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# Ecological Risks of Persistent Organic Pollutants in Highly Agriculturally Intensive Use in Al-Qassim Region, Saudi Arabia

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**Abstract**

Persistent organic pollutants (POPs) in agricultural soils pose significant environmental and human health risks. This study investigates the concentrations of POPs in agricultural soils from 30 locations in Buraydah, Saudi Arabia. The majority of the sampling sites exhibited undetectable pesticide levels, indicating low environmental risks. However, six locations showed varying degrees of pesticide contamination, with Cypermethrin (14.8–562.5 ppb) and Bifenthrin (25.2–156.1 ppb) being the most prominent pollutants. Location 16 exhibited the highest pesticide concentrations, while Location 20 posed the greatest potential health risk. A comprehensive carcinogenic risk assessment was conducted to evaluate cancer risks associated with ingestion, dermal contact, and inhalation exposure pathways. The total cancer risk (TCR) was computed as the sum of risks from all pathways, identifying specific locations requiring urgent remediation. Additionally, a non-carcinogenic risk assessment was performed using the Hazard Quotient (HQ) and Hazard Index (HI) to estimate cumulative risks from multiple substances. Although the overall POP levels were relatively low compared to global studies, the findings emphasize the need for continuous monitoring, sustainable agricultural practices, and stricter pesticide regulations to mitigate both carcinogenic and non-carcinogenic health risks.

**Keywords:** Pesticides (POPs), Soil Contamination, Health Risk Assessment, Environmental Pollution, Pesticide Residue, Cancer.

## 1. Introduction

Persistent Organic Pollutants (POPs) are a class of hazardous chemical substances that pose significant threats to environmental and human health due to their prolonged environmental persistence, bio-accumulative nature, and toxicological impacts. These pollutants, which include pesticides, industrial chemicals, and by-products of manufacturing processes, resist degradation through chemical, biological, or photolytic mechanisms, enabling them to persist in ecosystems for decades [1, 2]. The discovery of POPs in the environment shortly after World War II marked a turning point in environmental sciences, highlighting their global dispersion, bioaccumulation in living organisms, and capacity for long-range atmospheric transport. These properties make POPs a critical environmental issue, disrupting ecosystems, threatening biodiversity, and posing serious risks to human and wildlife health [3-5].

The Stockholm Convention on Persistent Organic Pollutants (2001) was established to address the global threat posed by POPs, aiming for the elimination or significant restriction of their production and use. Under this framework, twelve "legacy POPs," including aldrin, DDT, and PCBs, were initially identified and targeted for control, with additional pollutants such as perfluorooctanesulfonic acid (PFOS) added subsequently. Despite internationalfforts, the improper use and storage of pesticides, particularly in regions with intensive agricultural practices, remain pressing challenges. POPs are lipophilic and hydrophobic, enabling them to bioaccumulate in fatty tissues and biomagnified through food chains, leading to long-term health impacts such as endocrine disruption, reproductive disorders, and increased cancer risks in humans and wildlife [6-8].

Agricultural practices are a major contributor to POP contamination. Pesticides containing POPs, such as DDT and aldrin, have historically been used extensively to enhance crop yields and manage pests [9]. However, their persistence in the environment, combined with improper handling and storage practices, exacerbates soil, water, and air contamination [10]. In Saudi Arabia, the Al-Qassim region, known for its significant agricultural productivity, is particularly vulnerable to the environmental and health risks posed by POPs. This region, characterized by its strategic location, fertile soils, and reliance on agriculture, faces challenges related to the overuse of chemical pesticides and fertilizers. Studies have documented the contamination of soil and water resources in Al-Qassim due to expired or banned pesticides, with evidence of bioaccumulation in the food chain [5, 11].

The agricultural practices in Al-Qassim, including the cultivation of dates, cereals, and fruits, are vital to the region's economy and food security. However, intensive farming has led to the accumulation of pesticide residues in the environment, resulting in risks to both agricultural sustainability and public health. The arid climate and limited freshwater resources in Al-Qassim further exacerbate the persistence of POPs, as their degradation is hindered under such conditions. Long-term exposure to

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these pollutants has been linked to hormonal imbalances, developmental disorders, and cancer in humans, as well as disrupted reproductive and immune systems in wildlife [12-14].

POPs are widely distributed across various environmental matrices, including soil, water, air, and biological systems. Their semi-volatile nature allows them to undergo long-range atmospheric transport, enabling their deposition in regions far from their original sources [15]. This phenomenon has been observed even in remote areas, such as the Arctic, where POP residues have been detected in wildlife. In the Al-Qassim region, pesticide residues in agricultural soils have been documented as a significant source of environmental contamination. These residues are not only persistent but also capable of bioaccumulating in food chains, posing dual threats to public health and ecological stability [16-18].

The health risks associated with POP exposure are profound. These pollutants are known endocrine disruptors and have been linked to developmental abnormalities, neurological disorders, immune suppression, and increased cancer risks [19, 20]. Vulnerable populations, such as children, are particularly at risk due to their developing biological systems. Wildlife also suffers from the bioaccumulation of POPs, with evidence of reproductive issues, immune dysfunction, and population declines in species exposed to these contaminants. The persistence of POPs in the environment ensures that their impacts are long-lasting, necessitating urgent regulatory and remedial actions [6, 21].

The Stockholm Convention has been instrumental in reducing the global production and use of POPs. However, the effective implementation of its guidelines requires robust national policies, capacity building, and public awareness [22]. In Saudi Arabia, efforts to address POP contamination include training programs for farmers, promoting integrated pest management (IPM), and encouraging the use of biopesticides and precision agriculture technologies. IPM strategies, such as crop rotation and biological controls, aim to reduce reliance on chemical pesticides while maintaining agricultural productivity. Additionally, there is a growing emphasis on sustainable agriculture in Al-Qassim, focusing on organic farming, efficient water use, and the development of drought-resistant crops [23, 24].

Despite these initiatives, challenges remain in managing and mitigating POP contamination. In Al-Qassim, the lack of stringent enforcement of pesticide regulations and improper disposal of agrochemical containers contribute to the persistence of POPs in the environment. Furthermore, the re-emission of long-banned substances retained in soil underscores the need for comprehensive monitoring and remediation strategies. Bioremediation, advanced filtration systems, and adsorption processes are among the techniques being explored to address POPcontamination in contaminated soils and water bodies [25, 26].

This study aims to evaluate the concentrations of POPs in agricultural soils in Al-Qassim, with a focus on Buraydah, to establish baseline data for environmental regulation and health risk assessment. By analyzing POP residues in soil samples, this research provides crucial insights into the extent of pesticide contamination and its associated risks. The findings underscore the importance of addressing the combined concerns of environmental degradation and public health threats in the region. Moreover, this study highlights the need for a multi-faceted approach, integrating scientific research, policy support, and community engagement, to transition towards sustainable agricultural practices in Al-Qassim [19, 20].

By prioritizing environmental stewardship, food security, and public health, Al-Qassim can serve as a model for other regions facing similar challenges. Addressing the issue of POP contamination requires international cooperation, investment in education and training, and the adoption of innovative remediation technologies. This research's findings contribute to the development of future environmental legislation, remediation projects, and public health measures, ensuring the preservation of natural resources for future generations.

## 2. Materials and Methods

### *2.1 Sampling*

The study was conducted in the agricultural region of Buraydah, Al-Qassim, Saudi Arabia, characterized by sandy loam soil, which is ideal for farming due to its strong drainage properties, absence of impermeable layers, and salinity. The region supports intensive agricultural activities, including the cultivation of dates and vegetables, sustained by modern irrigation techniques. Soil samples were collected from 30 agricultural locations of palm farms across Buraydah (Figure 1). At each sampling site, 5 g of soil was collected using pre-cleaned soil augers, stainless steel scoops, and spatulas. To prepare composite samples, 10 mL of distilled water was added to each soil sample and thoroughly mixed. The samples were wrapped in aluminum foil, placed in sealed polythene bags, and stored in a cooler box with ice packs at 4°C until further processing [27]. Soil samples were dried at 105°C for 24 hours to determine dry weightprior to analysis, with all POP concentrations expressed per dry mass.

