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ORIGINAL ARTICLE

A comprehensive analysis of organochlorine pesticides in Egyptian waters: distribution, ecological impacts, and health risks

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Abstract

Organochlorine pesticides (OCPs) are a pressing global issue, particularly in developing countries like Egypt. These pervasive pesticides pose an environmental and public health concern in Egypt due to their historical use and frequent identification in soils, water bodies, and food products. These present a potential long-term risk to human health and ecosystems. We collected water and Nile tilapia (*Oreochromis Niloticus*) samples in four Egyptian governorates: Alexandria, Port Said, Ismailia, and Faiyum. Our analysis, through using gas chromatography/mass spectrometry, spans 17 OCPs in depth. Our study revealed that certain OCPs, such as Heptachlor, Aldrin, Pentachloronitrobenzene, Heptachlor epoxide, and β-Endosulfan, are consistently found in higher concentrations among the 17 pesticides tested. Seasonal spikes were identified, particularly in Ismailia, Faiyum, and Alexandria, marking them as environmental risk hotspots. Certain OCPs demonstrated distinctive seasonal variations, such as 4,4′-DDE in Faiyum. Heptachlor, β-HCH, Endrin, and α-Endosulfan exhibited significant changes solely in Ismailia, while α-HCH, Heptachlor epoxide, and γ-HCH showed unique seasonal patterns only in Alexandria. The risk quotient (RQ) analysis highlighted that Aldrin, Heptachlor, 4,4′-Dichlorodiphenyltrichloroethane, and 2,4′-Dichlorodiphenyltrichloroethane pose a high environmental risk in all governorates, while 4,4′- Dichlorodiphenyltrichloroethane showed high risk only in Port Said (RQ > 1). Several OCPs posed an ecological risk with an RQ > 1. In addition, our results emphasized that there is negligible non-carcinogenic risk associated with dermal water exposure or the consumption of Nile tilapia. There is, however, a minor risk of cancer associated with consuming Nile tilapia or dermal exposure. Therefore, we recommend advocating for strict regulations, implementing monitoring programs, initiating public health initiatives, adopting effective alternatives, developing new remediation approaches, conducting long-term and association studies, and examining the consequences of climate change on the persistence of OCPs in the environment.

Keywords Organochlorine pesticides · Ecological risk assessment · Human health risk assessment · Nile tilapia · Wastewater

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Introduction

Organochlorine pesticides (OCPs) are ubiquitous in the chlorinated hydrocarbon family of compounds that combat pests and weeds (Jayaraj et al. 2016; Ohoro and Wepener 2023). They are very prevalent in both agriculture and industry. For instance, certain OCP compounds such as Hexachlorocyclohexane (HCH), Dichlorodiphenyltrichloroethane (DDT), Aldrin, and Dieldrin are considered to be among the most used agrochemicals in developing countries worldwide (Abou-Elwafa Abdallah et al. 2017; Gupta 2004; Odongo et al. 2024; Thompson et al. 2017). OCPs are well known for their high toxicity and persistence in the environment due to several factors, including their lipophilicity, resistance to degradation (prolonged half-life), stability, and their tendency for bioaccumulation (Jayaraj et al. 2016; Mrema et al., 2014; Sharma et al., 2024). Therefore, most OCPs were banned or restricted under the Stockholm Convention in 2001 (Lallas 2001; Ohoro and Wepener 2023). Nevertheless, due to their ability to accumulate in organisms, they are considered to be a risk to public health and the whole ecosystem (Chen et al. 2020; Liu et al. 2020). OCP residuals can be distributed in the environment in air, water, and soil and can significantly impact the ecosystem.

The overuse or misuse of OCPs dramatically impacts the ecosystem, and their adverse health effects have been previously reported (Jayaraj et al. 2016). For instance, they are well-known as endocrine disruptors, neurological deregulators, metabolic and lipid deregulators, immunosuppressors, teratogens, and reproduction inhibitors (Martyniuk et al. 2020; Ohoro and Wepener 2023). They are also considered to be environmental estrogens; therefore, they are supposed to be a high-risk factor for carcinogenesis development, especially with hormonal cancer such as breast cancer. One study investigated the effect of low concentrations of 2,4′-DDT, 4,4′-Dichlorodiphenyldichloroethylene (DDE), and 4,4′-Dichlorodiphenyldichloroethane (DDD) on breast cancer cells MCF-7 and MDA-MB-231. It concluded that those compounds were significantly implicated in the proliferation and progression of the disease (Pestana et al. 2015). McGlynnet et al. (McGlynn et al. 2008) revealed an association between exposure to 4,4′-DDE and the likelihood of developing testicular germ cell tumors. Another study demonstrated an association between OCPs and the occurrence of diabetes mellitus type 2 and insulin resistance in adult men (Lee et al. 2007). OCPs are a potent stimulant for central nervous system toxicity. A good example is the induction of various neurotransmitter releases due to exposure to OCPs (Jayaraj et al. 2016).

Besides humans, birds also can be affected by OCPs exposure. Fry et al. showed that exposure to OCPs results in decreased fertility, a decrease in the number of birds, and increased teratological effects and skeletal abnormalities (Fry 1995). Likewise, farm animals can also be highly affected by OCPs exposure (Jayaraj et al. 2016). Similarly, the misuse of OCPs in developing countries can leak those compounds into lakes and rivers (Kuranchie-Mensah et al. 2012; Montuori et al. 2020; Ogbeide et al. 2015; Oginawati et al. 2022; Ogola et al. 2024; Sarkar et al. 2008; Wan et al. 2005).

The improper use of OCPs is widespread in developing countries, including Egypt, which deal with the ramifications of the previous environmental pollution due to OCPs, even though they have been banned for many years in the form of persistent pollution of water, food, and human samples despite being banned for decades which result in serious health issues (Mahmoud et al. 2016). Our previous study evaluated the seasonal distribution and health risks associated with OCPs exposed to Egypt's Kafr El-Sheikh governorate water. We found increased ecological risks, especially with Heptachlor, 2,4'- DDT, 4,4'- DDT, and Aldrin exposure. However, we observed insignificant risks related to human health associated with the Nile tilapia intake. These findings underscore the potential health risks related to OCPs exposure in the region and the urgent need for further research and possible regulatory actions (Shamma et al. 2024). Given the persistent nature and ecological hazards of OCPs, there is an urgent need to assess their current distribution in key agricultural and aquatic environments across Egypt. In this comprehensive study, we aim to evaluate the variations in the spatiotemporal distribution of OCPs in water and Nile tilapia across four governorates in Egypt with a special focus on areas of intensive agricultural activity and aquaculture activities. These regions were selected due to their high agrarian activity, aquaculture presence, and environmental vulnerability. We have thoroughly evaluated these findings' ecological and human health risks, comprehensively assessing the associated carcinogenic and non-carcinogenic risks. In addition, we have significantly increased the sample size and examined multiple areas of Egypt spanning various governorates. This research seeks to provide valuable baseline data for future monitoring, public health strategies, and regulatory efforts to control legacy pesticide pollution in Egypt.

Materials and methods

Reagents and standards

Certified standard mixtures of OCPs were purchased from SUPLECO (Bellefonte, PA, USA), and all chemicals were of analytical grade. The following compounds were used in this study, along with their CAS numbers and purities: α-Hexachlorocyclohexane-d6 (CAS No. 86194–41-4,

purity ≥ 98%), α-Hexachlorocyclohexane (CAS No. 319–84-6, purity ≥ 98%), hexachlorobenzene (CAS No. 118–74-1, purity ≥ 99%), β-Hexachlorocyclohexane (CAS No. 319–85-7, purity ≥ 98%), γ-Hexachlorocyclohexane or Lindane (CAS No. 58–89-9, purity ≥ 99%), Pentachloronitrobenzene (PCNB) (CAS No. 82–68-8, purity ≥ 98%), Heptachlor (CAS No. 76–44-8, purity ≥ 98%), Aldrin (CAS No. 309–00-2, purity ≥ 99%), Heptachlor epoxide (CAS No. 1024–57-3, purity ≥ 98%), α-Endosulfan (CAS No. 959–98-8, purity ≥ 98%), Dieldrin (CAS No. 60–57-1, purity ≥ 98%), 4,4′-DDE (4,4′-DDE; CAS No. 72–55-9, purity ≥ 98%), Endrin (CAS No. 72–20-8, purity ≥ 98%), β-Endosulfan (CAS No. 33213–65-9, purity ≥ 98%), 4,4′-DDD-d8 (p,p′-DDD-d8; CAS No. 93952–20-6, purity ≥ 98%), 4,4′-DDD (4,4′-DDD; CAS No. 72–54-8, purity ≥ 98%), 2,4′-DDT (2,4'-DDT; CAS No. 789–02-6, purity ≥ 98%), 4,4′-DDT-d8 (4,4′-DDT-d8; CAS No. 1189–64-6, purity ≥ 98%), 4,4′-DDT (4,4′-DDT; CAS No. 50–29-3, purity ≥ 99%), and Methoxychlor (CAS No. 72–43-5, purity ≥ 99%).

All deuterated internal standards, including α-HCH-d6, 4,4′-DDD -d8, and 4,4′-DDT-d8, were obtained from Toronto Research Chemicals (ON, Canada). HPLC-grade solvents were purchased from Fisher Scientific (Pittsburgh, PA), and ultrapure water was produced using a Millipore Q Water Purification System (Bedford, MA) with a resistivity of 18 MΩ cm. Anhydrous sodium sulfate (99%) was procured from Sigma-Aldrich (St. Louis, MI), and QuEChERS extraction kits (part numbers 5982–5650 and 5982–5156) were sourced from Agilent Technologies (Wilmington, DE).

Study area

The water and fish samples were collected from various locations in four Egyptian governorates, including Alexandria, Port Said, Ismailia, and Faiyum, from August 2021 to December 2022. Sampling sites were selected based on their ecological relevance and proximity to agricultural, industrial, and residential activities. Sites were chosen to reflect spatial variability in potential OCP contamination across the four governorates. Samples were collected across the four seasons, and all sampling coordinates were recorded employing the global positioning system (Fig. 1). Each governorate exhibits distinct seasonal climatic conditions that may influence OCP distribution and behavior. Faiyum experiences cooler winters (9–17 °C), relatively dry springs (17–27°C), hot and dry summers (27–37°C), and mild autumns (19–29°C). Ismailia is marked by mild winters (10–18°C), moderately warm springs (18–28°C) often

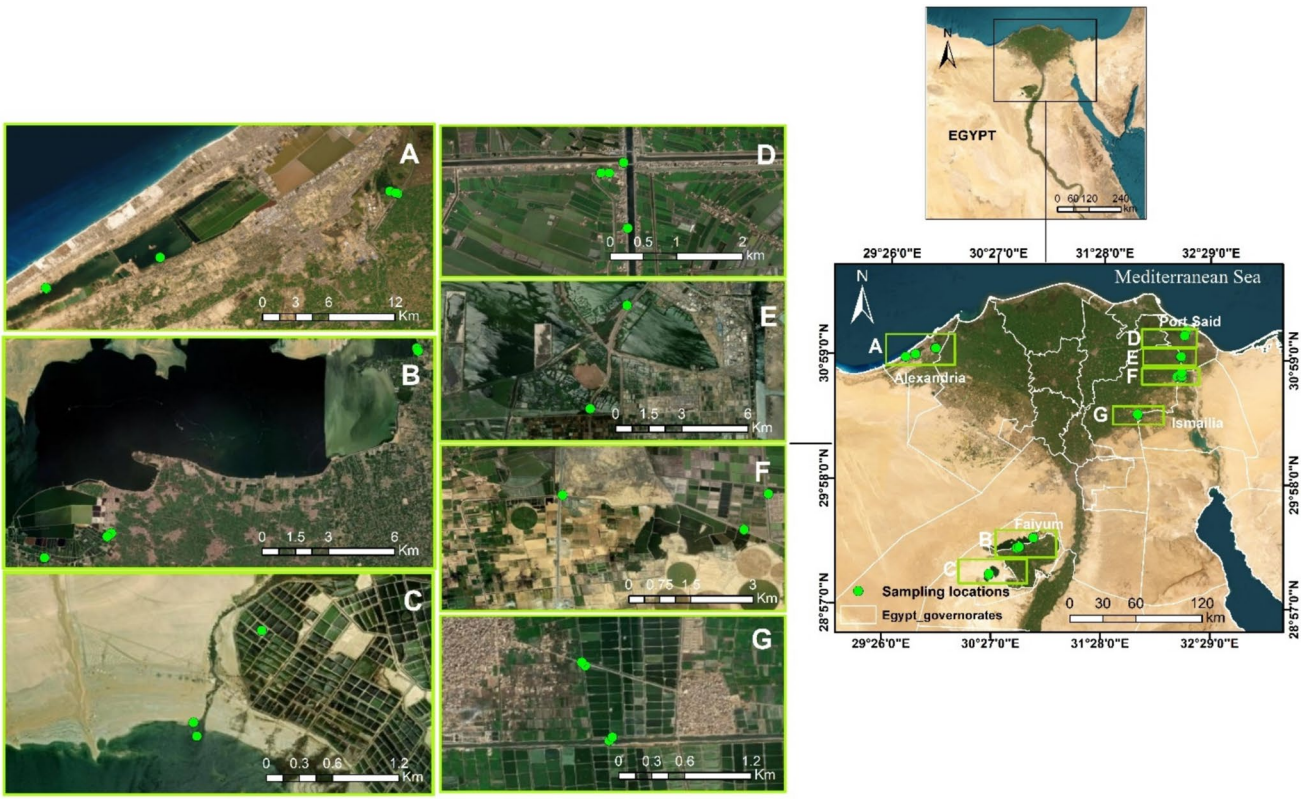


Fig. 1 Geographic distribution of sampling sites across all governorates: **A** Alexandria, **B**, **C** Faiyum, **D**, **E** Port Said, and **F**, **G** Ismailia. Sampling was conducted at multiple locations within each governorate to represent diverse environmental conditions. Maps were generated using ArcMap 10.8 software

