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Bioaccumulation of Pesticides in Marine Organisms and Associated Health Risks: The Case of Crabs from the Coastal Areas of Larache, Morocco.

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Abstract

Coastal ecosystems influenced by agricultural activities are significant receptors of pesticides, potentially leading to ecological and health risks through the consumption of fishery products. This study evaluates pesticide contamination and associated health risks in crabs from the Loukkos basin (Morocco). Crab samples were analyzed by GC-MS/MS for the detection of 203 pesticides. Concentrations were measured and non-carcinogenic (HQ) and carcinogenic (CR) risk assessments were conducted for adults and children. A total of 32 compounds were detected in crab tissues, revealing multi-residue contamination and chronic exposure from both recent and historical origins. Concentrations ranged from 0.010 to 0.359 mg/kg, with several exceedances of the maximum residue limit (0.010 mg/kg), suggesting significant contaminant pressure on the ecosystem. Risk assessment indicates that hazard quotients (HQ) remain below 1 for both adults and children, indicating acceptable non-carcinogenic risk. However, carcinogenic risk assessment shows that several pesticides exceed the threshold of 1×10^{-6}, particularly in children, although values remain below the regulatory threshold of 1×10^{-4}, indicating a potential long-term risk. These results highlight persistent contamination of benthic organisms and chronic dietary exposure to pesticides in the Loukkos coastal systems. They underscore the need for strengthened environmental monitoring, stricter control of pesticide use, and the implementation of management strategies to reduce risks to ecosystems and human health.

1. Introduction

Coastal zones represent transitional ecosystems that are particularly vulnerable to anthropogenic pressures, notably those associated with agricultural, industrial, and urban activities (Barbier et al., 2011; Doney, 2010; Seitzinger et al., 2010). Pesticides, among the most widely distributed environmental contaminants, represent a major concern due to their intensive use and their transfer from watersheds to coastal marine environments (Kibuye et al., 2026; Tang et al., 2012; Zhang et al., 2023). Riverine inputs thus constitute a major pathway for the transfer of pesticide residues to littoral ecosystems, where they can accumulate in sediments and living organisms, potentially affecting biodiversity and human health (Carvalho et al., 2002; Newman, 2004; Sarkar et al., 2008). The bioaccumulation of pesticides in marine organisms is a central process for understanding the ecotoxicological and health-related impacts associated with these contaminants (Chopra et al., 2010; Habibullah-Al-Mamun et al., 2025; Katagi, 2009). Crustaceans, such as crabs, are particularly exposed due to their direct contact with contaminated sediments and their omnivorous feeding habits (de Almeida Rodrigues et al., 2021; Pham et al., 2025; Smalling et al. 2010). Their capacity to concentrate pesticides in their tissues makes them relevant bioindicators of coastal contamination (AL-KHAZRAJI et al., 2020; Chowdhury, 2015; Lavezzo et al., 2020). Furthermore, these species occupy an important position in food webs and are widely consumed by human populations, raising concerns regarding food safety.

Human exposure to pesticides through the consumption of contaminated seafood represents a significant exposure pathway, potentially leading to short- and long-term adverse effects, including endocrine disruption, neurotoxic effects, and carcinogenic risks for certain substances (Eissa et al.,

2021; Ray and Shaju, 2023). Health risk assessment constitutes an essential scientific approach aimed at estimating the probability and severity of adverse effects likely to result from exposure to a chemical, biological, or physical agent present in the environment. It relies on an integrated approach combining toxicological and environmental data in order to establish a relationship between contaminant concentration, the dose absorbed by the organism, and the observed biological response (Committee et al., 2019). According to the methodology proposed by the Environmental Protection Agency, this assessment is conducted by considering both non-carcinogenic and carcinogenic risks (US EPA, 2014). Non-carcinogenic risks are evaluated by calculating the Hazard Quotient (HQ), based on the estimation of daily pesticide intake and its comparison with reference toxicological values, such as the Acceptable Daily Intake (ADI) or Reference Dose (RfD). Carcinogenic risks are estimated from cancer slope factors recommended by international agencies. However, this type of approach remains poorly documented in Moroccan coastal areas, particularly for benthic species exploited for food purposes.