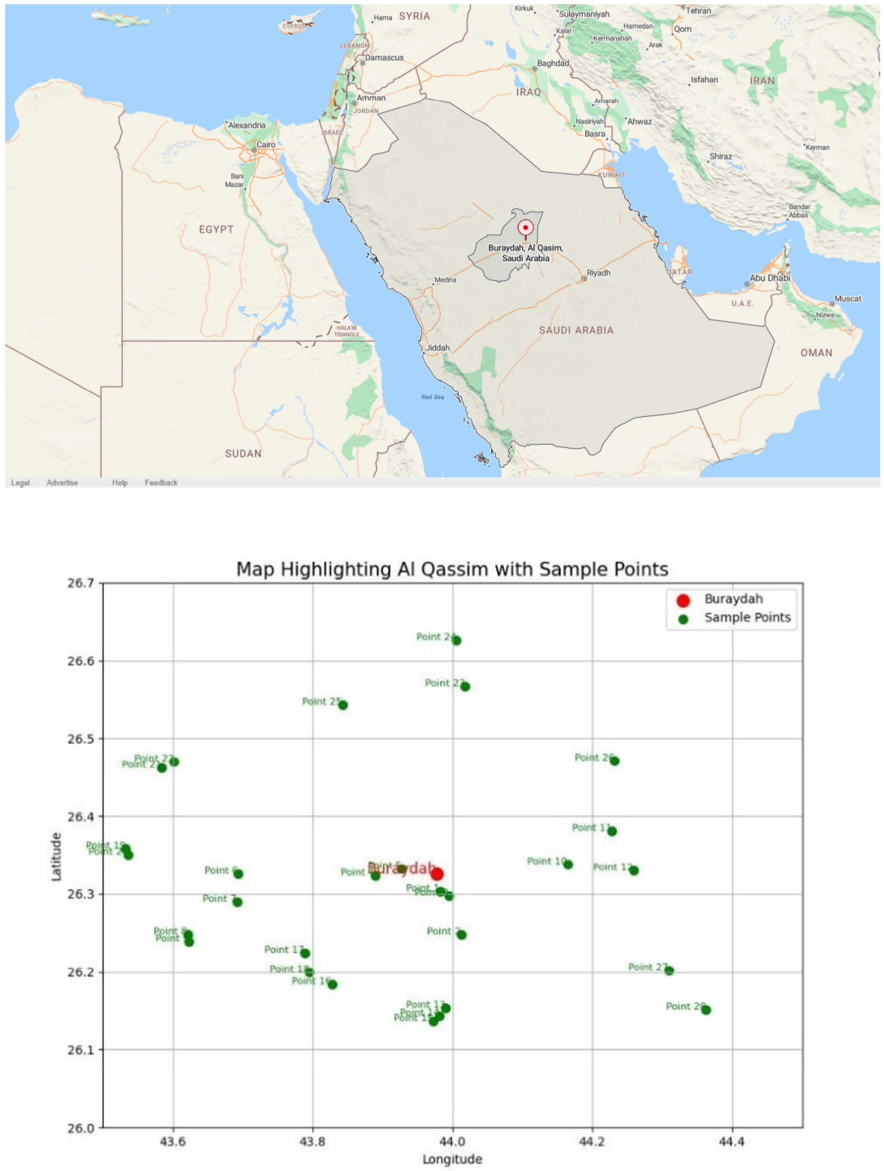


**Fig.1.The sampling locations are in Buraydah, Saudi Arabia.**

*2.2 Extraction and Analysis*

The extraction of persistent organic pollutants (POPs) from soil samples followed the US-EPA DIN EN 15662:2018-07 method. Homogenized 5 g soil samples were placed in 50 mL centrifuge tubes and mixed with 10 mL of distilled water. To maintain the integrity of pesticide residues, the samples were stored at −20°C before analysis. An internal standard solution (100 µL of PCB-52 at 5 ppm) was added to account for matrix effects and ensure accurate quantification of pesticide residues [28, 29].

For solvent extraction, 10 mL of acetonitrile (ACN) was added to the samples, which were then shaken at 300 rpm for 20 minutes. The tubes were centrifuged at 5000 rpm for 5 minutes to separate the organic phase containing extracted pesticides from soil particulates. The supernatant was transferred to new tubes, where a QuEChERS (Quick, Easy, Cheap, Effective, Rugged,and Safe) clean-up kit was added to remove matrix interferences such as lipids and pigments. The mixture was shaken for 15 minutes and centrifuged again under the same conditions.

After clean-up, 10 µL of formic acid in ACN was added to each extract, and 1 mL of the solution was transferred into vials for analysis using Gas Chromatography-Tandem Mass Spectrometry (GC-MS/MS). To prevent contamination, blank ACN samples were injected before soil extracts, followed by calibration standards to construct calibration curves for quantification.

The GC-MS/MS system used a 30-meter Rxi-5ms column (0.25 mm inner diameter, 0.25 µm film thickness) with helium as the carrier gas. The temperature program began at 90°C, held for 1 minute, ramped to 130°C at 30°C/min, and then to 330°C at 10°C/min, with a total run time of 24.3 minutes. The mass spectrometer operated in multiple reaction monitoring (MRM) mode, with the detector set at 230°C and nitrogen as the collision gas. Injection was performed in split-less mode with a 1 µL injection volume and an injector temperature of 250°C. Pesticide residues were confirmed if their concentrations exceeded the limit of detection (LOD), set at 20 parts per billion (ppb).

*2.3 Quality Assurance and Quality Control (QA/QC)*

Comprehensive QA/QC measures were applied to ensure the reliability and precision of the analytical process. Instrument calibration was performed using five concentration levels, with linearity checks ensuring deviations between calculated and actual concentrations remained within ±20%. Matrix effects were evaluated by comparing solvent standards with matrix-matched standards, and adjustments were made for signal suppression or enhancement exceeding 20%.

The limit of quantification (LOQ) was established based on the lowest spike level meeting recovery and precision criteria, ensuring that method detection limits (MDLs) were below the maximum residue limits (MRLs). Specificity was assessed using reagent blanks and blank controls, with a response threshold of 30%. Recovery rates for spiked levels were maintained within 70–120%, and relative standard deviation (RSD) values remained below 20%. Validation ensured reproducibility within the laboratory, with retention times deviating by no more than ±0.1 minutes.

The method demonstrated high accuracy and precision in pesticide residue analysis. Recovery rates ranged from 94.2% to 99.9%, with the highest recovery obtained for Cypermethrin-3 at 0.05 µg/g (99.9%), and the lowest for Dichlorvos at 0.025 µg/g (94.2%). Linearity values ($r^2$) ranged from 0.9980 to 0.9999, confirming the method's suitability for quantifying pesticides across a wide concentration range. Matrix effects varied between 10% and 50%, emphasizing the need for matrix-matched calibration for accurate quantification.

*2.4 Carcinogenic Risk Assessment*

Carcinogenic risks associated with ingestion, dermal contact, and inhalation of contaminated soil particles were evaluated using equations adapted from U.S. EPA guidelines.