accompanied by dust storms, hot summers (29–38°C), and warm, transitional autumns (21–31°C). Port Said typically experiences mild winters with moderate rainfall (11–18°C), warm springs (19–29°C), very hot and humid summers (29–39°C), and moderately warm autumns (21–30°C). Alexandria is characterized by relatively cool winters (10–17°C), mild to warm springs (17–26°C), hot and humid summers (27–34°C), and mild autumns (20–28°C). The samples were collected from 31 points in the four governorates, as depicted in Table S1. These four governorates are strategically located as they are connected through Egypt's coastal and inland waterways, such as the Nile and the Suez Canal, highlighting their significance for the current study. Geographically, Alexandria is situated on the Mediterranean coast in northern Egypt. Moving northeast along the Mediterranean is Port Said, which marks the north entrance of the Suez Canal. South of Port Said is Ismailia. In contrast, Faiyum is located southwest of Cairo.

Water sample collection and preparation

Water samples were collected from a depth of 50 cm below the surface. At each site, 1 L of water was collected in an amber glass bottle pre-treated with 1 mL of 1 N HCl (50% v/v) to inhibit microbial activity. The bottles were closed with Teflon screw caps and placed in ice packs in the absence of light while being transported until they were stored at 4°C for up to 48 h before being analyzed.

Water extraction was performed using the EPA method 6630 (Shamma et al. 2024). Each 1 L water sample was spiked with 50 ng of the three deuterated internal standards, and the extraction was performed in triplicate. Following the addition of 60 mL of dichloromethane (DCM), the mixture was vigorously shaken for 5 min in a separatory funnel. The organic phase containing the OCPs was collected and passed through anhydrous sodium sulfate to remove residual moisture. The organic extracts from the three replicates were combined and concentrated using a rotary evaporator (Buchi Labortechnik GmbH, Essen, Germany). The dried residue was reconstituted in 1 mL of n-hexane and transferred to autosampler vials for analysis by gas chromatography-mass spectrometry (Wilmington, DE).

Fish sample collection and preparation

At each site, three healthy adult fish of similar size (approximately 200–300 g) were randomly collected from local aquaculture farms adjacent to the sampling points to ensure consistency in environmental exposure. After being cleaned twice with distilled water, the fish samples were kept in labeled Ziploc bags in a dry-ice box and transferred for final storage at -80°C. Before starting the analysis, the fish were thawed on ice. Subsequently, 10 g of tissue was taken from the lateral muscle of each sample using a sterile surgical blade. A QuEChERS-based method was used to extract the fish samples. Briefly, 10 g of homogenized muscle tissue was mixed with 10 mL of acetonitrile (ACN) and vortexed for 1 min. A salt mixture of 4 g of anhydrous magnesium sulfate, 1 g of sodium chloride (NaCl), 1 g of sodium citrate, and 0.5 g of disodium citrate was added, followed by an additional 1-min vortex. For clean-up, 6 mL of the ACN extract was transferred to a QuEChERS dispersive clean-up tube and vortexed for 2 min. The mixture was centrifuged at 4000 × g for 4 min at 4°C, and the resulting supernatant was collected and transferred to autosampler vials for GC–MS analysis.

Instrumental analysis, method validation, and accuracy check

The analysis was performed using the Agilent 7890B gas chromatograph (Wilmington, DE) in tandem with the Agilent 5977B mass spectrometric detector (Wilmington, DE). The HP-5MS column was utilized with an internal diameter of 30 m × 0.25 mm and film thickness of 0.25 µm obtained from J&W Scientific (Wilmington, DE). Helium (99.995%) was served as the carrier gas with a 1 mL/min flow rate, adopting the spitless mode. Moreover, the injection volume was adjusted up to 1 µL, the temperature was consistently kept at 160°C for 4 min, then raised to 230°C at the rate of 3 °C/min with the injector and detector temperatures maintained at 250°C and 260 °C, respectively. The electron ionization was used to identify and quantify compounds based on SIM mode retention time, target, and qualifier ions (Fig. S1). Six points were used from the OCPs standard mixture to establish the calibration curve. The calibration curve correlation coefficient (R^2) values ranged from 0.995 to 0.999, as illustrated in Fig. S2.

The limits of detection (LOD) for the analyzed OCPs ranged from 0.096 to 0.44 ng/mL, while the limits of quantification (LOQ) were between 0.199 and 0.996 ng/mL. In addition, the recovery percentages for all OCPs in spiked water and fortified fish samples demonstrated an average recovery of 87.7% and 80.1%, respectively, at a concentration of 50 ppb. The relative standard deviation values were below 7%, implying the reliability of the applied method. The recovery percentages of the deuterated internal standards ranged from 60.1 to 123.01%, mainly due to matrix effects. Yet all recovery percentages remained within acceptable ranges.

Ecological risk assessment for surface water

The ecological risk assessment evaluates how human activities may impact the environment. The risk quotient (RQ) was calculated for surface water using Eq. 1. It is a crucial

measure used by regulatory bodies like the United States EPA to assess the risk of pesticide exposure (USEPA 2024). An RQ of less than one suggests that the exposure poses minimal risk to health, while an RQ greater than one indicates a potential health risk. The measured environmental concentration (MEC) in mg/L was determined to get the RQ, and the predicted no-effect concentration (PNEC) was estimated using acute toxicity data obtained from the U.S. Environmental Protection Agency's Ecological Structure–Activity Relationship (ECOSAR) database. This model provides toxicity predictions for aquatic organisms, including freshwater, fish, invertebrates, and aquatic plants. The PNECs were calculated by dividing the median lethal concentration (LC_{50}) or median effective concentration (EC_{50}) by an assessment factor (AF) of 10 (Eqs. 2 and 3) (USEPA 2024). This AF was selected based on the availability of toxicity data from multiple trophic levels and the short life span of the studied species. Risk levels were interpreted as follows: $RQ < 0.1$ (low risk), $0.1 \leq RQ < 1.0$ (moderate risk), and $RQ \geq 1.0$ (high risk). The carcinogenic risk calculation estimates the likelihood of cancer over a lifetime due to continuous exposure to contaminants. Risk values less than 10^{-6} denote negligible cancer risk. Values between 10^{-6} and 10^{-4} indicate a minor cancer risk requiring careful monitoring, while values exceeding 10^{-4} represent significant risk levels necessitating intervention

$$RQ = \frac{MEC}{PNEC} \tag{1}$$

$$PNEC = \frac{LC50}{AF} \tag{2}$$

$$PNEC = \frac{EC50}{AF} \tag{3}$$

Non-carcinogenic risk assessment through fish consumption

We aimed to investigate whether the consumption of Nile tilapia would pose adverse health outcomes to human health. Therefore, we calculated the target hazard quotient(THQ) to examine whether fish consumption in the long term could threaten human health. It measures the non-carcinogenic risks in nature and gives an idea about the cumulative risk of exposure to specific hazards such as pesticides, metals, and persistent organic pollutants (ATSDR, 2022). The impact of OCP exposure on human health due to the food intake of Nile tilapia was evaluated using the THQ with $THQ < 1$, indicating that the human consumption of the studied fish has no health-associated adverse effect on the human. Meanwhile, $THQ > 1$ suggests an associated health effect (Alam et al. 2023; Maxted, 1989). Equation 4 was used to calculate THQ, where C represents the concentration of OCP in fish tissue in mg/kg. Assuming daily intake, an EF of days/year was used to indicate the exposure frequency. An ED of 30 years was used to represent the exposure duration, typical for adult lifetime exposure. The food consumption rate, FCR, was assumed to be 0.055 kg/day, consistent with the daily consumption of Nile tilapia fish raised in Egyptian aquaculture (A.Wally 2016.). In addition, the BW refers to an average adult's weight, set at 70 kg. Whereas AT stands for averaging time, it is calculated as ED × 365 days for non-carcinogens. Finally, the R*f*D denotes the reference dose for the OCP provided by the USEPA.

$$THQ = \frac{C \times EF \times ED \times FCR}{BW \times AT \times RfD} \tag{4}$$

Non-carcinogenic risk assessment through dermal exposure

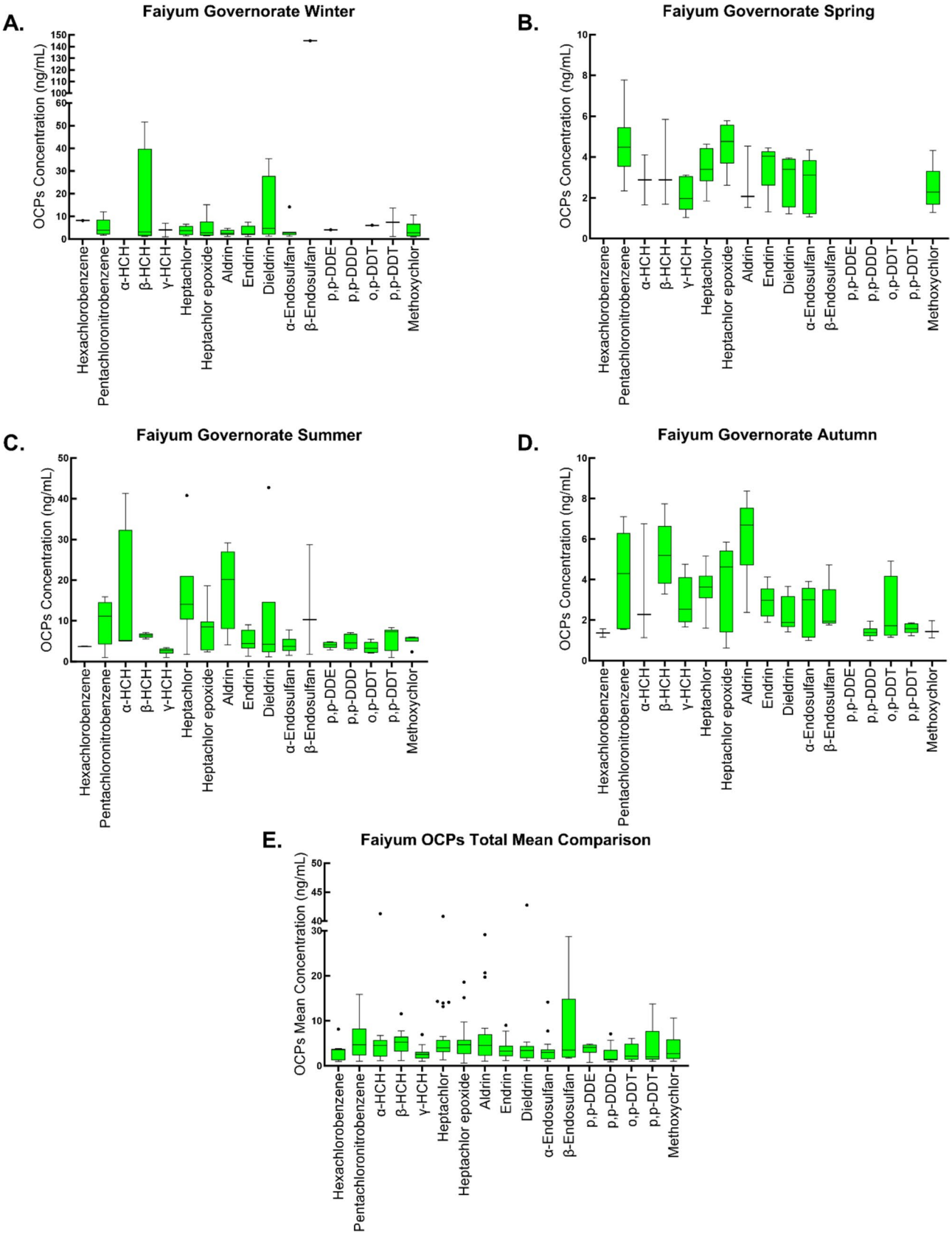
Humans can be exposed to OCP contamination through several routes, including inhalation, ingestion, and dermal exposure. Therefore, the hazard index (HI) was calculated by combining exposure and toxicological data to determine the effect of dermal exposure on human health (Baqar et al. 2018; Yang et al. 2014). E_{Dermal} is the dermal exposure to OCPs from surface water through the dermal route, as in Eq. 5. Where C (mg/L) is OCPs concentration in surface water; τ (assumed to be 1 h) is the lag time for each contaminant; TE (0.4 h) is bath time; k (0.001 $cm.h^{-1}$) is dermal permeability parameter; A_{sb} (16,600 cm^2) is body surface area; EF (365 days. year $^{-1}$) is the frequency of exposure; FE (0.5 times. Day^{-1}) is bathing frequency; ED (67 years) is exposure duration; BW (72 kg) is average body weight; AT (25,550 days) is the average time; and *f* (assumed to be 1) is the absorption ratio (He et al. 2012). The HI is calculated according to Eq. 6. E Dermal (mg/kg·day) is the exposure level to OCPs contaminating surface water, and RfD (mg/kg·day) is the reference dose previously described.