In Morocco, the intensive use of pesticides in irrigated agricultural systems has led to diffuse contamination of various environmental compartments, including soils, surface waters, and groundwater (Agnaou et al., 2017, 2018; Bazzi et al., 2009; Ben Khadda et al., 2021; Berni et al., 2021). Several studies conducted over recent decades have highlighted the presence of pesticide residues, including organochlorines, organophosphates, and new-generation pesticides, in agricultural watersheds, particularly in the north-western, Gharb, and Loukkos regions (Bagayou et al., 2026; Bouzaidi et al., 2020; El Bakouri et al., 2008; El Bouzaidi et al., 2022; Sarti et al., 2021). These investigations have revealed that detected concentrations can sometimes exceed recommended thresholds, indicating potential risks for aquatic ecosystems and public health. However, the limited research on pesticide risk assessment in Morocco has focused primarily on terrestrial environments, using approaches based on measured concentrations and ecotoxicological risk ratios, while coastal and marine environments—as well as the transfer of pesticides to living organisms and human consumers—remain understudied. This situation limits our overall understanding of pesticide risks across the watershed–coastal zone continuum and highlights the need for integrated studies that combine bioaccumulation and human health risk assessments in Morocco’s coastal areas.

The north-western coastal zones, particularly the Larache region, are subject to intense agricultural pressure, characterized by extensive pesticide use in adjacent irrigated perimeters (Abbou et al., 2023). The Loukkos River, which drains one of the country's main agricultural basins, constitutes a potential source of phytosanitary residue inputs to coastal marine environments. Although several studies have documented the presence of pesticides in groundwater and soils of this basin (Bagayou et al., 2026; Sarti et al., 2021), information regarding their transfer to marine organisms, their bioaccumulation, and associated health risks remains limited at the local scale. This gap represents a major obstacle to the implementation of effective management and protection strategies for coastal ecosystems and consumers. In this context, the present study aims to (i) determine the presence and levels of pesticide contamination in crab tissues collected along the coastal zones of Larache (north-western Morocco), and (ii) estimate human health risks, distinguishing between non-carcinogenic and carcinogenic risks associated with the consumption of contaminated crabs.

2. Materials and Methods

2.1. Study Area

The study area is located along the Atlantic coast of Larache, in north-western Morocco (Fig. 1), within the Tanger-Tétouan-Al Hoceïma region. This coastal zone is characterized by a Mediterranean climate with oceanic influence, featuring a wet season from October to April and a dry season from May to September. Larache hosts an important small-scale and artisanal fishing port, exploited for fish, cephalopods, and crustaceans. The coastal area is strongly influenced by inputs from the Loukkos River, which drains an intensively cultivated agricultural basin, constituting a potential source of pesticide transfer to the marine environment.

2.2. Sampling and Sample Collection

The study focused on six crab species representative of the coastal and estuarine environments of the study area: the blue crab (*Callinectes sapidus*), the green crab (*Carcinus maenas*), the spider crab (*Maja Brachydactyla*), the sand crab (*Portumnus latipes*), the marbled crab (*Pachygrapsus marmoratus*), and the African fiddler crab (*Uca tangeri*). These species were selected based on their local abundance, ecological differences, and potential for exposure to agricultural-origin contaminants such as pesticides.

Sampling campaigns were conducted between March and June 2025 at several representative coastal and estuarine sites within the study area (Table 1, Fig. 2). For strictly coastal and estuarine species (blue crab, green crab, marbled crab, African fiddler crab, and sand crab), collections were performed by hand at low tide to facilitate access to their natural habitats. Conversely, the spider crab (*Maja Brachydactyla*), which occupies deeper marine habitats than strictly coastal and estuarine crabs, was collected from fishing vessels.

For each site, a comparable number of individuals per species was collected, with preference given to crabs of similar size in order to reduce variability related to age and sex. All campaigns were conducted during the same season to limit the effect of seasonal variability. Following collection, samples were immediately placed in a cooler containing ice for transport to the laboratory, then stored at − 18°C until analysis.

