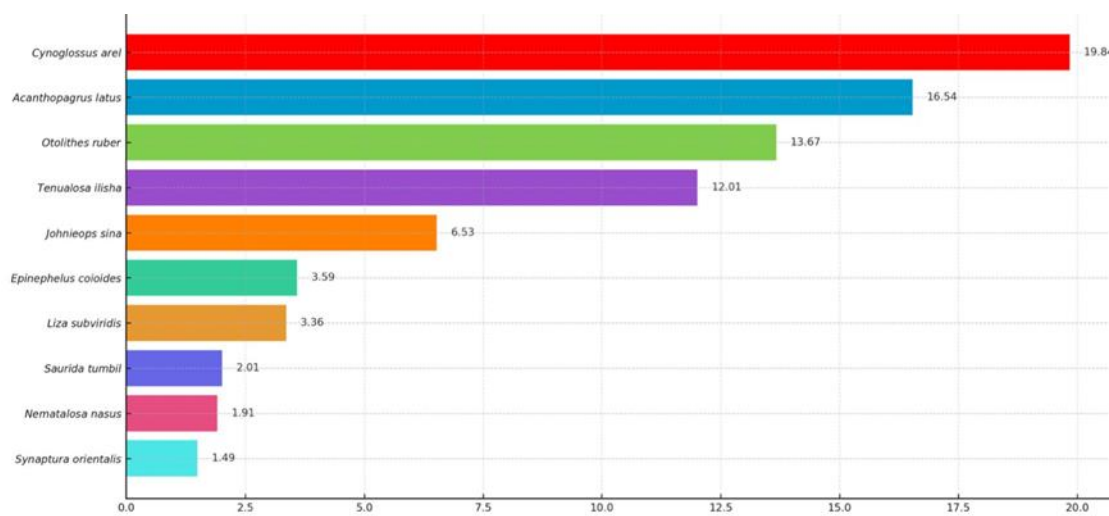


Fig. 2. Total lipid content (%) in fish muscle samples.

2. OCP Concentrations in Fish Species

The concentrations of the 14 OCP compounds in the ten fish species are presented in Table (3) and Fig. (3). Total OCP concentrations (Σ OCPs) ranged from 1.44 ± 0.28 mg/kg wet weight in *Nematalosa nasus* to 26.13 ± 5.24 mg/kg in *Saurida tumbil*. Significant interspecies variability was detected (Kruskal-Wallis test, $H = 38.76$, $df = 9$, $p < 0.001$), with *Saurida tumbil* showing substantially higher concentrations than all other species (Dunn's post-hoc test, $p < 0.01$).

Table 3. OCP concentrations (mg/kg wet weight, mean $\pm$ SD) in fish species.

Pesticide	<i>N. nasus</i>	<i>C. arel</i>	<i>J. sina</i>	<i>L. subviridis</i>	<i>S. orientalis</i>	<i>O. ruber</i>	<i>A. latus</i>	<i>T. ilisha</i>	<i>E. coioides</i>	<i>S. tumbil</i>
Alpha-lindane	0.02077	0.1132	0.04899	0.00852	0.00787	0.0255	0.0776	0.1147	0.0284	0.0394
Lindane	0.2077	0.0754	0.00544	0.3409	0.2295	0.3839	0.7765	0.206	0.5284	8.0915
δ -lindane	0.1384	0.1006	2.1	0.2083	1.331	0.2559	0.6532	1.469	1.2195	3.5523
Heptachlor	0.0346	0.31446	0.06528	0.00189	0.0745	0.0639	0.2912	0.0441	0.0325	0.1973
Aldrin	0.0692	0.1886	0.637	0.0947	0.05737	0.01279	0.3106	0.1118	0.1219	2.3682
heptachlor epoxide	0.4154	0.371	0.373	0.142	1.09	0.05119	0.152	0.1	1.908	6.5127
D.D.E	0.0692	0.1635	0.03264	0.0473	0.05163	0.0895	0.1941	0.0441	0.0813	0.3157
Dieldrin	0.0346	0.2767	0.02176	0.1704	0.0459	0.1407	0.063	0.0559	0.0609	0.1184
D.D.D	0.1384	0.05031	0.05984	0.0189	0.1663	0.0127	0.1358	0.0264	0.0365	0.3552
Endrin aldehyde	0.05539	0.08805	0.0544	0.00947	0.00573	0.0255	0.097	0.0588	0.0447	1.0657
Endrin Ketone	0.1938	0.178	0.07072	0.1326	0.11475	0.1023	0.091	0.209	0.1016	0.9473