***2.4.1*** *Ingestion Risk:*

The cancer risk due to soil ingestion (CRingest) was calculated using the concentration of the contaminant in soil (Csoil, measured in mg/kg), ingestion rate (IngR, measured in mg/day), exposure frequency (EF, expressed in days/year), exposure duration (ED, in years), body weight (BW, in kg), averaging time (AT, measured in days) , conversion factor, and oral slope factor.

$$CRingest = \frac{Csoil \times IngR \times EF \times ED}{BW \times AT} \times CF \times SFsoil \quad (1)$$

***2.4.2*** *Dermal Risk:*

The dermal cancer risk (CRdermal) was estimated based on the surface area of exposed skin (SA, measured in cm²), soil adherence factor (AFsoil, in mg/cm²), chemical-specific dermal absorption factor (ABS), and gastrointestinal absorption fraction (GIABS).

$$CRdermal = \frac{Csoil \times SA \times AFsoil \times ABS \times IngR \times EF \times ED}{BW \times AT} \times CF \times SFsoil \times GIABS \quad (2)$$

***2.4.3*** *Inhalation Risk:*

The risk from inhalation of contaminated soil particles (CRinhale) incorporated the inhalation rate (InhR, measured in m³/day), lung absorption factor (AFinh), particle emission factor (PEF, set at $1.36 \times 10^9$ m³/kg), and inhalation unit risk (IUR, equal to 5.7E−01 $(mg/m^3)^{-1}$).

$$CRinhale = \frac{Csoil \times SA \times InhR \times AFinh \times EF \times ED}{PEF \times AT} \times IUR \quad (3)$$

The total cancer risk (TCR) was computed as the sum of risks from all exposure pathways. A parallel non-carcinogenic risk assessment was conducted using the Hazard Quotient (HQ) and Hazard Index (HI), representing cumulative risks from multiple substances.

$$\boldsymbol{CR = Exposure \times Cancer\ Slope\ Factor\ (CSF)} \quad (4)$$

$$\boldsymbol{TCR} = \sum_{i=1}^{n} \mathrm{CRi} = \mathrm{CR1} + \mathrm{CR2} + \cdots + \mathrm{CRn} \quad (5)$$

$$\boldsymbol{HQ} = \frac{\boldsymbol{Exposure}}{\boldsymbol{Refrence\ dose}} \quad (6)$$

$$\boldsymbol{I} = \sum_{i=1}^{n} \mathrm{HQi} = \mathrm{HQ1} + \mathrm{HQ2} + \cdots + \mathrm{HQn} \quad (7)$$

### ***2.5*** *Statistical Analysis*

Descriptive statistics were performed using Jamovi (version 2.6.13) to summarize the findings.

## 3. Results and Discussion

### ***3.1*** *Levels of POPs*

The present study investigated the presence of POPs across 30 agricultural soil locations in Buraydah, Saudi Arabia. Soil samples were collected from these locations, which are detailed in Table 1. Statistical analysis was performed using Jamovi (version 2.6.13) to detect and evaluate the presence of pesticides across the locations. The main objective was to assess the presence of 59 different pesticides and determine their distribution among the 30 sampling points.Descriptive statistics conducted across all observed locations revealed significant findings. Many of the sample points showed no detectable pesticides, indicating a promising absence of contaminants in a majority of the study locations. Specifically, no pesticides were detected at sample points 1, 2, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27, and 28, which are detailed in Figure 2. This finding suggests a broad absence of POPs across most of the locations surveyed an encouraging sign for both soil health and environmental safety in Buraydah. The lack of contamination in these areas points to a reduced risk of pesticide exposure and affirms the suitability of the soil for agricultural activities. Conversely, pesticides were detected at sample points 3, 5, 6, 16, 20, and 30 (Table 1). Although the number of detected pesticides at these locations ranged from 1 to 4 from the 59 pesticides per sample, their presence suggests that attention is needed in these specific areas. The contamination, while not widespread, indicates that pollution exists in a limited capacity and requires ongoing monitoring. The relatively low number of pesticides per location is a positive sign, indicating that contamination is not severe and may remain manageable. Results indicated that the majority of study locations showed no detectable POPs contamination (hereafter termed 'non-contaminated zones'), while some locations exhibited moderate contamination levels (designated as 'localized contamination zones' with ∑POPs concentrations ranging from 14.8 to 910.1 ppb).

After this initial assessment, the sample points with no detectable pesticides were excluded from further analysis. This exclusion allowed for a more focused examination of the locations where pesticide contamination was confirmed. The ∑POPs concentrations presented in Table 2 are the sum of all present pesticides in each location. In location 3, the total POPs concentration is 189.1 ppb, with a standard deviation of 20.69, and the maximum observed concentration is 156.1 ppb. Location 6 shows a lower total concentration of 14.8 ppb, with a minimal deviation of 1.92 and a maximum concentration of 14.8 ppb. In location 20, the total concentration is 60.6 ppb, with a standard deviation of 6.13 and a maximum concentration of 44.5 ppb. Location 5 records the lowest concentration among all sites, with a total of 13.1 ppb, a deviation of 1.71, and a maximum concentration of 13.1 ppb. Location 16 shows the highest total POPs concentration at 910.1 ppb, with a large standard deviation of 81.58, and a maximum concentration of 562.5 ppb. Lastly, location 30 records a total POPs concentration of 61.3 ppb, with a standard deviation of 4.48, and a maximum concentration of 25.2 ppb. The overall ∑POPs concentration across all six locations totals 1,249 ppb in Buraydah, Saudi Arabia.

The average concentration of ΣPOPs in the present study was found to be 6.245 ng/g. This value is comparatively lower than those reported in Dalki and Shabankare in Iran [30], Mexico [31], Wuhan, China [32], southern farms in the United States [33], Palakkad, India [34], Kenya, Eastern Africa [35], and Riyadh, Saudi Arabia [36]. Conversely, it is slightly higher than the residual values reported in Pakistan [37] and Sulaibia, Kuwait [38]. These findings suggest that elevated pesticide levels in the study area may be associated with recent agricultural activities or improper pesticide usage.

The observed elevated concentrations of Cypermethrin-1, Cypermethrin-2, Cypermethrin-3, Bifenthrin, and Diazinon in soil samples could be attributed to the respective half-lives of these compounds, which significantly influence their persistence in the environment. Cypermethrin-1, Cypermethrin-2, and Cypermethrin-3 have half-lives ranging from 2 to 8 weeks [39], indicating a potential for relatively rapid degradation under ideal conditions. However, the detection of these compounds suggests either recent pesticide application or environmental factors—such as temperature, moisture, and microbial activity—that may have inhibited their degradation, allowing them to persist longer in the soil. Bifenthrin, in contrast, has a significantly longer half-life, ranging from 122 to 345 days, which accounts for its prolonged presence in the soil even long after application. Its persistence is further reinforced by its strong affinity for binding to soil particles, which reduces its bioavailability and, consequently, slows down its degradation [40]. Moreover, the detection of Diazinon, which under aerobic conditions typically degrades within 2 to 4 weeks, indicates either recent application or suboptimal conditions for its breakdown. Diazinon generally degrades more rapidly in the presence of oxygen, and its persistence in the soil may also result from factors such as low oxygen levels or improper application techniques [41]. Thus, the elevated levels of these pesticides in the study area could reflect both their inherent persistence due to their chemical properties and the improper or excessive use of pesticides in agricultural practices. These findings underscore the necessity of monitoring pesticide application and advocating for sustainable agricultural practices to mitigate environmental contamination and minimize associated human health risks.

These findings offer both reassuring and concerning insights into pesticide contamination in the agricultural soils of Buraydah. On the positive side, the majority of the sampled locations did not exhibit detectable levels of pesticides, indicating a relatively low environmental risk from persistent organic pollutants (POPs) in these areas. However, the presence of pesticides, even in small quantities and concentrations in a few locations, underscores the necessity of ongoing monitoring and remediation. This highlights the critical need for targeted environmental assessments, providing valuable data that can inform policymakers and agricultural authorities in their efforts to mitigate future contamination risks. Thus, this study serves as a foundation for future research and proactive interventions aimed at preserving soil health and safeguarding public health.