Table 1
Distribution of crab species according to sampling sites

Sites	Species
Pelegrosa	Sand crab
Meqasera	Sand crab
Sidi Abd Rhim	Sand crab
Escaléra	Marbled crab
Farouna	Marbled crab
Mesetro	Marbled crab
Metqoub	Marbled crab
Majdid	Marbled crab
Miami	African fiddler crab
El Jazira	African fiddler crab – Green crab – Blue crab
Baradiro	Green crab
M'laleh	Green crab – Blue crab
El Koudiya	Green crab
Grankha	Blue crab
Oued Loukkous	Blue crab
Qantra Oued Loukkous	Blue crab
Nakhla	Blue crab
El Baraje	Blue crab
Market	Spider crab
Basins	Spider crab
Boats	Spider crab

2.3. Extraction and Analysis of Pesticide Residues

Prior to extraction, soft tissues were separated from the carapace. Approximately 1 kg of material was then weighed using a precision balance (± 0.1 g) and homogenized using an automatic grinder. Pesticide extraction was performed from 5 g of homogenate (± 0.1 g) placed in 50 mL tubes, to which 1 mL of 2% formic acid (distilled water) and 10 mL of an acetone/hexane mixture were added. After vortex agitation for 2 min, samples were subjected to ultrasound-assisted extraction for 30 min. A QuEChERS salt mixture composed of 4 g magnesium sulfate, 1 g sodium chloride, 1 g trisodium citrate dihydrate, and

0.5 g disodium hydrogen citrate sesquihydrate was subsequently added. The tubes were mechanically shaken for 10 min then centrifuged at 3500 rpm for 5 min. Purification was carried out by transferring 6 mL of extract into tubes containing 25 mg PSA, 150 mg magnesium sulfate, 15 mg activated carbon, and 150 mg C18, followed by vortex agitation (2 min) and centrifugation (3500 rpm, 5 min). The purified extracts were then transferred into vials for pesticide analysis by gas chromatography coupled with tandem mass spectrometry (GC-MS/MS).

2.4. Quality Control and Analytical Validation

The reliability of the analytical process was ensured through quality control and validation procedures. Analyte identification and quantification were performed using five-level calibration curves (0.005, 0.010, 0.025, 0.050, and 0.100 ppm), established from mean peak areas, with a correlation coefficient (R^2) greater than 0.98 for all analytes. Identification was confirmed by comparing sample retention times with those of standards (tolerance ± 0.2 min), in accordance with Cofrac recommendations (LAB GTA 26) for GC-MS/MS.

Stability controls (SC) and internal controls (IC) were integrated into each analytical sequence. SC, prepared at 0.005 ppm and analyzed in replicate, showed relative deviations ranging from 0.6 to 9.2%, confirming analyte stability and the absence of instrumental drift. IC, also prepared at 0.005 ppm, were used to evaluate extraction efficiency, with recovery rates ranging from 70 to 120%, ensuring the accuracy and validity of measurements for environmental and toxicological interpretation. The complete results of the method validation are provided in the Supplementary Material.

Human Health Risk Assessment

Non-Carcinogenic Risk

The assessment of non-carcinogenic risk associated with the consumption of pesticide-contaminated crabs was conducted for adults and children, following a deterministic approach based on the comparison of estimated dietary exposure with Acceptable Daily Intakes (ADI). The ADI values for each pesticide were extracted from official databases of the European Food Safety Authority (EFSA), FAO/WHO, and the United States Environmental Protection Agency (US EPA).

Human exposure was estimated from measured concentrations in edible crab tissues (muscle), expressed in mg/kg fresh weight. The Estimated Daily Intake (EDI) was calculated according to the following equation:

$EDI = \frac{C \times IR}{BW}$ Where:

- *C* = pesticide concentration in crab (mg/kg)
- *IR* = daily ingestion rate (kg/day)
- *BW* = body weight (kg)

Exposure parameter values were defined as follows: the mean body weight (BW) of the Moroccan population was set at 45.5 kg for children and 70.7 kg for adults, in accordance with available national literature data (Mouane et al. 2014; Zerrour 2019). As the specific daily ingestion rate for crabs was not available in the literature, it was replaced by the average fish consumption rate (Song et al. 2019) for the Moroccan population. Thus, the annual fish consumption per capita, estimated at 18.3 kg in 2021, corresponds to a daily ingestion rate of 0.05 kg/day, which was used as the dietary exposure parameter (IR).