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Methoxy chlor	0.0346	0.0754	0.16864	0.2083	0.086	0.1151	0.1747	0.0824	0.2439	0.7499
Endrin	0.02077	0.06289	0.2176	0.2746	0.0975	0.1407	0.33	0.1236	0.4065	1.0262
Endosulfan	0.00692	0.304	2.575	0.0947	0.482	0.348	1.5143	0.2089	0.1991	0.7894
Total pesticide	1.43975	2.36211	6.43031	1.75258	3.84005	1.76768	4.861	2.8547	5.0132	26.1292

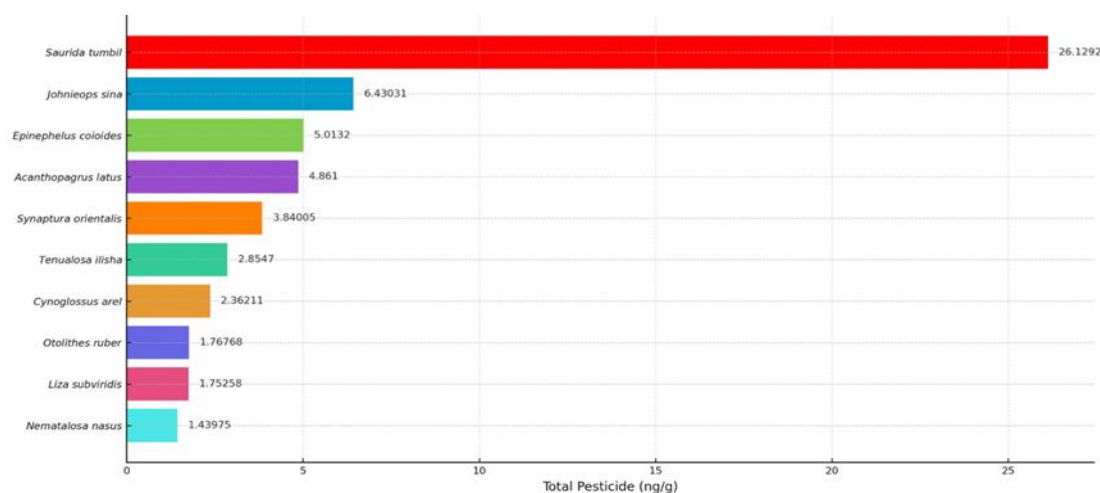


Fig. 3. Total OCP concentrations in fish samples.

The predominant compounds across species were lindane, δ -lindane, and heptachlor epoxide. In *Saurida tumbil*, lindane (8.09 ± 1.22 mg/kg) and heptachlor epoxide (6.51 ± 0.98 mg/kg) accounted for approximately 56% of the total OCP burden. *Johnieops sina* showed elevated endosulfan (2.58 ± 0.39 mg/kg) and δ -lindane (2.10 ± 0.32 mg/kg), whereas *Epinephelus coioides* showed high heptachlor epoxide (1.91 ± 0.29 mg/kg) and δ -lindane (1.22 ± 0.18 mg/kg).

3.3 Relationship between Lipid Content and OCP Accumulation

A moderate positive correlation was observed between lipid content and Σ OCP concentration across all species (Spearman's $\rho = 0.65$, 95% CI: 0.08-0.91, $p = 0.04$). However, *Saurida tumbil* was a marked outlier (Grubbs' test, $G = 3.42$, $p < 0.05$), exhibiting the highest OCP burden (26.13 ± 5.24 mg/kg) despite relatively low lipid content ($2.01 \pm 0.28\%$). When *Saurida tumbil* was excluded, the correlation strengthened (Spearman's $\rho = 0.78$, 95% CI: 0.42-0.94, $p = 0.01$). *Synaptura orientalis* also showed relatively high OCPs (3.84 ± 0.68 mg/kg) with low lipid content ($1.49 \pm 0.21\%$), suggesting that factors other than lipid content influenced accumulation.