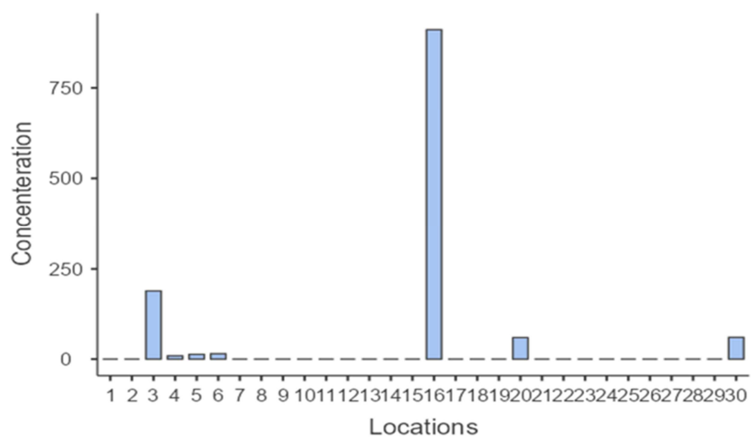


**Fig. 2. Bar plot showing the detected pesticide concentrations (ppb) at 30 sample points.**

*3.2 Health risk assessment*

This study evaluates human health risks associated with persistent organic pollutant (POP) residues in agricultural soils across the Buraydah region of Al-Qassim, Saudi Arabia. In the current study a comprehensive cancer risk assessment was conducted for adult populations through three primary exposure pathways: soil ingestion, dermal contact, and particle inhalation. The analysis revealed detectable cancer risks in six monitored areas, with total risk values ranging from $6.37 \times 10^{-12}$ to $1.48 \times 10^{-3}$. While these values represent the lowest risk levels among comparable global studies (Table 4), the significant variability across sampling locations indicates potential hotspots of contamination. This spatial heterogeneity likely stems from differential pesticide application practices and local environmental factors, including soil composition and agricultural management techniques. Comparative analysis with international datasets demonstrates that Buraydah's risk profile remains favourable relative to other agricultural regions worldwide. However, the upper range of detected risk values approaches concerning levels, particularly in areas with intensive pesticide use.

**Table 1: The geographical positions of observed locations.**

| Sample point number | Latitude | Longitude | Sample point number | Latitude | Longitude |
|---|---|---|---|---|---|
| 1 | 26.30369 | 43.98208 | 16 | 26.22499 | 43.78827 |
| 2 | 26.24801 | 44.01213 | 17 | 26.1999 | 43.79511 |
| 3 | 26.29793 | 43.99461 | 18 | 26.3584 | 43.53247 |
| 4 | 26.33237 | 43.92704 | 19 | 26.35042 | 43.53667 |
| 5 | 26.32587 | 43.69299 | 20 | 26.46219 | 43.5842 |
| 6 | 26.29018 | 43.69177 | 21 | 26.47006 | 43.60163 |
| 7 | 26.24802 | 43.62122 | 22 | 26.56691 | 44.01775 |
| 8 | 26.23875 | 43.62303 | 23 | 26.62634 | 44.00535 |
| 9 | 26.33771 | 44.16426 | 24 | 26.54337 | 43.84266 |
| 10 | 26.38124 | 44.22767 | 25 | 26.47111 | 44.23184 |
| 11 | 26.3303 | 44.25859 | 26 | 26.20416 | 44.30892 |
| 12 | 26.1533 | 43.99016 | 27 | 26.15162 | 44.36222 |
| 13 | 26.14317 | 43.98105 | 28 | 26.15224 | 43.95825 |
| 14 | 26.13602 | 43.97239 | 29 | 26.2563 | 44.02586 |
| 15 | 26.18417 | 43.8272 | 30 | 26.5569 | 43.8527 |

The results presented in Figures 3, 4, and 5 illustrate the estimated cancer risks associated with the three exposure routes: ingestion, dermal contact, and inhalation in adults across different locations in the Buraydah region. The ingestion risk, as shown in Figure 3, varied significantly among the studied locations, with Location 20 having the highest estimated cancer risk, approximately $1.2\times10^{-5}$. This indicates that soil contamination at this location might be higher due to improper or excessive pesticide use. On the other hand, lower ingestion risks were observed in Locations 5, 6, and 16, indicating relatively lower levels of pesticide contamination in these areas. This variability in risk is likely influenced by differences in pesticide usage patterns, as well as environmental factors such as soil properties and agricultural practices. For dermal exposure, as depicted in Figure 4, Location 20 also recorded the highest risk value, approximately 0.0015. This suggests that the pesticides present at this location have properties that make them more prone to skin absorption. This finding highlights the importance of taking precautionary measures, particularly for agricultural workers who come into direct contact with the soil in this area. Conversely, the lower dermal risks observed in other locations such as 3, 5, and 16 reflect lower contamination levels and less potential for dermal absorption. Although the inhalation risk was significantly lower compared to ingestion and dermal contact, as shown in Figure 5, Location 20 again recorded the highest value, around $4\times10^{-10}$. This suggests that while the risk from inhalation is very low, it should not be entirely dismissed, especially in areas with higher contamination levels. The small magnitude of inhalation risk can be attributed to limited dispersal of soil particles in the air and reduced bioavailability of pesticides in aerosol forms. Thus, the estimated cancer risks across the three exposure pathways consistently highlight Location 20 as the most contaminated area, with significantly higher risk levels compared to other sampled locations. This suggests either recent or prolonged pesticide exposure, improper pesticide management, or environmental factors that favor the persistence of these pollutants in the soil. The elevated cancer risks, particularly through ingestion and dermal contact, emphasize the need for targeted environmental assessments and mitigation efforts at Location 20.

**Table 2: The descriptive statistics of locations containing pesticides**

| locations | Mean | Sum (ppb) | SD | Minimum | Maximum (ppb) |
|---|---|---|---|---|---|
| 3 | 3.205 | 189.1 | 20.69 | ND | 156.1 |
| 6 | 0.250 | 14.8 | 1.92 | ND | 14.8 |
| 20 | 1.028 | 60.6 | 6.13 | ND | 44.5 |
| 5 | 0.222 | 13.1 | 1.71 | ND | 13.1 |
| 16 | 15.425 | 910.1 | 81.58 | ND | 562.5 |
| 30 | 1.039 | 61.3 | 4.48 | ND | 25.2 |

These efforts should include remediation measures, stricter pesticide regulations, and awareness campaigns aimed at promoting more sustainable agricultural practices to reduce contamination. In contrast, the relatively lower risks observed at other locations, such as 5, 6, and 16, suggest that these areas are less affected by pesticide residues, potentially benefiting from better agricultural practices or favorable environmental conditions for pesticide degradation. However, continued monitoring is still recommended to ensure that contamination levels remain low. Based on these findings, it is crucial for environmental and agricultural authorities to focus on improving pesticide management practices to minimize both environmental and health risks. The study's results provide valuable data that can guide future efforts to safeguard soil quality and public health, especially in areas identified with higher risk levels.

**Table 3: the comparative studies of cancer risk assessment along the particular locations around the World.**

| Locations | Adult | References |
|---|---|---|
| Southeast China | $5.07 \times 10^{-4}$ | [42] |
| Shabankare, Iran | $7.98 \times 10^{-9}$ | [30] |
| China | $10^{-11}$ to $10^{-6}$ | [43] |
| Korba, India | $7.8 \times 10^{-9}$ | [44] |
| Sulaibiya, Kuwait | $6.173 \times 10^{-10}$ to $274.3 \times 10^{-10}$ | [38] |
| Buraydah, Saudi Arabia | $6.37 \times 10^{-12}$ to $1.481094 \times 10^{-3}$ | Present study |

Carcinogenic Risk (CR): Each pesticide's CR value estimates the potential cancer risk associated with exposure to that specific substance. This value is calculated by multiplying the concentration (C) by a cancer slope factor (CSF). Lower CR values imply minimal cancer risk for individual pesticides, while higher values suggest a more significant cancer risk. Total Carcinogenic Risk (TCR): The TCR aggregates the individual CR values for all pesticides, representing the total risk of developing cancer from exposure to the entire set of pesticides in this study. In our dataset, this combined risk value is particularly useful as it reflects the overall exposure risk, providing a comprehensive view that might be missed when looking at individual pesticides alone. Typically, TCR values are compared against accepted safety thresholds (such as 1 in 1,000,000 or 1 in 10,000) to determine if action is needed to mitigate risk. Hazard Quotient (HQ): Each pesticide's HQ value represents the risk of non-cancer-related health effects. It's calculated by dividing the concentration by the reference dose (RfD), a measure of the maximum safe exposure level. If an individual pesticide has an HQ greater than 1, it may pose a risk of adverse health effects. In this dataset, the HQ values allow us to evaluate each pesticide's non-carcinogenic risk independently. Hazard Index (HI): The HI aggregates the HQ values for all pesticides, representing the combined risk of non-cancer-related health issues. An HI greater than 1 implies that the cumulative exposure from all pesticides may surpass safe levels, suggesting a risk of combined effects that could potentially harm health.