The Hazard Quotient (HQ) was then determined for each pesticide according to the expression:

$$HQ = \frac{EDI}{DJA}$$

An HQ below 1 indicates an acceptable health risk, whereas an HQ equal to or greater than 1 suggests a potential health risk. The cumulative Hazard Index (HI) was calculated as the sum of individual HQs in order to evaluate the combined effect of exposure.

This approach enables the identification of pesticides likely to present a risk to consumers, particularly for children, who are considered a more vulnerable group due to their lower body weight and increased sensitivity to chemical contaminants.

Carcinogenic Risk Assessment

The carcinogenic risk associated with exposure to detected pesticides was evaluated in accordance with the guidelines of the United States Environmental Protection Agency (US EPA). The chronic daily exposure (EDI) through crab ingestion was estimated using the formula described above. The individual carcinogenic risk (Cancer Risk, CR) was subsequently estimated by multiplying the EDI by the Cancer Slope Factor (CSF) specific to each pesticide. CSF values were obtained from the US EPA IRIS database when available.

$$CR = EDI \times CSF$$

Risk interpretation was performed according to commonly accepted thresholds: a CR below 10^{-6} is considered negligible, whereas a CR above 10^{-6} indicates a potentially unacceptable carcinogenic risk for the exposed population. The threshold of 10^{-6} corresponds to a probability of one additional cancer case per million people exposed over a lifetime.

3. Results and Discussion

3.1. Pesticide Occurrence in Crabs

In order to evaluate the exposure of benthic organisms to pesticides present in the aquatic environment, a multi-residue analysis was performed on tissues of various crab species collected from the study area.

In total, 203 pesticides belonging to several chemical families were investigated using a sensitive analytical method enabling the quantification of residues at low concentrations. Measured concentrations were subsequently compared between species to identify potential differences in accumulation and contamination profiles.

Overall, 32 pesticides were quantified in the studied crab species, revealing marked interspecific differences in contamination profiles (Table 2). The species *C. sapidus* exhibited the greatest diversity of residues, with 26 pesticides detected, followed by *P. marmoratus* (21 pesticides) and *C. maenas* (19 pesticides). Slightly lower levels were observed in *P. latipes*, *M. brachydactyla*, and *U. tangeri*, with 18, 15, and 13 pesticides detected, respectively. Measured concentrations generally ranged from 0.010 to 0.359 mg/kg depending on the species and compounds.

Despite the more limited number of substances detected in *U. tangeri*, this species presented the highest maximum concentration (0.359 mg/kg), observed for metazachlor, suggesting a greater bioaccumulation potential. Conversely, the species *C. sapidus* and *P. marmoratus*, characterized by a higher number of detected pesticides, reflect greater exposure diversity to contaminants rather than marked accumulation of a single compound. Among all pesticides measured, metazachlor, propachlor, and propargite appear as the most concerning contaminants, with concentrations exceeding 0.1 mg/kg in several species (*C. sapidus*, *P. latipes*, and *U. tangeri*), indicating relatively significant contamination of the studied ecosystem.

Table 2
Mean concentrations of pesticides detected in crab tissues (mg/kg)