For individual compounds, significant positive correlations with lipid content were observed for p,p'-DDE ($\rho = 0.72$, $p = 0.02$), Endrin ($\rho = 0.68$, $p = 0.03$), and dieldrin ($\rho = 0.64$, $p = 0.04$). Conversely, lindane ($\rho = 0.42$, $p = 0.23$) and heptachlor epoxide ($\rho = 0.38$, $p = 0.28$) showed non-significant

correlations, suggesting these compounds may accumulate primarily through dietary exposure rather than lipid partitioning.

4. Species-Specific Accumulation Patterns

Distinct species-specific accumulation patterns were observed (Table 4). *Saurida tumbil* exhibited the highest levels of several OCPs, including lindane, aldrin, heptachlor epoxide, endrin aldehyde, endrin ketone, methoxychlor, and endrin. *Cynoglossus arel* showed the highest concentrations of α -lindane, heptachlor, p,p'-DDE, and dieldrin, whereas *Johnieops sina* had the highest levels of δ -lindane and endosulfan. *Synaptura orientalis* recorded the highest p,p'-DDD concentration (0.166 ± 0.025 mg/kg).

Table 4. Fish species with highest levels of specific OCPs.

OCP Compound	Species with Highest Level	Concentration (mg/kg, Mean $\pm$ SD)
α -Lindane	<i>Cynoglossus arel</i>	0.113 ± 0.018
Lindane	<i>Saurida tumbil</i>	8.092 ± 1.215
δ -Lindane	<i>Johnieops sina</i>	2.100 ± 0.315
Heptachlor	<i>Cynoglossus arel</i>	0.314 ± 0.048
Aldrin	<i>Saurida tumbil</i>	2.368 ± 0.356
heptachlor epoxide	<i>Saurida tumbil</i>	6.513 ± 0.977
p,p'-DDE	<i>Cynoglossus arel</i>	0.164 ± 0.025
Dieldrin	<i>Cynoglossus arel</i>	0.277 ± 0.042
p,p'-DDD	<i>Synaptura orientalis</i>	0.166 ± 0.025
Endrin Aldehyde	<i>Saurida tumbil</i>	1.066 ± 0.160
Endrin Ketone	<i>Saurida tumbil</i>	0.947 ± 0.142
Methoxychlor	<i>Saurida tumbil</i>	0.750 ± 0.113
Endrin	<i>Saurida tumbil</i>	1.026 ± 0.154
Endosulfan	<i>Johnieops sina</i>	2.575 ± 0.386

5. Diagnostic Ratios for Source Identification

Diagnostic ratios were calculated to distinguish between historical residues and possible recent OCP inputs (Table 5). The α -HCH/ γ -HCH ratio ranged from 0.01 to 9.80 across species. Most species had values <1 , indicating the predominance of lindane (γ -HCH), whereas the higher ratios in *Johnieops sina* and *Cynoglossus arel* may reflect localized technical HCH signatures or differential degradation.

The DDT/(DDE+DDD) ratio ranged from 0.14 to 1.42. Values <1 in most species indicated weathered or historical DDT residues. However, *Johnieops sina* showed a ratio >1 , suggesting possible recent DDT input or spatially localized exposure. The DDE/DDT ratio was >1 in *Cynoglossus arel* and *Nematalosa nasus*, indicating aerobic degradation of DDT to DDE.

Heptachlor/heptachlor epoxide ratios were generally < 1 (range: 0.03-0.85), suggesting transformation of heptachlor to its epoxide form, consistent with historical application.

Table 5. Diagnostic ratios for OCP source identification.

Species	α -HCH/ γ -HCH	DDT/(DDE+DDD)	DDE/DDT	Heptachlor/heptachlor epoxide
<i>N. nasus</i>	0.10	0.33	1.38	0.08
<i>C. arel</i>	1.50	0.72	2.01	0.85
<i>J. sina</i>	9.80	1.42	0.47	0.17
<i>L. subviridis</i>	0.03	0.22	0.75	0.01
<i>S. orientalis</i>	0.04	0.21	0.75	0.07
<i>O. ruber</i>	0.07	0.73	1.07	1.25
<i>A. latus</i>	0.10	0.53	0.95	1.92
<i>T. ilisha</i>	0.56	0.69	0.84	0.44
<i>E. coioides</i>	0.05	0.64	0.67	0.02
<i>S. tumbil</i>	0.01	0.25	0.26	0.03

6. Comparison with International Maximum Residue Limits

Comparison of OCP concentrations with international maximum residue limits (MRLs) indicated that several species exceeded safety thresholds (Table 6). *Saurida tumbil* exceeded EU MRLs for lindane by approximately 16-fold, aldrin plus dieldrin by approximately 12-fold, and endrin by approximately two-fold. *Johnnieops sina* exceeded the EU MRL for endosulfan by approximately five-fold.