**Table 4: POPs concentrations around the World**

| Location | ΣPOPs (ng/g) | |
|---|---|---|
| Dalki, Iran (14 compounds) | 6.83 | [30] |
| Shabankare, Iran (14 compounds) | 15.05 | [30] |
| Mexico (14 compounds) | 50.59 | [31] |
| Wuhan, China (14 compounds) | 169.8 | [32] |
| Southern farms, USA (9 compounds) | 220.79 | [33] |
| Palkkad, India (5 compounds) | 23.36 | [34] |
| Catchment area, Pakistan (15 compounds) | 3.48 | [37] |
| Kenya | 7.74 | [35] |
| Riyad, Saudi Arabia | 557 | [36] |
| Sulaibia, Kuwait | 3.06 | [38] |
| India | 47.4 | [34] |
| Riet Spruit | 62.8 | [35] |
| Buffalo River | 153.7 | [45] |
| Crocodile River | 207.3 | [46] |
| Olifants River | 27.6 | [47] |
| Loskop Dam | 116.9 | [48] |
| Theewaterskloof Dam | 39.2 | [49] |
| Buraydah, Saudi Arabia | 6.245 | Present study |

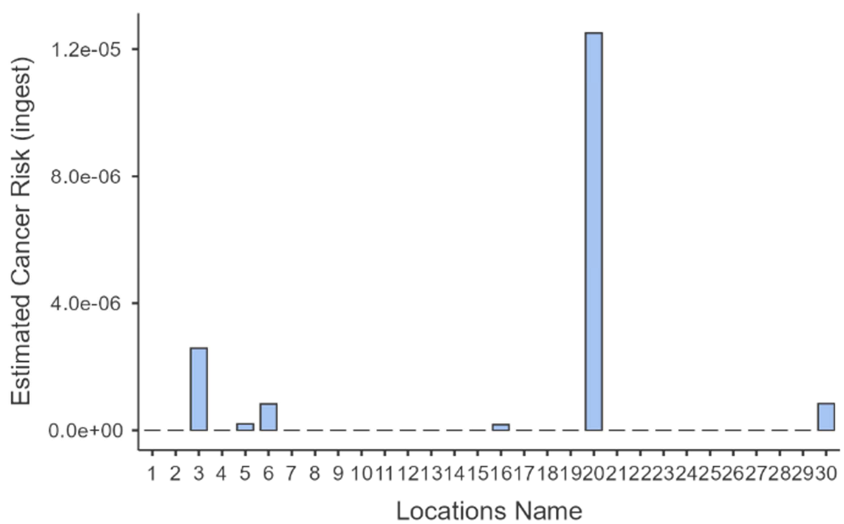


**Fig. 3. Estimated Cancer Risk (ingest) in an adult**

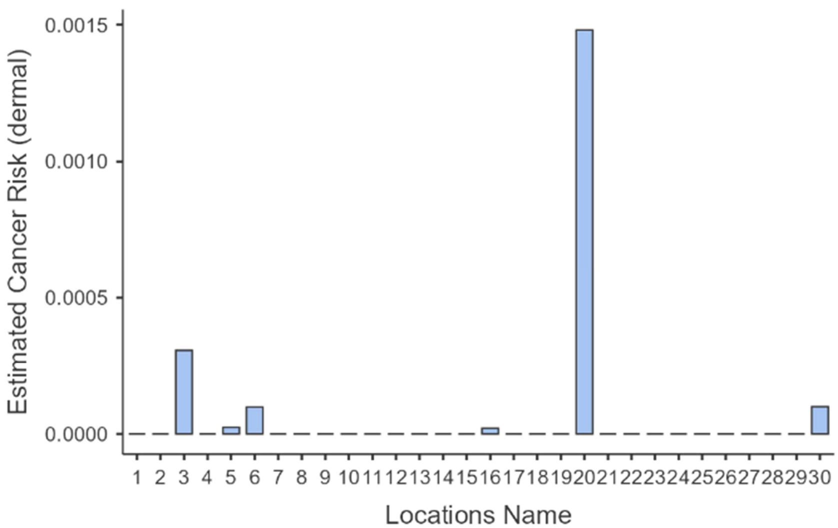


**Fig. 4. Estimated Cancer Risk (dermal) in an adult**

Carcinogenic Risk (TCR): The TCR result provides insight into the cancer risks from exposure to multiple pesticides simultaneously. A TCR value that exceeds acceptable thresholds suggests a need for regulatory review or interventions to reduce exposure, especially in vulnerable populations who may face heightened risks. Non-Carcinogenic Risk (HI): The HI result is essential for understanding the potential for non-cancer-related health effects from cumulative exposure to various pesticides. If HI exceeds 1, it indicates a need to evaluate how combined exposures might impact health, especially if these pesticides are prevalent in food or water sources. Thus, the results highlight potential risks from both cancer-related and non-cancer-related exposures (Figures 6 & 7). A higher TCR points to an increased risk of cancer over a lifetime due to these pesticides, while a higher HI suggests that non-carcinogenic effects, such as respiratory or neurological impacts, might also be of concern. Together, these values underscore the importance of monitoring and regulating pesticide exposure to ensure public safety.

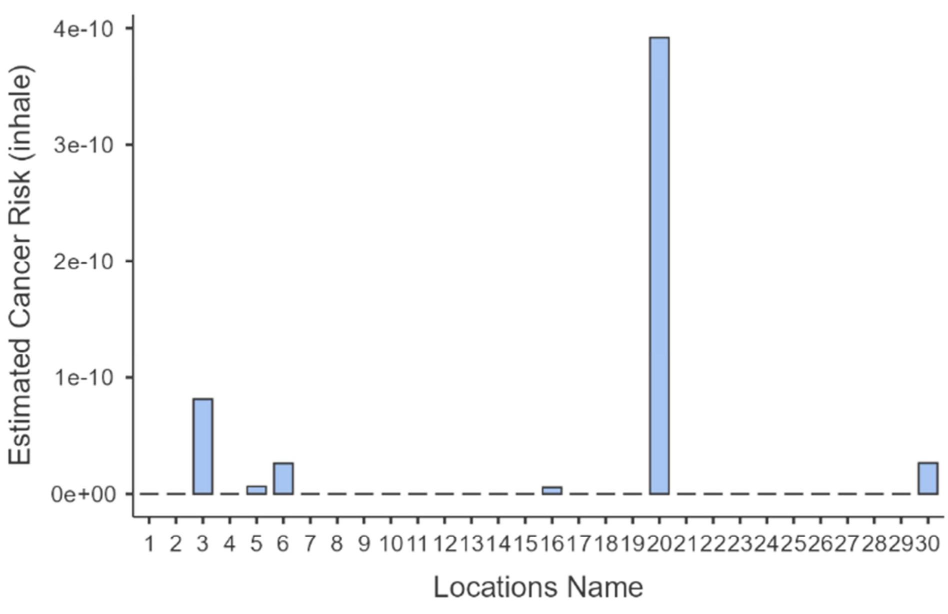


**Fig. 5. Estimated Cancer Risk (inhale) in an adult**

### *3.2 Comparative study between our results and previous works*

In SA, there are also few studies on POPs and pesticide residues. El-Mubarak et al.[50] found that the ambient air in Riyadh, the capital of Saudi Arabia, had a high concentration of POPs. The average concentrations of pesticides ranged from 2 to 8,216 ng/m3, indicating heavy use within the capital and possibly long-distance transportation [50]. Since treated wastewater is utilized for agriculture, the discovery of traces of harmful endocrine disruptors including phthalate esters and bisphenol-A in South Africa is extremely concerning [51]. The majority of SA research on humans focused on another family of POPs called polycyclic aromatic hydrocarbons. These studies of PAHs in Saudi children with asthma revealed that, among other things, naphthalene, bezanthracene, and benzoacephenanthrylene were the most common PAHs in circulation, accounting for between 54.5% and 90.9% of the positive samples [52]. Since these PAHs coincided with indicators of asthma in Saudi children, such as IgE, interferon gamma, and several interleukins, they were also linked to respiratory illnesses [53].