$$E_{Dermal} = \left(6\tau \times \frac{TE}{\pi}\right)^{0.5} \times \frac{C \times k \times A_{sb} \times EF \times FE \times ED}{500 \times BW \times TA \times f} \tag{5}$$

$$HI = \frac{E}{RfD} \tag{6}$$

Carcinogenic risk assessment through fish ingestion and dermal exposure to surface water

The carcinogenic risk associated with dermal exposure through exposure to contaminated surface water and fish consumption was calculated according to Eqs. (7–9). The


A.
Faiyum Governorate Winter
OCPs Concentration (ng/mL)
B.
Faiyum Governorate Spring
OCPs Concentration (ng/mL)
C.
Faiyum Governorate Summer
OCPs Concentration (ng/mL)
D.
Faiyum Governorate Autumn
OCPs Concentration (ng/mL)
E.
Faiyum OCPs Total Mean Comparison
OCPs Mean Concentration (ng/mL)
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor

◂**Fig. 2** Spatiotemporal comparison of OCPs concentrations in the Faiyum Governorate. **A**-**E** Box and whisker plots illustrate the interquartile range (25th to 75th percentile). Whiskers indicate the range, excluding outliers, while dots represent outliers, showing the concentrations (ng/mL) of 17 OCPs measured in water samples across all seasons in Faiyum: **A** Winter, **B** Spring, **C** Summer, and **D** Autumn. **E** displays the total mean concentration of OCPs across all seasons in Faiyum. Seasonal variations were observed for several OCPs, with higher levels of compounds such as PCNB and Heptachlor detected in autumn, summer, and spring compared to winter. Autumn and spring exhibited lower concentrations than summer, while winter had the lowest overall, except for the fluctuating levels of *β*-Endosulfan. Data are expressed as the mean and standard error of the mean (SEM)

estimated dose of chronic daily intake (CDI) received through fish consumption was calculated using Eq. 7, where C (mg/kg) is the concentration of the OCPs in fish. The IR is the average ingested rate of fish (0.055 kg/day). The EF is the exposure frequency, typically 365 days/year, and the ED is the exposure duration, usually 70 years, for carcinogenic risk to represent a lifetime. The BW (70 kg) is the average body weight for an adult, and the AT is the average time (70 years × 365 days/year) for carcinogenic effects. The carcinogenic risk ($R_{ingestion}$) using Eqs. 8 and 9 was adopted from the Environmental Protection Agency (USEPA, 2009; Yang et al. 2014). The cancer slope factor (CSF) was used to estimate the increased risk associated with exposure to OCPs (measured as the increased risk per exposure unit in mg/kg/day). A higher CSF indicates a more potent carcinogen. A carcinogenic risk of 10^{-6} chances of developing cancer from exposure is generally considered an acceptable or negligible cancer risk. On the other hand, 10^{-4} risk levels may require mitigation or intervention (Basu et al. 2021; U.S. Environmental Protection Agency Washington, 2005).

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \tag{7}$$

$$R_{ingestion} = CDI \times CSF \tag{8}$$

$$R_{Dermal} = E_{Dermal} \times CSF \tag{9}$$

Statistical analysis

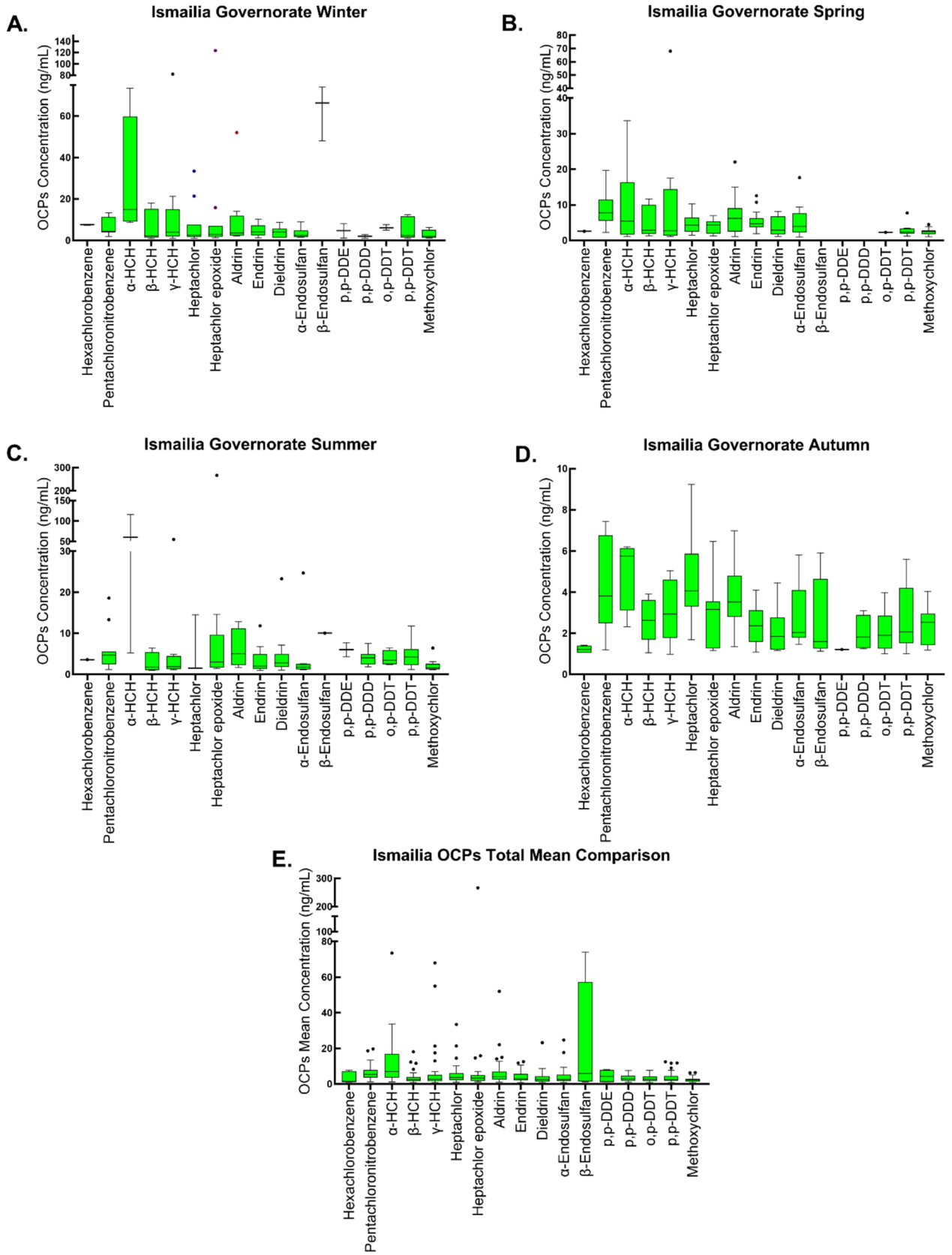
To represent the spatiotemporal distribution of different OCPs in the four governorates, descriptive statistics were analyzed using GraphPad Prism software version 9.1 and Python 3.11.12 on a 64-bit Linux system (GCC 11.4.0) in the Google Colaboratory Platform (Python Software, 2024). Data are represented as the mean and standard error of the mean (SEM). Our dataset encompasses 19 features; governorates, seasons, and 17 OCPs. The data normality check was performed using the Shapiro–Wilk normality test. In addition, we used the Kruskal–Wallis H test, followed by Dunn's post hoc test with Bonferroni correction for the adjusted *p*-values, to examine seasonal and regional and variations of with various OCPs.

Results

Spatiotemporal analysis of OCPs in the Faiyum governorate

The spatiotemporal analysis measured different OCPs in the respective governorate during various time intervals across the four seasons (spring, summer, autumn, and winter). In the Faiyum governorate, a significant difference was observed between the OCPs in each season and between different seasons (Fig. 2). Several OCPs such as PCNB, Heptachlor, Heptachlor epoxide, Aldrin, and *β*-Endosulfan were showed to have an increased concentration in autumn, summer, and spring compared to winter (Fig. 2A-D). A noticeable reduction in the concentration of OCPs was observed in autumn and spring compared to summer (Fig. 2A-C). In the winter, OCP concentration was the lowest among all other seasons except for *β*-Endosulfan, which varies considerably. Furthermore, we aimed to examine whether OCP concentrations differ significantly across seasons within each governorate, identify the variation of OCPs between pairs of seasons using Dunn's post hoc test, and determine whether seasonal effects are specific to certain regions or chemicals. Our data revealed that 4,4′-DDT exhibited significant seasonal variation in spring–summer and summer–winter. Likewise, 4,4′-DDD showed marked differences between the autumn-spring and autumn–winter pairs. Additionally, 4,4′-DDE displayed substantial variation among several pairs, including autumn-summer, spring–summer, and summer–winter. In contrast, PCNB only exhibited significant variation between summer and winter. Similarly, Aldrin varied noticeably between autumn and spring. Furthermore, several OCPs showed no seasonal differences, such as *β*-HCH, *α*-HCH, γ-HCH, Dieldrin, Endrin, Heptachlor epoxide, α-Endosulfan, and Heptachlor. Additionally, we noted that only 4,4′-DDE exhibited distinct variation in Faiyum, while Methoxychlor was observed in Alexandria and *β*-Endosulfan in Ismailia (Table S2).

The total mean comparison could give an idea of OCPs concentration in the four seasons and the cumulative risk of those OCPs. Our data showed that in the Faiyum governorate, the PCNB, Heptachlor epoxide, and Aldrin concentrations remain steadily elevated across all seasons. In contrast, others, such as Heptachlor, Aldrin, and Dieldrin concentrations vary in different seasons (Fig. 2E). Our data showed that in the Faiyum governorate, the level of OCP concentrations was significant during the summer, remained high in spring and autumn, and is lowest in winter. This


A.
Ismailia Governorate Winter
OCPs Concentration (ng/mL)
B.
Ismailia Governorate Spring
OCPs Concentration (ng/mL)
C.
Ismailia Governorate Summer
OCPs Concentration (ng/mL)
D.
Ismailia Governorate Autumn
OCPs Concentration (ng/mL)
E.
Ismailia OCPs Total Mean Comparison
OCPs Mean Concentration (ng/mL)
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor

◂**Fig. 3** Spatiotemporal comparison of OCPs concentrations in the Ismailia Governorate. Box and whisker plots demonstrate the interquartile range (25th to 75th percentile). Whiskers show the range, excluding outliers, while dots represent outliers, showing the concentrations (ng/mL) of 17 OCPs measured in water samples across all seasons in Ismailia. **A** Winter, **B** Spring, **C** Summer, and **D** Autumn. **E** represents the total mean concentration of OCPs across all seasons in Ismailia. Seasonal variations with distinct patterns were observed. OCPs such as PCNB, Heptachlor, Aldrin, and γ-HCH were notably higher in autumn and spring. The highest concentrations of *β*-Endosulfan, PCNB, Heptachlor epoxide, Aldrin, γ-HCH, and *α*-HCH were observed in winter. Data expressed as mean and SEM

pattern likely corresponds to pesticide application and environmental changes throughout the year. These findings emphasize the significance of ongoing monitoring to address the area's enduring ecological threats from persistent OCP contamination.