Table 6. Comparison with international maximum residue limits (MRLs).

Species	Compound	Detected (mg/kg)	EU MRL (mg/kg)	Codex MRL (mg/kg)	USEPA Tolerance (mg/kg)
<i>S. tumbil</i>	Lindane	8.09	0.5	0.5	0.5
<i>S. tumbil</i>	Aldrin+Dieldrin	2.49	0.2	0.2	0.3
<i>S. tumbil</i>	Endrin	1.03	0.5	0.5	0.1
<i>J. sina</i>	Endosulfan	2.58	0.5	0.5	0.5
<i>C. arel</i>	Heptachlor	0.31	0.3	0.3	0.2

7. Human Health Risk Assessment

Estimated daily intake (EDI), hazard quotients (HQs), and hazard index (HI) values for fish consumption are presented in Table (7). The highest EDI was calculated for *Saurida tumbil* (43.55 $\mu\text{g/kg bw/day}$). For this species, individual HQs ranged from 0.5 to 8.2, with lindane, heptachlor epoxide, and aldrin contributing most strongly to potential non-carcinogenic risk. The HI for *Saurida tumbil* was 15.6, indicating potential non-carcinogenic health effects for frequent consumers. Moderate risks were also estimated for *Johnnieops sina* (HI = 3.8) and *Epinephelus coioides* (HI = 2.9).

Carcinogenic risk assessment for DDT and dieldrin in *Saurida tumbil* yielded cancer risks of 2.6×10^{-5} and 4.5×10^{-5} , respectively, within the USEPA acceptable range (10^{-6} to 10^{-4}) but approaching the upper bound for frequent consumers.

Table 7. Human health risk assessment parameters.

Species	EDI ($\mu\text{g/kg bw/day}$)	HI	Cancer Risk (DDT)	Cancer Risk (Dieldrin)
<i>N. nasus</i>	2.40	0.2	6.0×10^{-7}	1.4×10^{-7}
<i>C. arel</i>	3.94	0.6	2.8×10^{-6}	1.1×10^{-6}
<i>J. sina</i>	10.72	3.8	5.6×10^{-7}	8.8×10^{-8}
<i>L. subviridis</i>	2.92	0.4	8.0×10^{-7}	6.8×10^{-7}
<i>S. orientalis</i>	6.40	1.2	8.8×10^{-7}	1.8×10^{-7}
<i>O. ruber</i>	2.95	0.5	1.5×10^{-6}	5.6×10^{-7}
<i>A. latus</i>	8.10	1.8	3.3×10^{-6}	2.5×10^{-7}
<i>T. ilisha</i>	4.75	0.9	7.5×10^{-7}	2.2×10^{-7}
<i>E. coioides</i>	8.35	2.9	1.4×10^{-6}	2.4×10^{-7}
<i>S. tumbil</i>	43.55	15.6	2.6×10^{-5}	4.5×10^{-5}

DISCUSSION

1. Residue Distribution by Compound and Species

The results demonstrate clear interspecies variability in OCP concentrations, with *Saurida tumbil* showing the highest total OCP burden (26.13 ± 5.24 mg/kg) among the ten species. This pattern is consistent with previous reports from the northern Arabian Gulf, where predatory fish species showed elevated OCP levels (DouAbul *et al.*, 1988; Al-Shahristani *et al.*, 2005). The dominance of lindane, δ -lindane, and heptachlor epoxide across most species is also consistent with historical pesticide use in Iraq and neighboring regions (Al-Shami *et al.*, 2018).

The high concentrations in *Saurida tumbil* may be attributed to multiple factors. As a benthic predator that feeds mainly on small fish and crustaceans (Froese & Pauly, 2024), *S. tumbil* occupies a relatively high trophic position, which can enhance biomagnification through the food web. Its bottom-dwelling habit may also increase contact with contaminated sediments, where hydrophobic OCPs tend to accumulate (Paez-Osuna, 2001).