A study has shown that; in comparison to other cities worldwide, Riyadh had higher ambient air PM concentrations of POPs (PAHs, insecticides, and PCBs). The majority originates locally, but some are probably transferred over large distances. The majority of Riyadh's air pollution is caused by waste burning, agribusiness, the petrochemical industry, and road traffic. Authorities should work to keep an eye on and control dangerous emissions. Research and development efforts in the direction of a clean air act are crucial and strongly recommended [50].

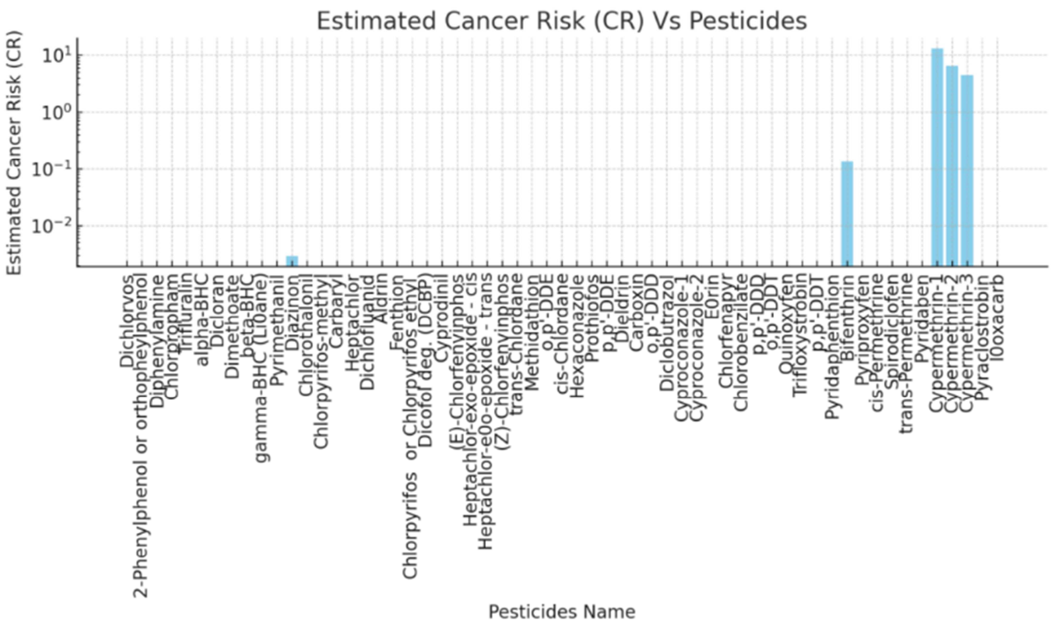


**Fig. 6. Estimated Cancer Risk (CR) Vs. Pesticides**

In another study, the detection rates of pesticide residues in different local produce by season were evaluated and compared through the use of QuEChERS extraction technology along with LC-MS/MS for determination and GC-MS/MS. Cypermethrin was found to be the most frequently detectable residue of pesticides, especially in South Africa which has a high prevalence for this season (Table 4). Although they are more commonly found in winter, thiamethoxam levels are higher in summer harvests [54]. The extra resources will be able to give a more comprehensive picture of the degree of pesticide residue contamination in Saudi environments. To reduce the health concerns associated with exposure to pesticide residues, local agricultural goods and practices must be closely monitored in the interim [55].

Moreover, a large percentage of pesticide residues were found in key KSA regions; most of them were classified as moderately dangerous, and they were more prevalent in vegetables than in fruits. Consuming fruits and vegetables bought in Saudi Arabia may still be harmful to human health, hence care should be taken even if intake risk assessment was not done in this study. To determine the level of human exposure in Saudi environments, additional possible sources of pesticide contamination, including meat, water, soil, and aquatic goods, should be looked into. To eventually limit the use of more dangerous pesticides, public health campaigns to lower exposure and consumption of these substances are required, as is improved monitoring of regional agricultural practices and products [54, 56].

Extensive research works regarding the contaminating level of POPs in Saudi Arabia's ambient air is scanty. Understanding the levels and sources of emissions from POPs can aid in the characterization of the contribution of POPs to public health risks and environmental hazards. To assess the degree of POP contamination in the soil-water continuum, more research is needed, particularly in regions with agricultural importance [51]. This will entail determining the kinds of POPs that are there, their concentrations, and any possible impacts they may have on groundwater and crops. Also, few studies have been carried out regarding health impacts of POP exposure within the Saudi population. Such studies need to precisely establish POPs exposure and health effects like cancers, endocrine disruption, and reproductive problems. In addition to that, there is a need for research into how efficiently the current waste management activities are reducing the emissions of POPs [57]. This covers collection, treatment, and disposal of industrial and agricultural waste that might be contaminated with POPs. Control policies and regulations on mitigation should be strengthened. The research will assist in developing evidence-based policy for tackling the sources and risks of POPs. Moreover, increased public awareness about the dangers of POPs and safer agricultural practices can all help in reducing exposure. Research can provide educators with the necessary basis for developing educational programs and campaigns [58].

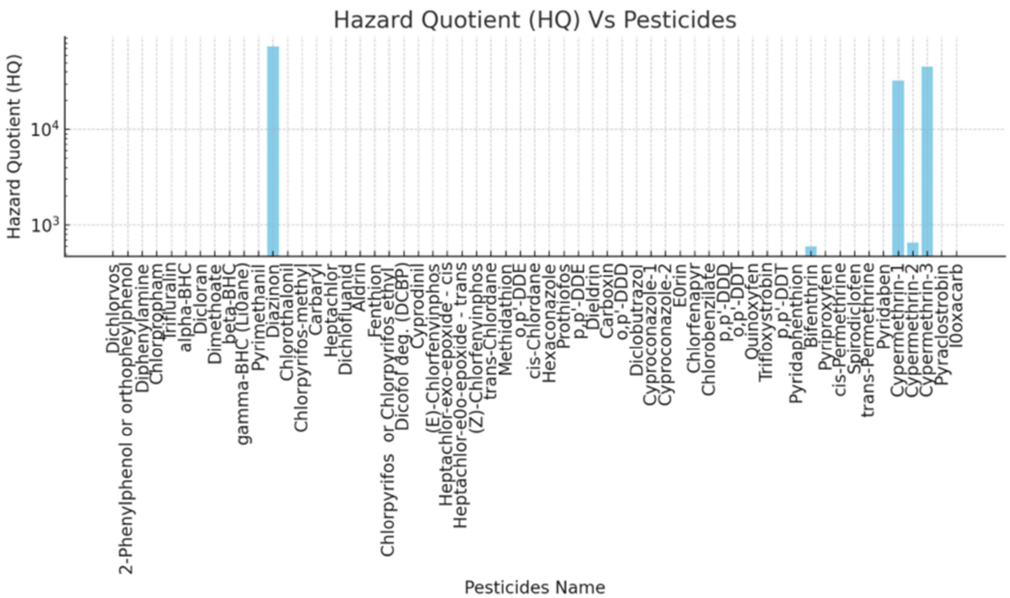


**Fig. 7. Hazard Quotient (HQ) Vs. Pesticides**

The average concentration of ΣPOPs in the present study was found to be 6.245 ng/g. This value is comparatively lower than those reported in Dalki and Shabankare in Iran [22], Mexico [23], Wuhan, China [24], southern farms in the United States [25], Palakkad, India [26], Kenya [27], Riyadh, Saudi Arabia [28], India [26], Riet Spruit [27], Buffalo River [41], Crocodile River [42], Olifants River [43], Loskop Dam [44], and Theewaterskloof Dam [45]. Conversely, it is slightly higher than the residual values reported in Pakistan [29] and Sulaibia, Kuwait [30] which are detailed in Table 4. These findings suggest that elevated pesticide levels in the study area may be associated with recent agricultural activities or improper pesticide usage.