Spatiotemporal analysis of OCPs in the Ismailia governorate

After that, we investigated how OCP concentration varies across seasons in the Ismailia governorate. Our data showed a considerable difference in OCP levels between each season and across seasons. Still, with an evident pattern (Fig. 3). In autumn, several OCPs, including PCNB, Heptachlor, Aldrin, and γ-HCH, have shown an increased level compared to other OCPs, which continues to the spring (Fig. 3A, B). In summer, there was increased variability in OCPs concentration, particularly in Heptachlor epoxide, followed by *α*-HCH, which displayed elevated levels compared to other OCPs. In winter, some OCPs such as *β*-Endosulfan PCNB, Heptachlor epoxide, Aldrin, γ-HCH, and *α*-HCH showed a substantial increase compared to all other seasons, representing the peak in OCP concentration among other seasons, followed by summer and spring that exhibit moderate OCP concentration as compared to autumn that shows a reduced level of OCPs (Fig. 3A-D). Moreover, we aim to discover the variation of OCPs between pairs of seasons using Dunn's post hoc test and determine whether seasonal effects are specific to certain regions or chemicals. Our data highlighted that 4,4′-DDD exhibited significant seasonal variation in spring–summer and summer–winter. Heptachlor markedly differs between autumn-summer and spring–summer. Similarly, *β*-HCH greatly varied between autumn-spring and autumn-summer. Furthermore, several other OCPs showed significant variation between only one pair of seasons. For example, considerable variations in 2,4′-DDT were noted in autumn and spring. *α*-Endosulfan, Aldrin, and Endrin demonstrated marked variation between spring and summer. Likewise, *β*-Endosulfan and Hexachlorobenzene displayed considerable variation in autumn and spring. Meanwhile, 4,4′-DDT differs significantly between summer and winter. Additionally, various OCPs did not exhibit significant seasonal variations, including γ-HCH, Dieldrin, Methoxychlor, 4,4′-DDE, Heptachlor epoxide, *α*-HCH, and PCNB. Moreover, several OCPs displayed significant seasonal variation only in the Ismailia governorate, including Heptachlor, *β*-HCH, Endrin, and *α*-Endosulfan; in contrast, *β*-Endosulfan was also detected in Faiyum (Table S2).

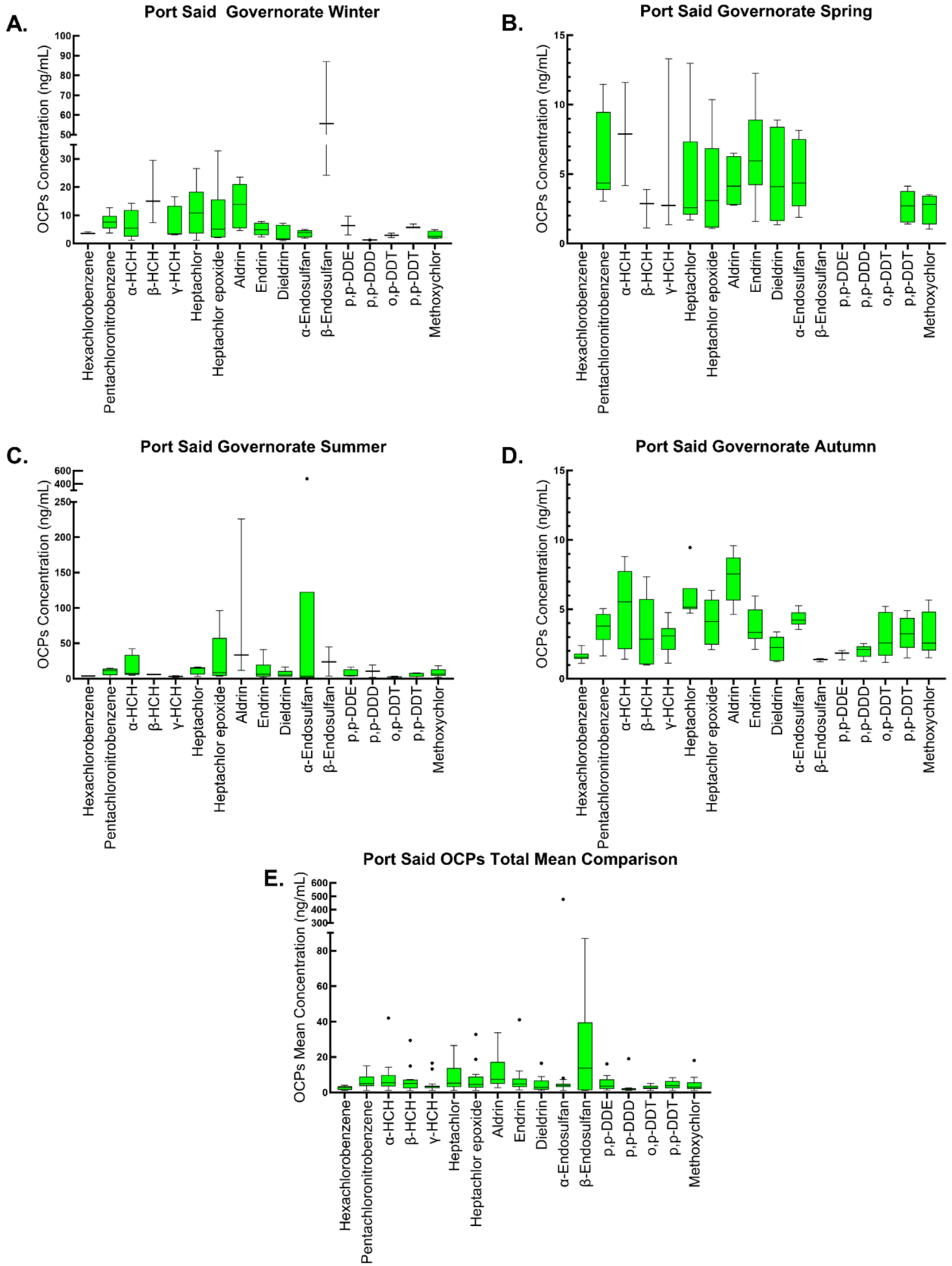
In Fig. 3E, the overall comparison of OCPs' mean levels shows variability in OCPs concentration of certain OCPs such as Heptachlor epoxide, PCNB, *α*-HCH, γ-HCH, and Aldrin compared to other OCPs insinuating the role of local factors such as usage patterns and environmental conditions that may change from season to season among governorates, leading to variations in the spatiotemporal distribution of OCPs (Fig. 3E).

Spatiotemporal Analysis of OCPs in the Port Said Governorate

Moreover, in the Port Said governorate, a significant difference was observed between the OCPs in each season and between different seasons (Fig. 4). Various OCPs such as *β*-Endosulfan, PCNB, *α*-HCH, Aldrin, Heptachlor, and Heptachlor epoxide were shown to exhibit elevated levels across all the seasons (Fig. 4A-D). A similar pattern was also identified in the distribution of OCPs in autumn and spring, which moderately elevated and peaked in the summer, showing a different pattern than the Faiyum and Ismailia governorates. Furthermore, we wanted to detect the variation of OCPs between pairs of seasons using Dunn's post hoc test and determine whether seasonal effects are specific to certain regions or chemicals. We noted minimal seasonal variation in Port Said, particularly observed for 4,4′-DDD and 2,4′-DDT during autumn (Table S2). The mean data revealed that the *β*-Endosulfan, Aldrin, Heptachlor epoxide, and Heptachlor concentrations were highly elevated across seasons compared to other OCPs (Fig. 4E).

Spatiotemporal analysis of OCPs in the Alexandria governorate

Finally, we assessed the spatiotemporal distribution of OCPs in the Alexandria governorate. Our data show a moderate difference between the OCPs in each season and between different seasons compared to Faiyum, Ismailia, and Port Said (Fig. 5). In addition, PCNB, *β*-Endosulfan, *β*-HCH, Aldrin, Heptachlor, and Heptachlor epoxide, and Endrin remain steadily elevated across all seasons (Fig. 5A-D). Moreover, we intended to examine the variation of OCPs between pairs of seasons using Dunn's post hoc test and figure out if seasonal effects are specific to certain regions or chemicals. For instance, we observed significant seasonal variation in PCNB during autumn-spring and spring-winter. Additionally, variations of 4,4′-DDT were markedly


A.
Port Said Governorate Winter
OCPs Concentration (ng/mL)
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor
B.
Port Said Governorate Spring
C.
Port Said Governorate Summer
D.
Port Said Governorate Autumn
E.
Port Said OCPs Total Mean Comparison
OCPs Mean Concentration (ng/mL)

◂**Fig. 4** Spatiotemporal comparison of OCPs concentrations in the Port Said Governorate. Box and whisker plots illustrate the interquartile range (25th to 75th percentile). Whiskers show the range, excluding outliers, while dots represent outliers, indicating the concentrations (ng/mL) of 17 OCPs measured in water samples throughout all seasons in Port Said. **A** Winter, **B** Spring, **C** Summer, and **D** Autumn. **E** represents the total mean concentration of OCPs across all seasons in Port Said. Several OCPs exhibited consistently elevated levels throughout the seasons, including *β*-Endosulfan, PCNB, *α*-HCH, Aldrin, Heptachlor, and Heptachlor epoxide, with a spike in the summer. Data expressed as mean and SEM

observed in autumn and spring. Meanwhile, γ-HCH, Methoxychlor, and Heptachlor epoxide showed notable changes during autumn and winter. *α*-HCH demonstrated variation in spring and winter. Conversely, there were no statistically significant seasonal variations for 4,4′-DDE, Dieldrin, *β*-Endosulfan, *α*-Endosulfan, 2,4′-DDT, Heptachlor, Endrin, and Aldrin. Moreover, we also observed that certain OCPs distinctly vary in Alexandria only across seasons, including *α*-HCH, Heptachlor epoxide, and γ-HCH. At the same time, Methoxychlor was specific to Alexandria and Faiyum (Table S2).

The total mean comparison shows that in the Alexandria governorate, γ-HCH displayed a spike in concentration, followed by Endrin, Aldrin, PCNB, Heptachlor epoxide, and *β*-Endosulfan, which exhibited increased concentrations across all seasons compared to other OCPs (Fig. 5E).

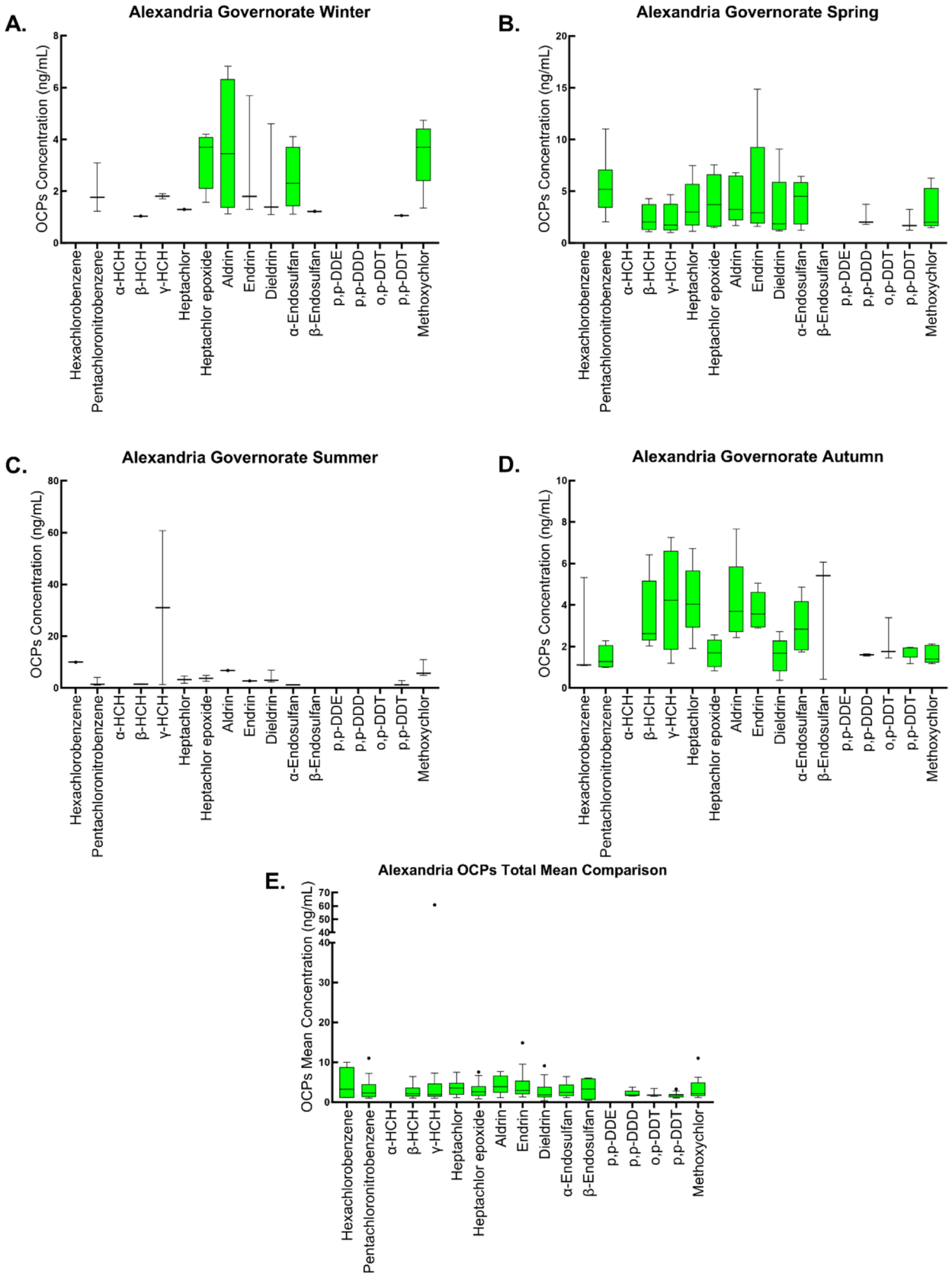
Comparative analysis of various OCPs concentrations in different seasons