Cynoglossus arel and *Johnnieops sina* also exhibited elevated OCP levels (2.36 and 6.43 mg/kg, respectively). *C. arel* is a benthic flatfish that feeds on benthic invertebrates, while *J. sina* is a demersal predator. Their higher OCP concentrations compared to pelagic species such as *Nematalosa nasus* (1.44 mg/kg) and *Tenuialosa ilisha* (2.85 mg/kg) support the hypothesis that benthic and demersal species are at greater risk of OCP accumulation due to sediment-associated exposure routes.

The species with the lowest OCP burdens (*N. nasus*, *L. subviridis*, and *O. ruber*) share characteristics such as pelagic or semi-pelagic feeding habits and shorter food chains. *N. nasus* is a filter-feeder that consumes plankton, while *L. subviridis* is an omnivorous pelagic species. Their lower OCP concentrations suggest that dietary exposure and trophic position are more important determinants of OCP accumulation than lipid content alone in these species.

2. Factors Influencing Bioaccumulation: Lipid Content, Trophic Level, and Habitat

The relationship between lipid content and OCP accumulation was complex. Although a moderate positive correlation was observed across species, *Saurida tumbil* and *Synaptura orientalis* had relatively high OCP burdens despite low lipid contents. This pattern indicates that lipid content alone cannot explain OCP accumulation in the study species and that feeding mode, habitat use, and sediment-associated exposure are important determinants.

Several mechanisms may explain the high OCP concentrations in low-lipid species:

1. Dietary bioaccumulation: Both *S. tumbil* and *S. orientalis* are benthic predators that consume contaminated prey, providing a direct dietary source of OCPs that may exceed passive partitioning from water (bioconcentration) (Paez-Osuna, 2001).
2. Sediment exposure: As benthic species, they are in close contact with contaminated sediments, potentially increasing OCP uptake through dermal absorption or ingestion of sediment-associated particles (Gissi et al., 2013).
3. Specific tissue partitioning: OCPs may partition differently among tissues, with muscle tissue in low-lipid species potentially containing higher concentrations due to limited storage capacity in adipose tissue (Mackay et al., 2006).
4. Metabolic differences: Species-specific differences in OCP metabolism and elimination rates may influence accumulation patterns (Tanabe, 1988).

The trophic position of fish species, as inferred from their feeding habits, showed a strong relationship with OCP accumulation. The highest concentrations occurred in top predators (*S. tumbil*, *J. sina*, *E. coiooides*), while lower concentrations were found in lower-trophic-level species (*N. nasus*, *L. subviridis*). This pattern is consistent with biomagnification, where OCP concentrations increase with each trophic level due to dietary transfer and inefficient elimination (Mackay et al., 2006; Jabeen et al., 2016).

Habitat preference also influenced OCP accumulation. Benthic and demersal species generally had higher OCP burdens than pelagic species, reflecting the higher contamination levels in sediments and the benthic food web. This finding is consistent with studies from other regions showing that sediment-associated contaminants pose a greater risk to benthic species (Paez-Osuna, 2001; Li et al., 2013).

3. Source Attribution Using Diagnostic Ratios

The diagnostic ratios calculated in this study provide valuable insights into OCP sources and degradation status. The α -HCH/ γ -HCH ratios (< 1 in all species) suggest that lindane (γ -HCH) is the predominant HCH isomer in the environment, rather than technical HCH (which contains 60-70% α -HCH, 10-12% β -HCH, and 8-15% γ -HCH) (Li et al., 2013). This indicates that the HCH residues in fish originate primarily from historical lindane application (used as an insecticide) rather than recent technical HCH usage. However, the presence of α -HCH in some samples suggests some technical HCH contamination or isomerization of lindane under environmental conditions.

The DDT/(DDE+DDD) ratio is widely used to distinguish between historical and recent DDT inputs. Values > 1 indicate recent input, while values < 1 suggest weathered or historical residues (Tanabe, 1988; Li *et al.*, 2013). In this study, most species had ratios < 1 (mean: 0.58 ± 0.37), indicating that DDT residues in Iraqi coastal fish are predominantly from historical sources that have undergone degradation. However, *Johnieops sina* showed a ratio of 1.42, potentially suggesting localized recent DDT input. This finding is concerning and may indicate continuing illegal DDT use in the region, despite global restrictions. Further investigation with sediment and water samples is needed to confirm this observation.