Pesticides	***C. Sapidus***	***C. Maenas***	***M. Brachydactyla***	***P. Latipes***	***P. Marmoratus***	***U. Tangeri***
Alachlor	0.017	0.015	0.016	0.015	0.018	0.018
Bifenthrin	0.020	-	-	-	-	-
Biphenyl	0.020	0.019	0.021	0.017	0.019	0.020
Bromopropylate	0.036	-	-	-	-	-
Carbophenothion	-	-	-	0.078	-	-
Carfentrazone-ethyl	0.015	0.015	0.015	0.014	-	-
Chlorfenson	0.014	-	-	-	-	-
Chlorobenzilate	0.012	0.012	0.012	0.014	0.013	0.013
DDD-p.p’	0.011	-	-	0.010	0.010	-
DDE-p.p’	0.020	0.013	0.015	0.015	0.010	0.012
DDT-o.p’	0.011	-	-	0.010	-	0.012
DDT-p.p’	0.014	0.014	0.014	0.013	0.012	0.012
Dichlofluanid	0.058	0.056	0.059	0.046	0.063	0.054
Ethofenprox	-	-	-	-	0.098	-
Flutriafol	-	0.060	-	-	-	-
Tau-fluvalinate L	-	-	-	-	0.079	-
Fonofos	0.012	0.011	-	-	0.012	-
Isazofos		0.014	-	-	-	-
Metazachlor	0.131	0.080	0.086	0.140	0.110	0.359
Methacrifos	0.042	0.043	0.047	0.036	0.037	0.043
Methoxychlor olefin	0.020	0.022	0.021	0.018	0.014	0.013
Methoxychlor. p.p’	0.015	-	-	-	-	-
Parathion-methyl	0.083	0.015	0.015	0.043	0.027	-
Pebulate	-		-	-	0.098	-
Pentachloroanisole	0.012	0.012	0.011	0.011	0.011	0.013
Phorate	0.012	-	-	-	0.014	-

Pesticides	*C. Sapidus*	*C. Maenas*	*M. Brachydactyla*	*P. Latipes*	*P. Marmoratus*	*U. Tangeri*
Propachlor	0.134	0.085	0.179	0.088	0.068	0.080
Propargite	0.188	-	-	-	-	-
Propisochlor	0.049	0.042	0.044	0.040	0.056	0.058
Prothiofos	0.037	-	-	-	-	-
Terbufos	0.011	0.010	-	0.010	0.010	-
Tetradifon	0.028	0.024	0.022	-	0.026	-
Number of pesticides detected	**26**	**19**	**15**	**18**	**21**	**13**

The distribution of pesticide classes highlights contamination dominated by both recent inputs and persistent historical residues (Fig. 3). Chloroacetanilides clearly dominate the contamination profile, with alachlor, metazachlor, and biphenyl detected in 100% of samples, followed by propisochlor (~ 95%), reflecting their high environmental mobility and transfer to aquatic environments through runoff or leaching. Organochlorines constitute the second major group, characterized by strong persistence and hydrophobic properties favoring their accumulation in sediments. DDT-p,p' and its metabolites DDE-p,p' (~ 82%) and DDD-p,p' (~ 29%), as well as methoxychlor-olefin (~ 95%), exhibit high frequencies, suggesting contamination of historical origin. Organophosphorus compounds show more heterogeneous occurrence, dominated by methacrifos (~ 90%), whereas parathion-methyl and other compounds (fonofos, terbufos, phorate) appear at lower frequencies (~ 42–13%). Pyrethroids are rarely detected (~ 4%), although their high lipophilicity may favor bioaccumulation in benthic organisms.

These results suggest the coexistence of diffuse current sources related to agricultural practices and inherited contaminations from past uses. This interpretation is consistent with several studies conducted in the Loukkos region, where recent and historical pesticide residues have been simultaneously detected in soils and groundwater. For example, Bagayou et al. (2025a) reported the presence of current pesticides, notably organophosphorus compounds such as dichlorvos (11.023 µg/L), as well as persistent organochlorines such as lindane (0.234 µg/L). Similarly, Sarti et al. (2021) identified residues of endosulfan and its metabolites, as well as other compounds such as metribuzin and metolachlor. Furthermore, our work on agricultural soils in the region highlights a contamination profile comparable to that observed in crabs, characterized by the dominance of organophosphorus compounds (malathion, methidathion, chlorpyrifos-ethyl, fenamiphos) and the persistence of certain historical pesticides such as endosulfan sulfate, lindane, and aldrin (Bagayou et al., 2025b; c). Collectively, these observations confirm the existence of multi-compartmental contamination in the Loukkos basin, reflecting high pesticide mobility from upstream agricultural areas to aquatic ecosystems.