Our previous results showed that OCPs vary significantly across multiple seasons. However, this does not imply a statistical difference between the different seasons. Furthermore, we aim to examine OCPs with either similar or distinctive seasonal patterns. Our results from the Kruskal–Wallis test indicated that several OCPs demonstrate substantial differences across the various seasons, including 4,4′-DDD, 4,4′-DDT, 2,4′-DDT, Hexachlorobenzene, 4,4′-DDE, *β*-HCH, PCNB, Dieldrin, γ-HCH, and *β*-Endosulfan. In contrast, Heptachlor, Aldrin, Methoxychlor, *α*-Endosulfan, Endrin, Heptachlor epoxide, and *α*-HCH did not vary significantly across the seasons (Table S2). In addition, our post hoc analysis showed that OCPs-season interaction is common between specific OCPs and certain season pairs. Specifically, 4,4′-DDD exhibited significant variability across all four seasons, whereas 4,4′-DDT differences were noted between the spring–summer and summer–winter pairs. Differences in 2,4′-DDT were also observed between autumn-spring, autumn–winter, and spring–summer. Hexachlorobenzene showed notable differences between autumn–spring and between spring–summer. Meanwhile, the differences in 4,4′-DDE greatly varied between spring and summer. Furthermore, *β*-HCH displays significant differences between autumn and spring, as well as between autumn and winter. In contrast, PCNB only exhibited substantial differences between autumn and spring. Dieldrin demonstrated a considerable difference between spring and winter. γ-HCH differences were observed solely between autumn and spring. Finally, *β*-Endosulfan showed a significant difference between autumn and spring.

Moreover, several OCPs demonstrated a considerable variance in specific seasonal pairs. For instance, PCNB, γ-HCH, *β*-Endosulfan, *β*-HCH, 2,4'-DDT, 4,4'-DDD, and Hexachlorobenzene exhibited substantial differences during autumn and spring. *β*-HCH, 2,4'-DDT, and 4,4'-DDD varied significantly between autumn and winter. 2,4'-DDT, 4,4'-DDD, Hexachlorobenzene, 4,4'-DDE, and 4,4'-DDT showed considerable variation between spring and summer. 4,4'-DDD and 4,4'-DDT exhibited significant differences between summer and winter, while Dieldrin varied markedly between spring and winter.

Comparative analysis of several OCPs concentrations in different governorates

We further examine if there is a statistical difference between various governorates. In addition, we aimed to assess whether OCPs exhibit a similar or distinctive regional pattern. Our data revealed that numerous OCPs show significant differences between various seasons, including 4,4′-DDT, *β*-Endosulfan, *β*-HCH, *α*-HCH, Heptachlor, Heptachlor epoxide, PCNB, Aldrin, *α*-Endosulfan, 4,4′-DDD, Methoxychlor, and 4,4′-DDE. In contrast, Endrin, Hexachlorobenzene, γ-HCH, 2,4′-DDT, and Dieldrin show no significant differences between regions, suggesting their relatively stable concentrations. Dunn's post hoc analysis revealed that certain OCPs varied substantially among governorate pairs. For instance, 4,4′-DDT showed considerable variation between Alexandria-Ismailia, Alexandria-Port Said, and Faiyum-Port Said. *β*-Endosulfan revealed a notable difference between Alexandria—Faiyum, Alexandria—Ismailia, and Alexandria—Port Said. Additionally, *β*-HCH exhibited considerable variation between Alexandria—Faiyum, Alexandria—Ismailia, and Alexandria—Port Said. *α*-HCH displayed differences between Alexandria—Faiyum, Alexandria—Ismailia, Faiyum—Port Said, and Ismailia—Port Said. Furthermore, Heptachlor varied significantly between Alexandria, Port Said, Ismailia, and Port Said. Meanwhile, PCNB showed considerable variability between Alexandria-Ismailia and Alexandria-Port Said. Aldrin demonstrated substantial variation among the Alexandria—Port Said pairs, Faiyum—Port Said, and Ismailia—Port Said. *α*-Endosulfan indicated only a significant variation between Alexandria and Port Said. Likewise, 4,4′-DDD exhibited variation between Alexandria and Ismailia. Methoxychlor differed


A.
Alexandria Governorate Winter
OCPs Concentration (ng/mL)
0
2
4
6
8
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor
B.
Alexandria Governorate Spring
OCPs Concentration (ng/mL)
0
5
10
15
20
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor
C.
Alexandria Governorate Summer
OCPs Concentration (ng/mL)
0
20
40
60
80
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor
D.
Alexandria Governorate Autumn
OCPs Concentration (ng/mL)
0
2
4
6
8
10
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor
E.
Alexandria OCPs Total Mean Comparison
OCPs Mean Concentration (ng/mL)
0
10
20
30
40
50
60
70
Hexachlorobenzene
Pentachloronitrobenzene
α-HCH
β-HCH
γ-HCH
Heptachlor
Heptachlor epoxide
Aldrin
Endrin
Dieldrin
α-Endosulfan
β-Endosulfan
p,p-DDE
p,p-DDD
o,p-DDT
p,p-DDT
Methoxychlor

◂**Fig. 5** Spatiotemporal comparison of OCPs concentrations in the Alexandria governorate. Box and whisker plots illustrate the interquartile range (the 25th to 75th percentile). The whiskers indicate the range, excluding outliers, while dots represent outliers, showing the concentrations (ng/mL) of 17 OCPs measured in water samples throughout all seasons in Alexandria. **A** Winter, **B** Spring, **C** Summer, and **D** Autumn. **E** represents the total mean concentration of OCPs across all seasons in Alexandria. A moderate seasonal difference was noted across the seasons. Several OCPs, such as PCNB, β-Endosulfan, β-HCH, Aldrin, Heptachlor, Heptachlor epoxide, and Endrin, remain consistently elevated throughout all seasons. Data expressed as mean and SEM

between Alexandria and Port Said. Finally, 4,4′-DDE varied between Ismailia and Port Said (Table S2).

Moreover, we also observed that certain OCPs varied significantly across certain regions. For example, β-Endosulfan, β-HCH, and α-HCH differed notably between Alexandria and Faiyum. Additionally, β-Endosulfan, β-HCH, α-HCH, 4,4′-DDD, PCNB, and 4,4′-DDT showed significant differences between Alexandria and Ismailia. Furthermore, β-Endosulfan, β-HCH, PCNB, 4,4′-DDT, α-Endosulfan, Methoxychlor, Aldrin, and Heptachlor were notably different between Alexandria and Port Said. α-HCH, 4,4′-DDT, and Aldrin showed significant differences between Faiyum and Port Said. Lastly, α-HCH, Aldrin, Heptachlor, and 4,4′-DDE differed notably between Ismailia and Port Said.

Ecological risk assessment

We evaluate the ecological risk and determine the RQ. Our study calculated the RQ for water in the four governorates throughout the season, as depicted in Fig. 6. Our data highlighted that in the Faiyum governorate, among all the 17 OCPs, only five have potential ecological risk, including Heptachlor, Aldrin, 4,4′-DDT, 2,4′-DDT, and 4,4′-DDE. Aldrin's highest ecological risk is in the summer and autumn, followed by winter and spring. Heptachlor spikes in the summer, whereas it has a high ecological risk in the spring and autumn and elicits the lowest environmental risk in winter. The 4,4′-DDT ecological risk increased in the summer, followed by autumn and winter. On the other hand, 2,4′-DDT seems to exhibit less environmental risk than 4,4′-DDT, as it shows risk in the summer followed by autumn (Fig. 6).

Like the Faiyum governorate, the RQ in the Ismailia governorate highlighted the potential ecological risk associated with Aldrin, Heptachlor, 4,4′-DDT, and 2,4′-DDT, respectively. Aldrin's highest ecological risk is in the winter, spring, autumn, and summer, with a similar pattern to its environmental risk in the Faiyum governorate yet with a distinctive pattern in the various seasons. In contrast to results from the Faiyum governorate, Heptachlor in the Ismailia governorate exhibits negligible risk in the summer and higher ecological risk in the winter, autumn, and spring, respectively. The 4,4′-DDT ecological risk was increased in the summer, similar to results from the Faiyum governorate, followed by high risk in the autumn and winter and the lowest environmental risk in the spring. In addition, the highest ecological risk for 2,4′-DDT was observed in autumn, followed by winter and summer (Fig. 7).

Furthermore, in the Port Said governorate, the RQ revealed that Aldrin, similar to other governorates, has the highest ecological risk, especially in the summer, winter, autumn, and spring, respectively. In addition, Heptachlor was second to Aldrin in posing ecological risk with a slight change in its distribution pattern in the different seasons, with winter having the highest Heptachlor ecological risk, followed by summer, autumn, and spring. Furthermore, a comparable risk was also noticed for 2,4′-DDT in summer and autumn. The peak environmental risk for 4,4′-DDT was observed in summer, autumn, winter, and spring. In contrast to other governorates, 4,4′-DDE elicited an ecological risk in Port Said for the first time in summer and winter (Fig. 8).

Finally, our results in the Alexandria governorate highlighted a similar pattern to those of other governorates. Aldrin was shown to pose the highest risk compared to the four seasons, with the peak in autumn. In contrast to other governorates, Heptachlor has ecological risk in only three seasons: autumn, spring, and summer. In addition, 4,4′-DDT was revealed to have high ecological risk only in autumn. On the other hand, 4,4′-DDT exhibits similar risks in summer and autumn (Table S3). Collectively, our results emphasized that only four OCPs can induce an ecological risk. Aldrin elicits the highest risk in different seasons compared to other OCPs, followed by Heptachlor, 4,4′-DDT, 4,4′-DDT. Interestingly, 4,4′-DDE exhibits a risk only in the Port Said governorate (Fig. 9).

Non-Carcinogenic Risk

Our study examined the spatiotemporal distribution of various OCPs in Nile tilapia due to its high bioaccumulation rate. Our data revealed no risk associated with Nile tilapia consumption in all the governorates during the year or in different seasons (Table 1). This is consistent with our previous finding in Kafr El-Sheikh governorate (Shamma et al. 2024).

Furthermore, we calculated the non-carcinogenic risk from dermal exposure through surface water. Our data emphasized a negligible effect of contaminated water with OCPs through dermal exposure without risk to human health (Table 2).