The DDE/DDT ratio, which indicates aerobic degradation of DDT to DDE, was > 1 in *Cynoglossus arel* (2.01) and *N. nasus* (1.38), suggesting aerobic conditions and historical degradation in these sampling areas. In contrast, *Saurida tumbil* (0.26) and *J. sina* (0.47) had ratios < 1 , which may indicate either more recent DDT input or anaerobic conditions in the sediments where these benthic species feed (Gissi *et al.*, 2013).

The heptachlor/heptachlor epoxide ratios were generally < 1 , indicating that heptachlor has been transformed to its epoxide form, consistent with historical application and environmental aging. However, *Acanthopagrus latus* (1.92) and *Otolithes ruber* (1.25) showed ratios > 1 , suggesting possible recent heptachlor input at these locations or slower degradation rates.

Overall, the diagnostic ratios indicate a complex mixture of historical residues and possible localized recent inputs, particularly for DDT- and heptachlor-related compounds. These interpretations should be considered as probable source indicators rather than definitive source apportionment, because diagnostic ratios can be influenced by degradation, trophic transfer, and species-specific accumulation.

4. Regional Comparison

Comparison of OCP concentrations in fish from the Iraqi coast with studies from adjacent regions showed that the present values, particularly in *Saurida tumbil* and *Johnieops sina*, were higher than many reported regional values (Table 8). This difference may reflect proximity to the Shatt Al-Arab discharge, historical pesticide use, sediment remobilization, and benthic dietary exposure.

Table 8. Regional comparison of OCP levels in fish.

Reference	Location	Species	OCP Levels (mg/kg)	Key Findings
DouAbul <i>et al.</i> (1988)	Kuwaiti Waters	Various fish, shrimp	p,p'-DDE: 0.59-3.8	DDT derivatives prevalent
Al-Majed & Preston (2000)	Saudi Arabian Gulf	Various fish	0.1-1.5	Lindane and Dieldrin at low levels
Qari, (1997)	Eastern Red Sea, Saudi Arabia	Commercial fish	0.05-2.0	Mainly DDT derivatives
Al-Mughairi <i>et al.</i> (2010)	Oman coast	Various fish	0.2-5.0	Heptachlor, Endosulfan present
Al-Shahristani <i>et al.</i> (2005)	Northern Gulf (Iraq & Iran)	Predatory fish	2.0-15.0	Elevated levels, species variation
Present Study (2025)	Iraqi coast, NW Arabian Gulf	<i>S. tumbil</i> , <i>J. sina</i>	Up to 26.13	Highest in <i>S. tumbil</i> ; Lindane, heptachlor epoxide dominant

Several factors may explain the higher OCP concentrations in Iraqi coastal fish:

1. Proximity to pollution sources: The Iraqi coast receives direct inputs from the Shatt Al-Arab River, which drains agricultural areas in Iraq and neighboring countries where OCPs have been used extensively (**DouAbul et al., 1988; Al-Shami et al., 2018**).
2. Historical usage: Iraq has a history of extensive pesticide use in agriculture and public health programs, contributing to legacy contamination (**Al-Shahristani et al., 2005**).
3. Less stringent enforcement: Compared to Gulf countries with stronger environmental regulations (e.g., Saudi Arabia, Oman), Iraq may have less enforcement of pesticide restrictions, potentially allowing continued OCP use (**Al-Majed & Preston, 2000; Al-Mughairi et al., 2010**).
4. Sediment remobilization: The shallowness of the northwest Arabian Gulf and high sediment resuspension rates may remobilize historically deposited OCPs, making them bioavailable to benthic species (**Gissi et al., 2013**).

The dominance of lindane, DDT derivatives, and heptachlor in OCP profiles across the region reflects similar historical pesticide usage patterns. The high levels found in this study, however, suggest that contamination may be more severe in Iraqi waters, warranting concern and further investigation.

5. Food Safety and Health Risk Implications

The concentrations of OCPs in several fish species, particularly *Saurida tumbil*, *Johnieops sina*, and *Epinephelus coioides*, exceeded international MRLs set by the European Union, Codex Alimentarius, and USEPA. These exceedances indicate potential food-safety concerns, especially for frequent consumers and vulnerable groups.