The observed elevated concentrations of Cypermethrin-1, Cypermethrin-2, Cypermethrin-3, Bifenthrin, and Diazinon in soil samples could be attributed to the respective half-lives of these compounds, which significantly influence their persistence in the environment [59]. Cypermethrin-1, Cypermethrin-2, and Cypermethrin-3 have half-lives ranging from 2 to 8 weeks [31], indicating a potential for relatively rapid degradation under ideal conditions. However, the detection of these compounds suggests either recent pesticide application or environmental factors—such as temperature, moisture, and microbial activity—that may have inhibited their degradation, allowing them to persist longer in the soil. Bifenthrin, in contrast, has a significantly longer half-life, ranging from 122 to 345 days, which accounts for its prolonged presence in the soil even long after application. Its persistence is further reinforced by its strong affinity for binding to soil particles, which reduces its bioavailability and, consequently, slows down its degradation [31]. Moreover, the detection of Diazinon, which under aerobic conditions typically degrades within 2 to 4 weeks [31], indicates either recent application or suboptimal conditions for its breakdown. Diazinon generally degrades more rapidly in the presence of oxygen, and its persistence in the soil may also result from factors such as low oxygen levels or improper application techniques. Thus, the elevated levels of these pesticides in the study area could reflect both their inherent persistence due to their chemical properties and the improper or excessive use of pesticides in agricultural practices. These findings underscore the necessity of monitoring pesticide application and advocating for sustainable agricultural practices to mitigate environmental contamination and minimize associated human health risks.

## 4. Conclusions

This study provides a comprehensive analysis of the concentrations of persistent organic pollutants (POPs) in agricultural soils across 30 locations in Buraydah, Saudi Arabia. The findings indicate that the majority of the sampling sites exhibited undetectable pesticide levels, suggesting minimal environmental risk. However, six sites showed detectable pesticide contamination, with notable compounds including Cypermethrin and Bifenthrin. Among these, Location 16 recorded the highest pesticide concentrations, while Location 20 posed the greatest cancer risk across all exposure pathways, highlighting the need for targeted remediation efforts and stricter pesticide regulations. Although the overall POP levels were relatively low compared to global studies, the results underscore the importance of continuous monitoring, the promotion of sustainable agricultural practices, and proactive measures to minimize both carcinogenic and non-carcinogenic exposure risks. Implementing stricter regulatory frameworks and fostering environmentally friendly pest management strategies will be essential in ensuring long-term soil health and public safety**.**

## 5. Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## 6. Acknowledgments

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## 7. References

1. Elkady, E.M. and A.M. Younis, *The potential accumulation of polycyclic aromatic hydrocarbons in macroalgae from the Egyptian coast of the Red Sea.* Egyptian Journal of Aquatic Research, 2023. **49**(4): p. 452-459.
2. M Younis, A., *Accumulation and rate of degradation of organotin compounds in coastal sediments along the Red Sea, Egypt.* Egyptian Journal of Aquatic Biology and Fisheries, 2020. **24**(5): p. 413-436.
3. Ashraf, M.A., et al., *Environmental impacts of metallic elements: speciation, bioavailability and remediation*. 2015.
4. Kovner, K., *Persistent organic pollutants: a global issue, a global response.* US Environmental Protection Agency, Washington, DC, 2009.
5. Sishu, F.K., et al., *Pesticide contamination of surface and groundwater in an Ethiopian Highlands' Watershed.* Water, 2022. **14**(21): p. 3446.
6. Shomrany, A.A., *Integrating GIS and Remote Sensing Data for Detecting Change in Agricultural Land during 1985-2024 in Qassim Region, Saudi Arabia.*
7. Scheringer, M., et al., *How many persistent organic pollutants should we expect?* Atmospheric Pollution Research, 2012. **3**(4): p. 383-391.
8. Sweetman, A.J., et al., *The role of soil organic carbon in the global cycling of persistent organic pollutants (POPs): interpreting and modelling field data.* Chemosphere, 2005. **60**(7): p. 959-972.
9. Lu, D., et al., *Assessment of POPs in foods from western China: Machine learning insights into risk and contamination drivers.* Environment International, 2025: p. 109458.
10. Younis, A.M., et al., *Polycyclic aromatic hydrocarbons (PAHs) in Egyptian red sea sediments: Seasonal distribution, source Identification, and toxicological risk assessment.* Arabian Journal of Chemistry, 2023. **16**(9): p. 104999.
11. Al-Jerash, M.A., *Soils and agricultural development in the region of Al-Qassim, Saudi Arabia*. 1968, Durham University.
12. Lau, M.H.Y., et al., *Environmental policy, legislation and management of persistent organic pollutants (POPs) in China.* Environmental pollution, 2012. **165**: p. 182-192.
13. Ashraf, M.A., *Persistent organic pollutants (POPs): a global issue, a global challenge*. 2017, Springer. p. 4223-4227.
14. Jones, K.C. and P. De Voogt, *Persistent organic pollutants (POPs): state of the science.* Environmental pollution, 1999. **100**(1-3): p. 209-221.
15. El-Naggar, M., et al., *Seasonal and temporal influence on polycyclic aromatic hydrocarbons in the Red Sea coastal water, Egypt.* Sustainability, 2021. **13**(21): p. 11906.
16. Chu, W., M.H. Wong, and J. Zhang, *Accumulation, distribution and transformation of DDT and PCBs by Phragmites australis and Oryza sativa L.: II. Enzyme study.* Environmental Geochemistry and health, 2006. **28**: p. 169-181.
17. Buccini, J., *The development of a global treaty on persistent organic pollutants (POPs).* Persistent organic pollutants, 2003: p. 13-30.
18. Zhao, Y., L. Yang, and Q. Wang, *Pulsed large volume injection gas chromatography coupled with electron-capture negative ionization quadrupole mass spectrometry for simultaneous determination of typical halogenated persistent organic pollutants.* Journal of the American Society for Mass Spectrometry, 2007. **18**: p. 1375-1386.