Carcinogenic risk

We investigated whether fish intake and dermal exposure could pose a cancer risk in the four governorates. Our previous results from measuring the non-carcinogenic risk

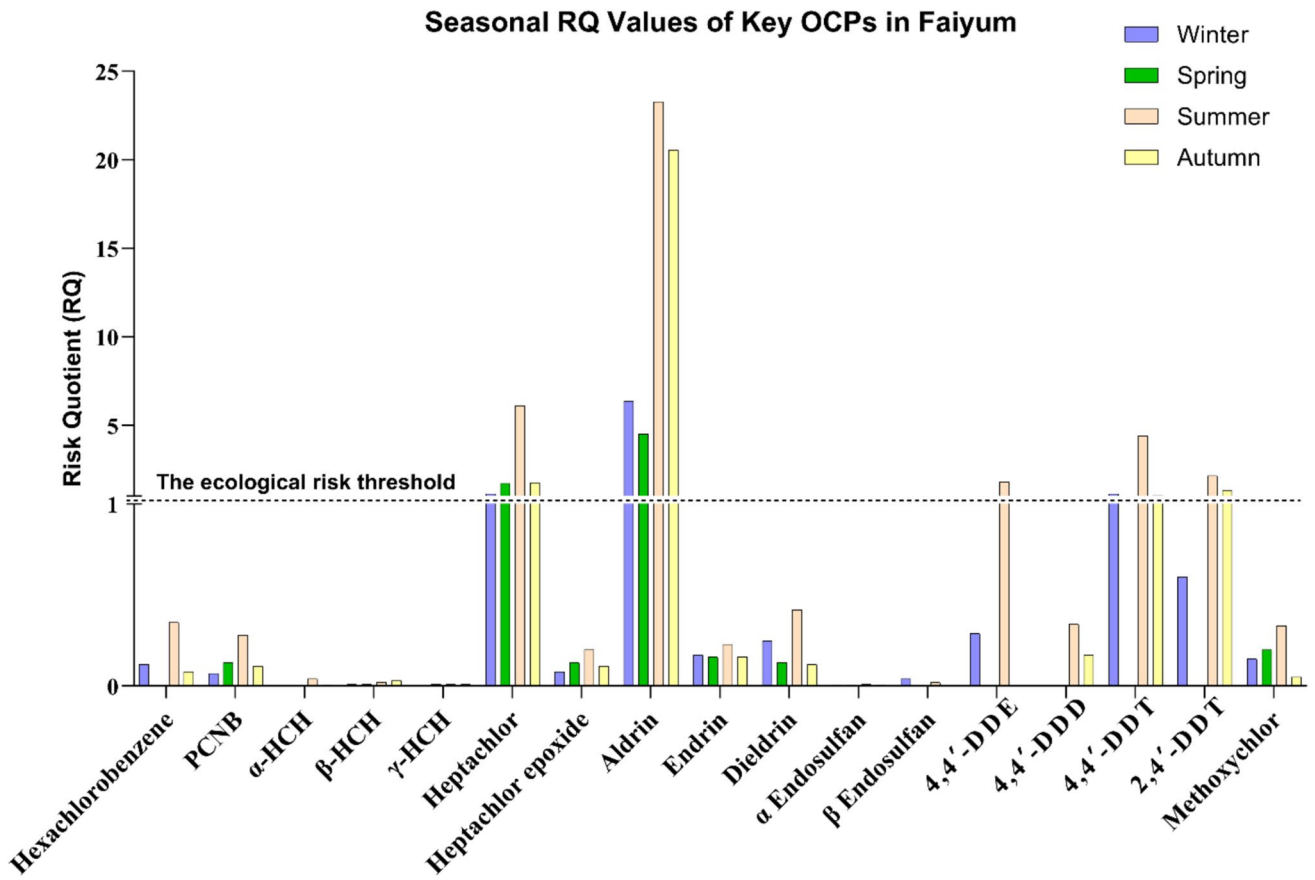


Fig. 6 Grouped bar charts depict the RQ values in Faiyum governorates in various seasons labeled as the following: spring (blue), summer (green), autumn (yellow), and winter (beige). OCPs are plotted on the x-axis, while RQ are plotted on the y-axis with a threshold set at RQ = 1. Only Aldrin and Heptachlor showed high ecological risk across various seasons

revealed negligible effect on human health. Fish consumption contributed to a minor to moderate cancer risk, whereas dermal exposure contributed to a minor to no cancer risk (Fig. 10A). Aldrin, Dieldrin, and Heptachlor contributed to the minor carcinogenic risk of fish consumption. Conversely, the dermal exposure data revealed negligible risk except for Aldrin, which contributed to a moderate risk for cancer development (Fig. 10B).

Discussion

The prevalence of OCPs is very high in the agricultural and industrial sectors worldwide (Abou-Elwafa Abdallah et al. 2017; Gupta 2004; Odongo et al. 2024; Thompson et al. 2017). They are acclaimed for their high toxicity and endurance in the environment (Jayaraj et al. 2016). Our study investigated the spatiotemporal distribution of OCPs in four governorates in Egypt. Our data suggest that among all the 17 OCPs, certain OCPs are commonly of higher concentration in different seasons in the four governorates, such as Heptachlor, Aldrin, PCNB, Heptachlor epoxide, and β-Endosulfan. Other OCPs have a moderate or low concentration, such as different α-HCH, β-HCH, and γ-HCH, Endrin, Dieldrin, α-Endosulfan, 4,4′-DDE, 4,4′-DDD, 4,4′-DDT, 2,4′-DDT depending on the season and the governorate. This is consistent with our previous results from the Kafr El-Sheikh governorate (Shamma et al. 2024). The elevated levels of OCPs detected in this study may originate from multiple potential sources, including agricultural runoff, especially in regions where OCPs were historically used, as residues can persist in soils. Industrial discharges might also contribute to improper waste management practices. Additionally, the recent illegal or unauthorized use of OCPs could further increase these high OCP levels.

Likewise, Barakat et al. (2013) investigated the prevalence and distribution of OCPs and other persistent pesticides in Qarun Lake in Egypt. It revealed a higher concentration of certain OCPs such as Aldrin, Heptachlor, Endosulfan I, and II, γ-HCH, Endrin, 4,4'-DDE, and oxychlordane were the most abundant compounds than in other urbanized regions worldwide. In addition, another study measured the

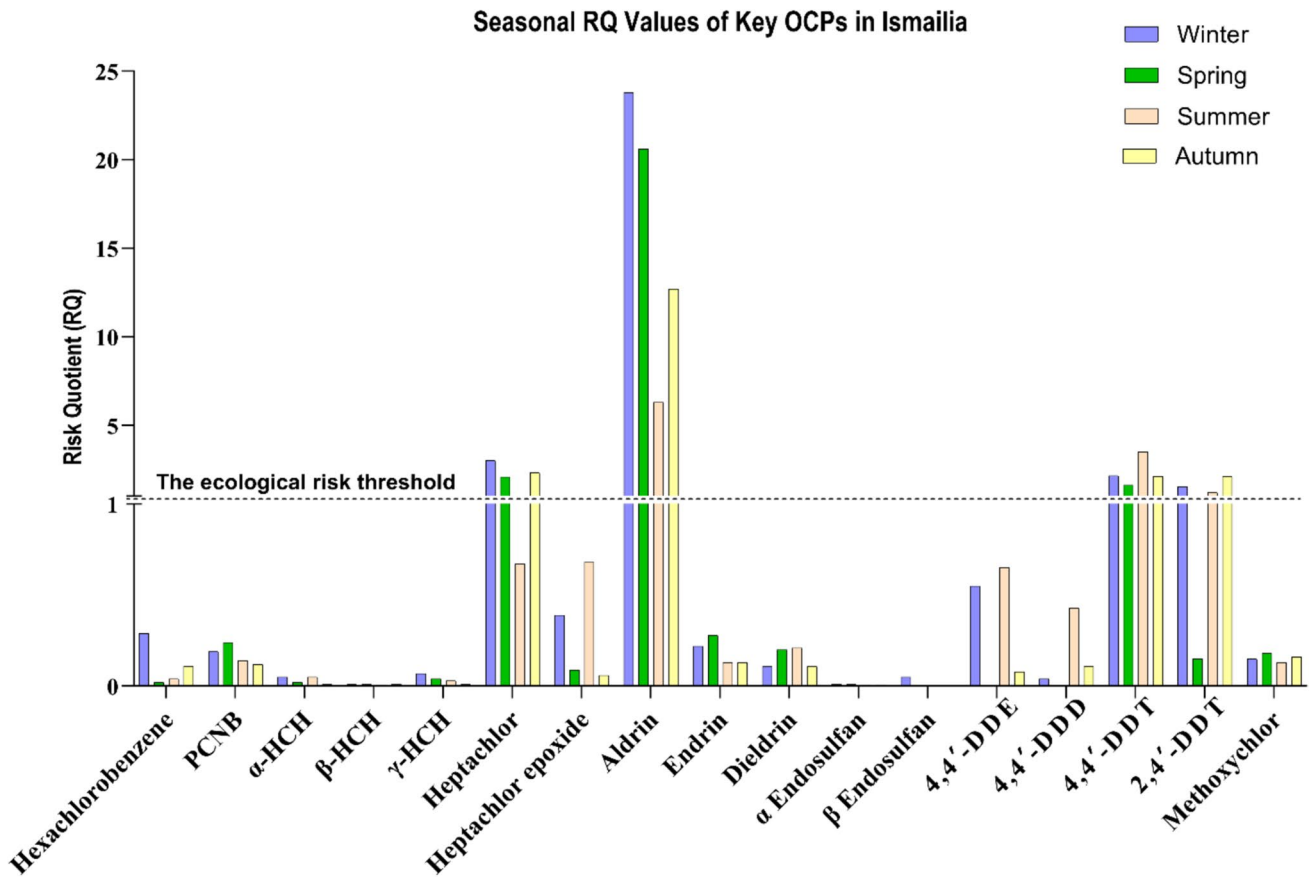


Fig. 7 Grouped bar charts illustrate the RQ values in Ismailia governorates during different seasons, labeled as follows: spring (blue), summer (green), autumn (yellow), and winter (beige). OCPs are plotted on the x-axis, while RQ values are plotted on the y-axis with a threshold set at RQ = 1. Only Aldrin, Heptachlor, 4,4′-DDT, and 2,4′-DDT indicated high ecological risk across the various seasons

OCPs concentration in camel, cattle, and sheep carcasses slaughtered in Sharkia governorate in Egypt. It revealed high percentages of DDTs, HCHs, Lindane, Dieldrin, Aldrin, Endrin, Toxaphene, HCB, and Chlordane, indicating the high risk for those OCPs to bioaccumulate and affect the ecosystem (Sallam and Mohammed Ali Morshedy, 2008). A study conducted in Ghana on water, fish, and sediment revealed that Aldrin has the highest concentration, and 4,4'- DDD has the lowest concentration (Akoto et al. 2016). Moreover, several studies have found high levels of OCPs in water and fish worldwide (Akoto et al. 2016; Hinojosa-Garro et al. 2016; Keswani et al. 2022).

On the contrary, Abou-Arab et al. (1995) conducted a study on the distribution of OCPs in fish, water, and sediment in two sampling areas in Egypt. The data revealed that DDT and its analogs were the most prevalent in fish samples from Manzala Lake. Meanwhile, total DDT, followed by Heptachlor, was the most pervasive in fish samples from the River Nile. Similarly, OCPs were detected in water samples in higher concentrations observed in the Manzala Lake samples compared to the River Nile during winter and summer. For sediments, the study emphasized specific descending orders of OCPs in sediment samples from Manzala Lake and the River Nile during winter and summer. Moreover, climate change can significantly affect OCPs' fate and behavior. For instance, temperature and precipitation play a pivotal role by interfering with volatilization and microbial degradation, consequently greatly affecting persistence and atmospheric transporting pathways. Likewise, rainfall or extreme weather conditions can increase runoff and leaching, resulting in the redistribution of OCPs from agricultural soils to nearby water bodies (Tang et al. 2021). These processes influence concentration, distribution, and environmental impact, ultimately contributing to seasonal variation.

We observed several statistically significant seasonal spikes in various governorates, most notably in Ismailia, Faiyum, and Alexandria, which can be identified as seasonal environmental risk hotspots. Notably, Aldrin, α-HCH, and β-HCH. Several other OCPs, including Endrin, Heptachlor, Methoxychlor, and 4,4′-DDE, also exhibited seasonal variation. Furthermore, our data indicated that several OCPs displayed distinctive significant seasonal variations.