The human health risk assessment revealed hazard indices (HI) > 1 for *Saurida tumbil* (HI = 15.6), *Johnieops sina* (HI = 3.8), and *Epinephelus coioides* (HI = 2.9), indicating potential non-carcinogenic health effects for frequent consumers. The highest individual hazard quotients were for Lindane (HQ = 3.2), heptachlor epoxide (HQ = 6.5), and Aldrin (HQ = 4.7) in *Saurida tumbil*. These compounds are known to have adverse effects on the nervous system, liver, immune system, and reproductive system (**Jabeen et al., 2016; USEPA, 2020**).

The cancer risk assessment showed that DDT and Dieldrin in *Saurida tumbil* pose cancer risks at the upper end of the acceptable range (10^{-5} to 10^{-4}). While these risks are within the USEPA acceptable range, they indicate that frequent consumption of this species could contribute to increased cancer risk over a lifetime. The combined exposure to multiple OCPs through fish consumption is particularly concerning due to potential additive or synergistic effects (**Jabeen et al., 2016**).

The health risk assessment findings are consistent with studies from other regions. **El-Agamy and Shaker (2021)** reported health risks from OCPs in fish from Edko Lake, Egypt, with DDT and Dieldrin posing potential health concerns. Similarly, **Hassan and El-Naggar (2024)** found that 15-80% of fish samples from Egyptian markets exceeded permissible limits for OCPs. The high concentrations found in Iraqi coastal fish suggest that comparable or greater health risks exist in this region.

Given the importance of fish as a protein source for coastal communities in Iraq (Al-Shami *et al.*, 2018), the present findings highlight the need for:

1. Regular monitoring: Implementation of systematic monitoring programs for OCPs and other contaminants in fish and seafood from Iraqi waters.
2. Consumption advisories: Issuance of consumption advisories for certain fish species, particularly *Saurida tumbil* and *Johnieops sina*, especially for vulnerable populations (children, pregnant women, and immunocompromised individuals).
3. Source control: Strengthening enforcement of pesticide restrictions and promoting sustainable agricultural practices to reduce OCP inputs to the marine environment.
4. Public awareness: Education of consumers about the potential health risks associated with consuming contaminated fish and guidance on safe consumption practices.

6. Limitations of the Study

Several limitations of this study should be acknowledged. First, the lack of concurrent sediment and water OCP measurements precludes direct comparison between environmental contamination levels and fish tissue residues. Such data would strengthen source attribution and provide a more complete picture of OCP cycling in the ecosystem.

Second, the relatively small sample size per species ($n = 10-15$) limits statistical power and may not capture the full range of intraspecies variability. Future studies with larger sample sizes would provide more robust estimates of species-specific OCP concentrations.

Third, without temporal sampling over multiple seasons or years, our results provide only a snapshot of OCP contamination and cannot capture seasonal or interannual variability. Seasonal differences in river discharge, agricultural practices, and fish physiology could influence OCP accumulation patterns.

Fourth, source attribution is based on limited diagnostic ratios and literature comparisons; confirmation would require analysis of additional environmental matrices and application of more sophisticated source-tracing methods (e.g., compound-specific isotope analysis, principal component analysis, or positive matrix factorization).

Fifth, our health risk assessment uses average consumption rates and may not reflect individual exposure variations or consumption of multiple contaminated species. The assumed body weight (60 kg) and daily fish consumption (100 g/day) may not be representative of all population groups, particularly children or individuals with higher or lower fish consumption patterns.

Finally, we did not analyze the stereochemical composition of OCPs or assess the presence of degradation products and metabolites that may have different toxicological profiles. Future studies should incorporate these aspects for a more comprehensive health risk assessment.

CONCLUSION

This study provides comprehensive data on the distribution, probable sources, and bioaccumulation of 14 OCPs in ten commercially important fish species from the Iraqi coast of the northwest Arabian Gulf. Total OCP concentrations varied significantly among species, with the highest burden in *Saurida tumbil* and the lowest in *Nematalosa nasus*. Lindane, δ -lindane, and heptachlor epoxide were the dominant compounds. OCP accumulation was influenced by lipid content, trophic position, habitat preference, and dietary exposure. Diagnostic ratios suggested mainly historical residues with possible localized recent inputs. Several species exceeded international MRLs, and the highest hazard index was estimated for *Saurida tumbil*. These findings support regular monitoring, source control, and risk-based consumption guidance for fish from the Iraqi coast.

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