19. Younis, A.M., et al., *Assessment of polycyclic aromatic hydrocarbons in surface sediments and some fish species from the Gulf of Suez, Egypt.* Egyptian Journal of Aquatic Biology and Fisheries, 2018. **22**(4): p. 49-59.
20. Younis, A.M., et al., *Assessment of health risks associated with heavy metal contamination in selected fish and crustacean species from Temsah Lake, Suez Canal.* Scientific Reports, 2024. **14**(1): p. 18706.
21. Annex, C., *of the Stockholm Convention on Persistent Organic Pollutants.* United Nations Environmental Programme, Geneva, 2008. **29**.
22. Younis, A.M., *Environmental impacts on Egyptian Delta Lakes' biodiversity: A case study on Lake Burullus.* Egyptian Coastal Lakes and Wetlands: Part II: Climate Change and Biodiversity, 2019: p. 107-128.
23. Ashraf, M.A., et al., *Study of contaminant transport at an open-tipping waste disposal site.* Environmental Science and Pollution Research, 2013. **20**: p. 4689-4710.
24. Curtean-Bănăduc, A., et al., *Assessment and Monitoring of Persistent Organic Pollutants in Lotic Ecosystems: Methodological Guide*. 2016: Editura Universităţii" Lucian Blaga" din Sibiu.
25. Wong, M.H. and B. Poon, *Sources, fates and effects of persistent organic pollutants in China, with emphasis on the Pearl River Delta.* Persistent organic pollutants, 2003: p. 355-369.
26. Thornton, J.W., M. McCally, and J. Houlihan, *Biomonitoring of industrial pollutants: health and policy implications of the chemical body burden.* Public Health Reports, 2002.
27. Galiulin, R. and R. Galiulina, *Inventory and recreation of soils and other components of landscape, chemical polluted by various contaminants. Report 2. Polychlorodiphenyls.* AGROKHIMIIA, 1997: p. 81-96.
28. Ukalska-Jaruga, A., et al., *Residues of persistent organic pollutants (POPs) in agricultural soils adjacent to historical sources of their storage and distribution—the case study of Azerbaijan.* Molecules, 2020. **25**(8): p. 1815.
29. Quality, I.A., *ENVIRONMENTAL PROTECTION AGENCY (EPA).* 2007.
30. Kafaei, R., et al., *Organochlorine pesticides contamination in agricultural soils of southern Iran.* Chemosphere, 2020. **240**: p. 124983.
31. Sánchez-Osorio, J.L., et al., *Organochlorine pesticides in residential soils and sediments within two main agricultural areas of northwest Mexico: Concentrations, enantiomer compositions and potential sources.* Chemosphere, 2017. **173**: p. 275-287.
32. Zhou, Q., et al., *Distribution and sources of organochlorine pesticides in agricultural soils from central China.* Ecotoxicology and environmental safety, 2013. **93**: p. 163-170.
33. Bidleman, T.F. and A.D. Leone, *Soil–air exchange of organochlorine pesticides in the Southern United States.* Environmental pollution, 2004. **128**(1-2): p. 49-57.
34. Gopalan, N.K. and S. Chenicherry, *Fate and distribution of organochlorine insecticides (OCIs) in Palakkad soil, India.* Sustainable Environment Research, 2018. **28**(4): p. 179-185.
35. Sun, H., et al., *Concentrations, distribution, sources and risk assessment of organohalogenated contaminants in soils from Kenya, Eastern Africa.* Environmental pollution, 2016. **209**: p. 177-185.
36. Albedair, L.A. and A.S. Alturiqi, *Evaluation of pesticide residues in the irrigation water, soil and assessment of their health risks in vegetables from sub-urban areas around Riyadh district, Saudi Arabia.* Environmental Forensics, 2021. **22**(1-2): p. 16-27.
37. Bajwa, A., et al., *Organochlorine pesticides (OCPs) in the Indus River catchment area, Pakistan: status, soil–air exchange and black carbon mediated distribution.* Chemosphere, 2016. **152**: p. 292-300.
38. Alshemmari, H., et al., *Pesticides driven pollution in Kuwait: The first evidence of environmental exposure to pesticides in soils and human health risk assessment.* Chemosphere, 2021. **273**: p. 129688.
39. Holden, M., *FDA–EPA Public Health Guidance on Fish Consumption.* Food and Drug Law Journal, 2015. **70**(1): p. 101-142.
40. Wang, P., *Development of a LC-MS-Based Approach to Study the Uptake, Impact and Thermal Degradation of Nanoencapsulated Pesticides (Azoxystrobin and Bifenthrin) in Strawberry Plants and Fruits*. 2022: McGill University (Canada).
41. Vickneswaran, M., *Holistic assessment of pesticide residues in Irish agricultural soil*. 2023, Dublin City University.
42. Liu, J., et al., *Contamination characteristics of organochlorine pesticides in multimatrix sampling of the Hanjiang River Basin, southeast China.* Chemosphere, 2016. **163**: p. 35-43.
43. Li, Q., et al., *Distribution, source, and risk of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) in urban and rural soils around the Yellow and Bohai Seas, China.* Environmental Pollution, 2018. **239**: p. 233-241.
44. Kumar, B., et al., *DDT and HCH (organochlorine pesticides) in residential soils and health assessment for human populations in Korba, India.* Human and Ecological Risk Assessment: An International Journal, 2014. **20**(6): p. 1538-1549.
45. Yahaya, A., et al., *Occurrences of organochlorine pesticides along the course of the Buffalo River in the Eastern Cape of South Africa and its health implications.* International journal of environmental research and public health, 2017. **14**(11): p. 1372.
46. Bouwman, H., et al., *Chlorinated, brominated, and fluorinated organic pollutants in Nile crocodile eggs from the Kruger National Park, South Africa.* Ecotoxicology and environmental safety, 2014. **104**: p. 393-402.
47. Van Gessellen, A., *The presence of persistent organic pollutants and heavy metals in sediment samples from rivers in the Kruger National Park*. 2015.
48. Seopela, M.P., et al., *Temporal and spatial variations of organochlorine pesticides (OCPs) and phthalates affecting the quality of water and sediment from Loskop Dam, South Africa.* Water SA, 2021. **47**(2): p. 221-234.

49. Davies, E.J., *Evaluating sources and environmental risk of pesticide pollution in Western Cape rivers*. 2023, Stellenbosch: Stellenbosch University.
50. El-Mubarak, A.H., et al., *Occurrence of high levels of persistent organic pollutants (POPs) in particulate matter of the ambient air of Riyadh, Saudi Arabia.* Arabian Journal for Science and Engineering, 2015. **40**: p. 81-92.
51. Al-Saleh, I., et al., *Assessing the concentration of phthalate esters (PAEs) and bisphenol A (BPA) and the genotoxic potential of treated wastewater (final effluent) in Saudi Arabia.* Science of The Total Environment, 2017. **578**: p. 440-451.
52. Al-Daghri, N.M., et al., *Polycyclic aromatic hydrocarbon distribution in serum of Saudi children using HPLC-FLD: marker elevations in children with asthma.* Environmental Science and Pollution Research, 2014. **21**: p. 12085-12090.
53. Al-Daghri, N.M., et al., *Polycyclic aromatic hydrocarbon exposure and pediatric asthma in children: a case–control study.* Environmental Health, 2013. **12**(1): p. 1-6.
54. Al-Daghri, N.M., et al., *Detection rates of pesticide residues in Saudi Arabian produce as influenced by season.* Arabian Journal of Chemistry, 2024. **17**(1): p. 105461.
55. Malhat, F., et al., *Results from the Egyptian monitoring programme and dietary risk assessment for pesticide residues in fruits during the period of 2018–2021.* International Journal of Environmental Analytical Chemistry, 2025: p. 1-22.
56. Zhou, W., M. Li, and V. Achal, *A comprehensive review on environmental and human health impacts of chemical pesticide usage.* Emerging Contaminants, 2024: p. 100410.
57. Nguyen, A.T. and L. Le Tran, *A review about the occurrence and effectiveness of conventional and advanced treatment technologies of persistent organic pollutants in surface water.* Reviews of Environmental Contamination and Toxicology, 2024. **262**(1): p. 11.
58. Akinrinade, O.E., et al., *Implementation of the Stockholm Convention on persistent organic pollutants (POPs) in Africa–progress, challenges, and recommendations after 20 years.* Environmental Science: Advances, 2024. **3**(5): p. 623-634.
59. Pan, S., et al., *Applications of mixture methods in epidemiological studies investigating the health impact of persistent organic pollutants exposures: a scoping review.* Journal of Exposure Science & Environmental Epidemiology, 2024: p. 1-13.