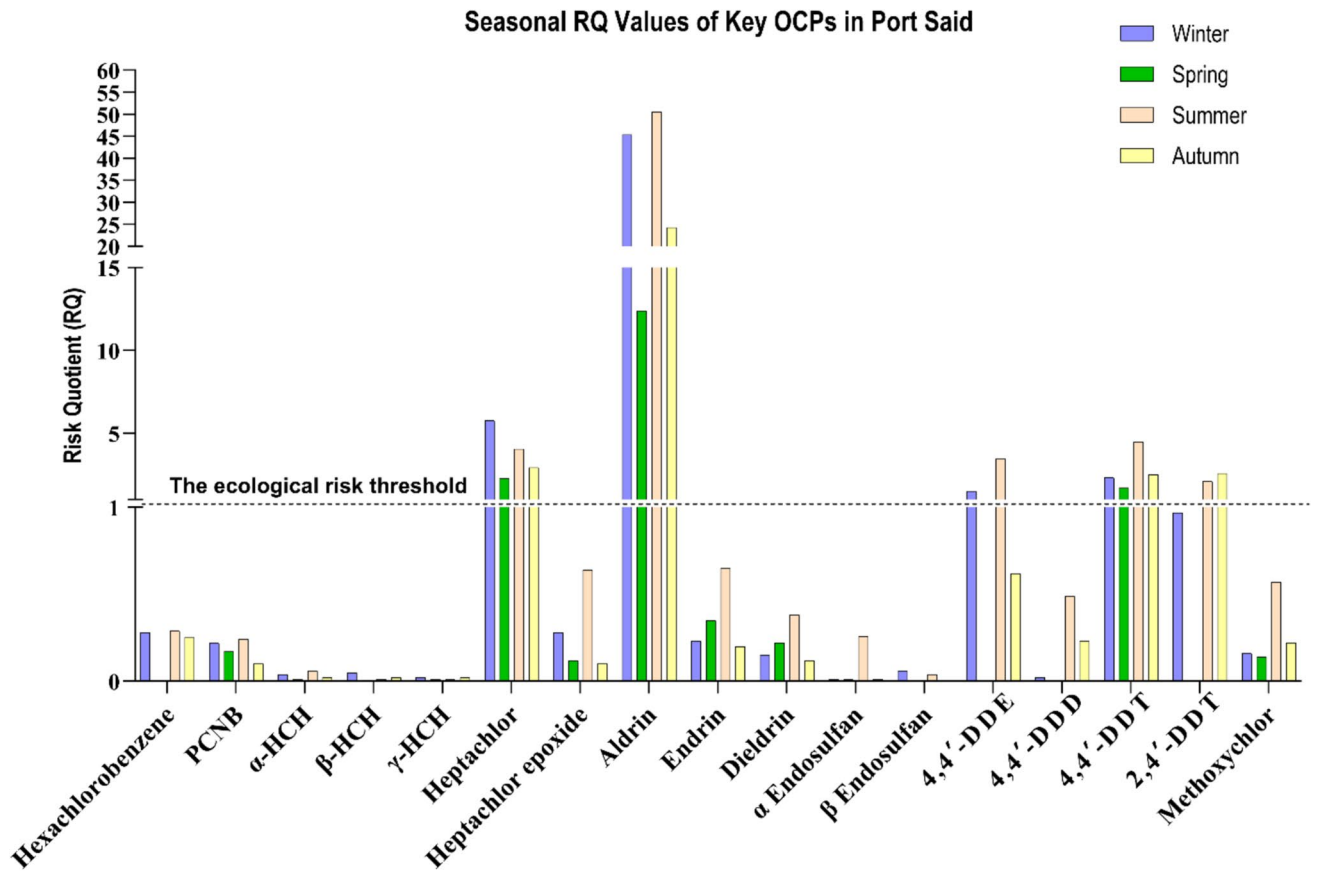


Fig. 8 Grouped bar charts display the RQ values in the Port Said governorates throughout different seasons, identified as spring (blue), summer (green), autumn (yellow), and winter (beige). OCPs are presented on the x-axis, while RQ values are represented on the y-axis, with a threshold set at RQ = 1. Only Aldrin, Heptachlor, 4,4′-DDT, and 2,4′-DDT showed high ecological risk across the various seasons

For instance, 4,4′-DDE showed noticeable fluctuations in Faiyum, while Methoxychlor was also found in Alexandria, and β-Endosulfan was identified in both Faiyum and Ismailia. Heptachlor, β-HCH, Endrin, and α-Endosulfan exhibited marked variation solely in the Ismailia governorate. Certain OCPs demonstrated unique seasonal variations only in Alexandria, including α-HCH, Heptachlor epoxide, and γ-HCH. These distinct chemical variations may arise from regional practices or climatic factors, such as agricultural practices, rainfall, temperature, soil retention, or urban versus rural dynamics, especially considering the minimal distinctive variation noted in Port Said.

We observed that 4,4′-DDT and 4,4′-DDE were sensitive to seasonal changes, as indicated by their concentration fluctuations across spatial and temporal distributions. In contrast, several OCPs, such as Dieldrin, γ-HCH, and Heptachlor epoxide, showed no seasonal variation in most areas, likely due to their environmental persistence, which necessitates investigation to identify sources and potential mitigation strategies. Factors contributing to these variations include seasonal and geographical changes, different agricultural practices, industrial activities, and urban influences. Further investigation is necessary to identify the source of exposure. Furthermore, while we discussed seasonal variation, there is an urgent need for longitudinal studies that analyze year-to-year trends and assess resistance to degradation and cumulative buildup in the environment.

Furthermore, our results illustrated differences in the interaction of OCPs across various governorates. Some OCPs exhibited significant variation among different governments, implying region-specific practices such as industrial activities, agricultural practices, and urbanization. These variations necessitate monitoring programs tailored to each region. Meanwhile, several OCPs persist in various areas, suggesting these chemicals may share similar sources that require further investigation, particularly regarding their stable concentrations and potential environmental impacts.

Furthermore, the ecological risk estimation using the RQ emphasized that out of the detected 17 OCPs, Aldrin, Heptachlor, 4,4′-DDT, and 2,4′-DDT have potential ecological risk in all the governorates, and 4,4′-DDE only show high risk in Port Said governorate. The magnitude of the risk generally follows the order: Aldrin > Heptachlor > 4,4′-DDT > 2,4′-DDT > 4,4′-DDE with a distinctive variation

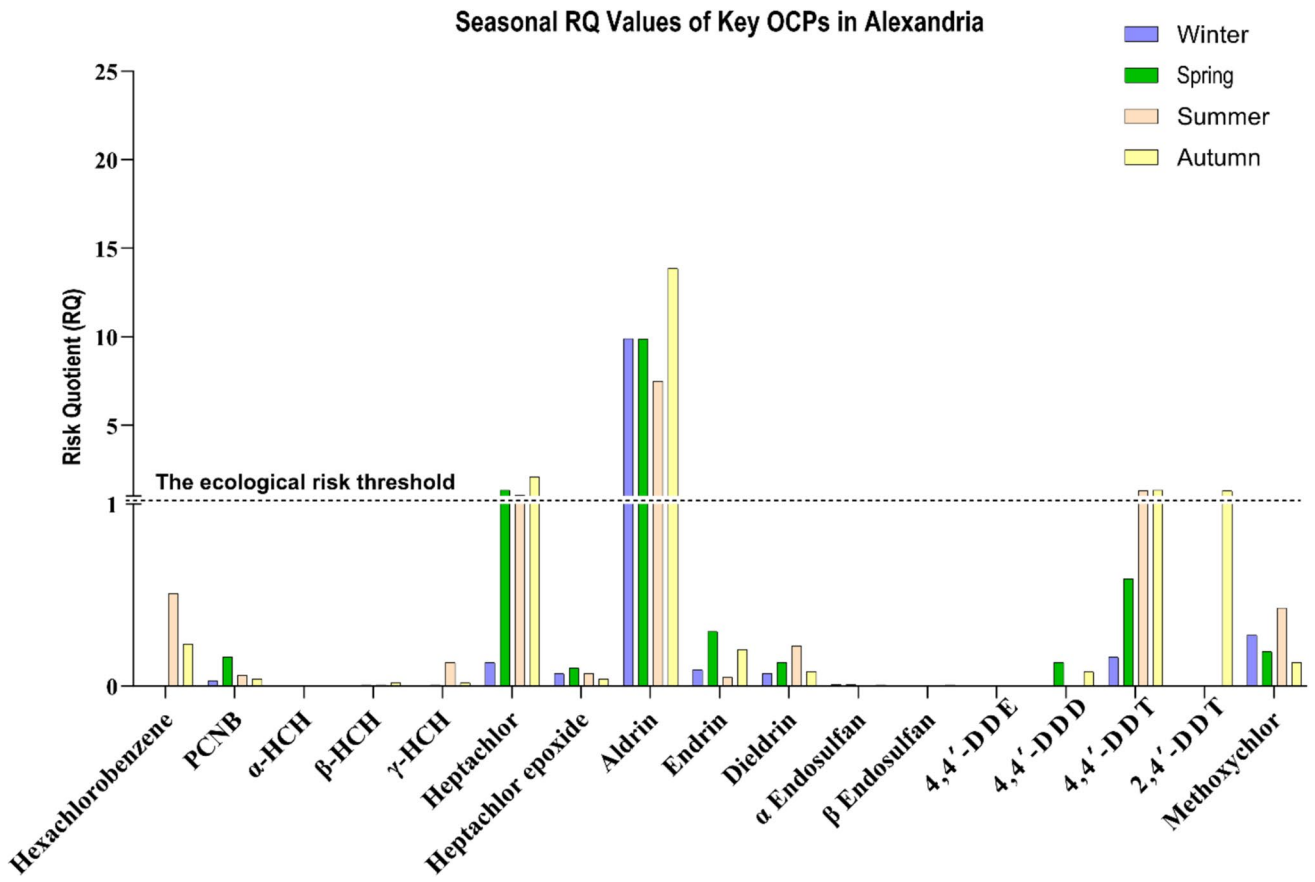


Fig. 9 Grouped bar charts display the RQ values across the Alexandria governorates during various seasons, identified as spring (blue), summer (green), autumn (yellow), and winter (beige). OCPs are shown on the x-axis, while RQ values are plotted on the y-axis, with a threshold set at RQ = 1. Aldrin presents the highest risk across different seasons than other OCPs, followed by Heptachlor and 4,4′-DDT

Table 1 Depicts the results from the THQ analysis in the Faiyum, Ismailia, Port Said, and Alexandria governorates

		Faiyum		Ismailia		Port Said		Alexandria	
OCPs	RFD (mg/ kg/day)	Mean(ng/g)	THQ	Mean(ng/g)	THQ	Mean(ng/g)	THQ	Mean(ng/g)	THQ
Hexachlorobenzene	0.00001	0.54	4.24E-02	0.65	5.13E-02	0.17	1.30E-02	0.35	2.73E-02
PCNB	0.003	0.65	1.71E-04	0.49	1.28E-04	0.13	3.44E-05	0.57	1.49E-04
α-HCH	0.008	1.19	1.16E-04	2.18	2.14E-04	1.51	1.48E-04	1.56	1.53E-04
β-HCH	0.008	0.76	7.49E-05	1.55	1.52E-04	4.95	4.86E-04	0.25	2.43E-05
γ-HCH	0.00001	2.06	1.62E-01	2.53	1.99E-01	1.36	1.07E-01	2.23	1.75E-01
Heptachlor	0.0001	3.53	2.77E-02	4.39	3.45E-02	3.98	3.13E-02	3.83	3.01E-02
Heptachlor epoxide	0.000013	1.08	6.54E-02	0.99	6.00E-02	0.23	1.38E-02	0.37	2.23E-02
α-Endosulfan	0.006	4.60	6.02E-04	15.68	2.05E-03	2.01	2.64E-04	5.74	7.51E-04
β-Endosulfan	0.006	1.09	1.42E-04	0.51	6.71E-05	0.22	2.93E-05	0.58	7.57E-05
Aldrin	0.00003	2.69	7.05E-02	3.79	9.92E-02	2.18	5.72E-02	3.28	8.60E-02
Endrin	0.0003	0.81	2.13E-03	0.67	1.75E-03	0.24	6.19E-04	0.34	8.93E-04
Dieldrin	0.00005	0.81	1.28E-02	0.68	1.07E-02	0.25	3.99E-03	0.51	8.07E-03
4,4-DDD	0.0005	1.11	1.75E-03	1.36	2.14E-03	0.38	5.89E-04	0.80	1.26E-03
4,4 DDE	0.0005	0.37	5.86E-04	0.46	7.25E-04	0.15	2.42E-04	0.24	3.75E-04
2,4 DDT	0.0005	0.96	1.51E-03	1.30	2.05E-03	ND	–	0.27	4.19E-04
4,4 DDT	0.0005	1.39	2.19E-03	1.58	2.48E-03	0.35	5.46E-04	0.69	1.09E-03
Methoxychlor	0.005	1.30	2.05E-04	0.89	1.39E-04	0.15	2.42E-05	0.62	9.76E-05

Table 2 Non-carcinogenic risk of dermal exposure to surface water contaminated with OCPs

Compounds	RfD (mg/ kg/day)	Faiyum	Ismailia	Port Said	Alexandria
Hexachlorobenzene	0.00001	1.91E-02	1.40E-02	2.60E-02	1.60E-02
PCNB	0.003	3.28E-04	4.08E-04	4.13E-04	1.99E-04
α-HCH	0.008	5.65E-05	1.50E-04	1.44E-04	ND
β-HCH	0.008	7.63E-05	4.77E-05	9.84E-05	3.57E-05
γ-HCH	0.00001	3.03E-02	1.32E-01	6.05E-02	8.68E-02
Heptachlor	0.0001	1.04E-02	7.70E-03	1.45E-02	4.64E-03
Heptachlor epoxide	0.000013	6.66E-02	1.57E-01	1.45E-01	3.98E-02
Aldrin	0.006	1.49E-04	1.55E-04	5.61E-04	1.01E-04
Endrin	0.006	1.07E-04	1.17E-04	2.11E-04	1.14E-04
Dieldrin	0.00003	2.84E-02	1.95E-02	2.57E-02	1.45E-02
α-Endosulfan	0.0003	1.72E-03	2.35E-03	1.50E-02	1.78E-03
β-Endosulfan	0.00005	2.47E-02	1.63E-02	3.01E-02	2.41E-03
4,4′-DDE	0.0005	3.05E-04	1.74E-04	7.55E-04	ND
4,4′-DDD	0.0005	3.46E-04	4.02E-04	5.18E-04	1.97E-04
2,4′-DDT	0.0005	4.08E-04	4.46E-04	5.47E-04	1.21E-04
4,4′-DDT	0.0005	8.77E-04	1.18E-03	1.38E-03	3.88E-04
Methoxychlor	0.005	8.70E-05	7.36E-05	1.28E-04	1.05E-04

between governorates and different seasons. Paradoxically, several OCPs that elicit high concentrations in all the seasons in most of the governorates, such as PCNB, Heptachlor epoxide, and β-Endosulfan didn't show high ecological risk, which might be due to certain factors associated with their bioavailability, toxic limits, degradation rate, and their distribution. Similarly, Chen et al. (2020) examined the ecological risk in an urbanized river network in Shanghai, China, and found that Aldrin, Heptachlor, 4,4′-DDT, 4,4′-DDE have higher ecological risk. In contrast, Zeng et al. (2018) reported no associated ecological risk with different OCPs in the surface waters of Qingshitan Reservoir in Southwest China. In addition, a study by Guo and colleagues (Guo et al., 2023) examined water from Beiluo River, China, and showed that HCB and endosulfan have the highest ecological risk.

Looking at the health risk, our data showed that OCPs have no risk in the four governorates in all seasons, indicating that long-term exposure from the consumption of Nile tilapia could not pose a health risk. This is consistent with our previous work, which revealed no risk associated with Nile tilapia consumption in all governorates throughout the year or in different seasons (Shamma et al. 2024). Likewise, our data highlighted the minor impact of contaminated water on OCPs through dermal exposure that has insignificant or no risk to human health (Table S2).

Moreover, dermal exposure through surface water contamination with OCPs contributes to a negligible likelihood of cancer risk (Fig. 6). Similarly, Bia et al. (2018) examined the carcinogenic risk of OCPs in Shaying River, China, and showed negligible to moderate carcinogenic in groundwater and surface water. A low cancer risk was observed when examining fish consumption data for several OCPs, particularly Aldrin, Dieldrin, and Heptachlor (Fig. 6). In this context, several studies revealed that high levels of OCPs in fish may pose a lifetime cancer risk for humans (Basu et al. 2021; Eqani et al. 2013; Yohannes et al. 2014). Therefore, we recommend implementing protective measures in specific areas, such as Ismailia and Port Said, to address sources of contamination. Continuous monitoring of these areas is essential, and additional risk reduction strategies should be considered in places with high OCP concentrations.

Together, our results emphasized that OCPs concentration exhibits significant variations in different geographical locations and seasons across the year, with only four OCPs possessing the ability to induce an ecological risk. Aldrin elicits the highest risk in different seasons compared to other OCPs, followed by Heptachlor, 4,4′-DDT, 4,4′-DDT. Interestingly, 4,4′-DDE exhibits a risk only in the Port Said governorate. Finally, our analysis concluded that there is no cumulative health risk associated with the consumption of Nile tilapia and minimal carcinogenic risk from fish consumption and dermal exposure to water contaminated with OCPs.

Conclusion

Although prohibited or limited in most countries, OCPs are still commonly utilized in developing countries. They can negatively impact human health by disrupting the neuroendocrine system, metabolism, lipid balance, and reproduction and can also cause congenital disabilities and cancer. Furthermore, OCPs can significantly affect the ecosystem, including avian, animal, and aquatic environments. Our data

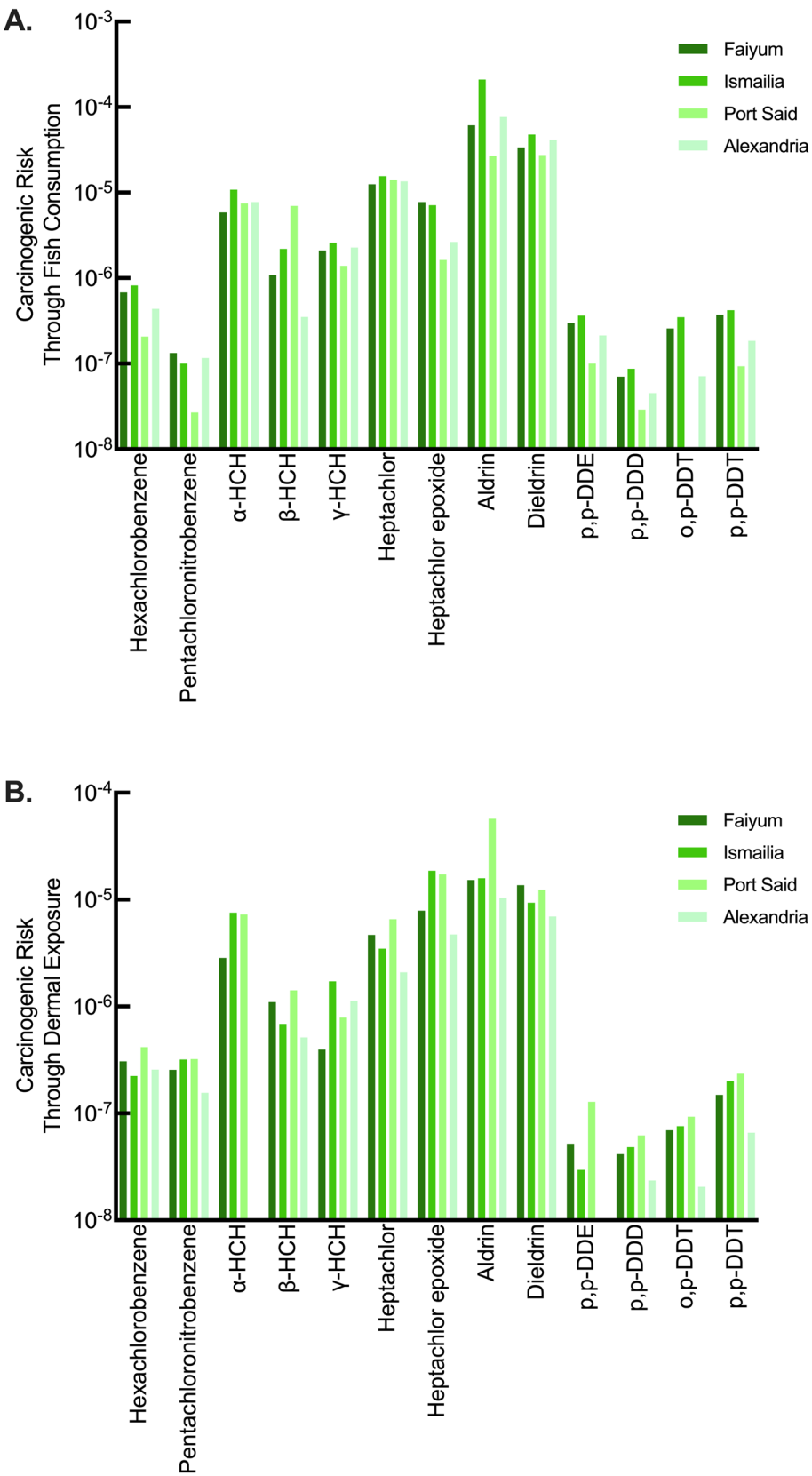


Fig. 10 Represents a log-scale line plot showing a comparative carcinogenic risk assessment of OCPs in Egypt. **A** Depicts the carcinogenic risk of OCPs in fish intake across different governorates, with higher points on the graph indicating greater carcinogenic risk. **B** Illustrates the carcinogenic risk of OCPs from dermal exposure across different governorates. A carcinogenic risk of 10^{-6} is generally seen as an acceptable or negligible cancer risk. Conversely, risk levels of 10^{-4} necessitate mitigation or intervention. In both exposure scenarios, Aldrin and Heptachlor epoxide present higher risk levels across governorates

indicate that the concentration of OCPs varies considerably among the four governorates in Egypt throughout the year. The analysis of 17 OCPs revealed certain pesticides, including Heptachlor, Aldrin, and β-Endosulfan, consistently have higher concentrations in specific seasons. In contrast, others, like α-HCH and Dieldrin, show moderate or low levels, varying by season and location. Seasonal spikes were identified, particularly in Ismailia, Faiyum, and Alexandria, marking them as environmental risk hotspots. Certain OCPs demonstrated distinctive seasonal variations, such as 4,4′-DDE in Faiyum. Heptachlor, β-HCH, Endrin, and α-Endosulfan exhibited significant changes solely in Ismailia, while α-HCH, Heptachlor epoxide, and γ-HCH showed unique seasonal patterns only in Alexandria. Only Aldrin, Heptachlor, 4,4′-DDT, and 2,4′-DDT pose an ecological risk in all four governorates, and only 4,4′-DDE poses an ecological risk in the Port Said governorate. Our data also show no human health risk associated with dermal exposure to surface water or the consumption of Nile tilapia, and there is minimal risk of cancer associated with consuming fish from the Nile or dermal exposure. These findings highlight the critical need for routine monitoring of OCPs and the implementation of science-based policies aimed at reducing environmental and public health risks. Targeted regulatory actions and educational campaigns are essential to increase community awareness and promote safer pesticide use in vulnerable regions.

The findings of this study have important implications for environmental monitoring and public health protection. Identifying seasonal and regional hotspots of OCP contamination highlights the need for targeted regulatory intervention and improved pesticide management practices. Moreover, the ecological risks and potential health impacts associated with OCP exposure underscore the urgency of developing long-term monitoring programs, enhancing public awareness, and implementing remediation strategies in high-risk areas. These efforts are crucial for informing environmental policies and safeguarding ecosystems and human populations in Egypt and similar contexts.

Recommendations and future perspectives

In this study, we emphasized the harmful effects of OCPs and the associated ecological risk. Our results showed significant seasonal variations in certain OCP levels while others remained persistent. This suggests customized seasonal monitoring programs for fluctuating OCPs and specific monitoring strategies for persistent OCPs to evaluate their endurance in the environment and develop potential mitigation strategies.

We recommend prioritizing innovative remediation methods that can effectively remove hazardous materials from air, soil, and water, as this will considerably reduce ecosystem risks. For example, seasonal monitoring programs should be implemented in hotspot areas such as Ismailia, Faiyum, and Alexandria to enhance observation efforts. Additionally, strict enforcement of regulations against high-risk, persistent chemicals is essential.

Longitudinal studies should be conducted for predictive modeling and proactive enforcement. Furthermore, we advocate for strict limitations on seasonal-sensitive OCPs, like 4,4'-DDT and 4,4'-DDE, during vulnerable periods. Although our data showed no associated non-cancerous risk, it is vital to endorse strict regulations, especially in areas with high OCP concentrations and employ monitoring programs that trace OCPs levels across broad regions and extended timeframes—implementing public health initiatives to increase awareness of the imminent risks of the OCPs (Garratt and Kennedy 2006) and adopting a more efficacious alternative with minimal risk to the ecosystem (Hoffmann 1971).

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Author contributions S.S. contributed to writing—review and editing, writing—original draft, validation, methodology, investigation, formal analysis, data curation, and conceptualization. M.A.H. was involved in writing—review and editing, writing—original draft, methodology, investigation, formal analysis, and data curation. E.M.E. and A.S. assisted in supervision and conceptualization. M.N.H. contributed to supervision, resources, methodology, formal analysis, and conceptualization. H.N.S. contributed to writing—review & editing, validation, methodology, and conceptualization.T.S. was involved in writing—review and editing, validation, methodology, investigation, formal analysis, data curation, and conceptualization. A.A. contributed to writing—review and editing, writing—original draft, validation, supervision, resources, project administration, methodology, investigation, funding acquisition, formal analysis, data curation, and conceptualization.

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Data availability Data are available upon request from the corresponding author.

Declarations

Competing interest The authors declare no conflict of interest.

Ethical approval (research involving animals) Nile tilapia (Oreochromis niloticus) were purchased post-harvest from different aquaculture farms for use as food-grade analytical samples. No live animals were handled. No endangered or protected species were involved.

Informed consent The study did not involve human participants or collect personal data; therefore, informed consent was not required.

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