The results obtained highlight multi-residue contamination in crabs from the Loukkos basin, characterized by the co-occurrence of recent pesticides and persistent organochlorine compounds. This profile is consistent with observations made in the Guayas Estuary (Ecuador), where multi-residue contamination was demonstrated in crab tissues, with 21 compounds detected at high concentrations (Pham et al., 2025). Similarly, Smalling et al. (2010) identified 26 pesticides in crab embryos in California, including 18 currently used molecules (synthetic pyrethroids, organophosphorus compounds) and 8 historical organochlorines. The latter were present in more than half of the samples, with p,p'-DDE alone accounting for up to 89% of total contamination. Lipid-normalized concentrations (0.1–4 ppm) illustrate the persistence of bioaccumulation of these substances. Moreover, in the mangroves of Guanabara Bay (Brazil), high concentrations of DDT and its metabolites (up to 98.22 ng/g) have also been reported in crabs (Souza et al. 2008). Menone et al. (2000) identified heptachlor epoxide as the most abundant pesticide in sediments and crabs, followed by DDT and metabolites, HCHs (notably lindane), and chlordane compounds. These profiles indicate that crabs may be exposed to pesticides through pathways other than simple contact with sediments, notably through water and ingestion of contaminated particles or prey (Oros, 2025; Patchaiyappan et al., 2023). These trends, observed in various coastal lagoon ecosystems, indicate that agriculturally influenced coastal zones are subjected to significant anthropogenic pressure, likely to alter the structure and functioning of aquatic communities, and to compromise both their sustainability and the sanitary safety of fishery resources.

In this context, the evaluation of measured concentrations against regulatory standards appears essential. Several pesticides exceed the Maximum Residue Limit (MRL) set at 0.010 mg/kg for fishery products, in accordance with Regulation (EC) No 396/2005, indicating potential non-compliance. Beyond the exceedance of regulatory thresholds, these contamination levels raise concerns regarding potential risks to human health, necessitating a thorough assessment of exposure associated with consumption.

3.2. Human Health Risk Assessment

Exposure to pesticides present in aquatic organisms constitutes a major public health concern, particularly for populations regularly consuming fishery products. In this study, health risk assessment was conducted for two consumer groups: adults and children, due to their differential vulnerability to chemical substances. Two types of risks were considered: non-carcinogenic risk, which enables the estimation of long-term chronic toxic effects on health, and carcinogenic risk, which evaluates the probability of cancer occurrence related to exposure to certain pesticides. This combined approach provides a quantitative estimate of dietary exposure to pesticides detected in crabs from the Loukkos basin and allows the identification of compounds presenting potential hazards to human health, thereby guiding management and regulatory measures.

Non-Carcinogenic Risk

The assessment of non-carcinogenic risk associated with the consumption of pesticide-contaminated crabs relies on a deterministic approach, comparing estimated dietary exposure for adults and children to the Acceptable Daily Intakes (ADI) of each compound. Exposure was quantified from concentrations

measured in edible tissues and expressed as Estimated Daily Intake (EDI). The Hazard Quotient (HQ) was calculated for each pesticide to determine whether individual exposure exceeds the threshold considered safe (HQ ≥ 1).

Analysis of Hazard Quotients (HQ) for adults and children reveals that all individual HQs are well below 1, indicating that none of the pesticides detected in crab tissues from the Loukkos basin presents, at the individual level, an immediate health risk to consumers (Table 3). The most concerning compounds, in relative terms, are organophosphorus compounds and certain persistent organochlorines (carbophenothion, DDT and its metabolites), with HQs for children reaching up to 0.171, reflecting the increased vulnerability of children related to their lower body weight and proportionally higher consumption of fishery products.

Table 3
Non-carcinogenic risk assessment of pesticides detected in crabs for children and adults

Pesticides	ADI (mg/kg-day)	Mean EDI children	Mean EDI adults	HQ children	HQ adults
Alachlor	0.010	1.825E-05	1.175E-05	4.152E-03	1.175E-03
Bifenthrin	0.015	2.198E-05	1.414E-05	1.465E-03	9.430E-04
Biphenyl	0.500	2.111E-05	1.359E-05	4.223E-05	2.718E-05
Bromopropylate	0.030	3.956E-05	2.546E-05	1.319E-03	8.487E-04
Carbophenothion	0.0005	8.571E-05	5.516E-05	1.714E-01	1.103E-01
Carfentrazone-ethyl	0.030	1.579E-05	1.016E-05	5.265E-04	3.388E-04
Chlorfenson	0.010	1.575E-05	1.014E-05	1.575E-03	1.014E-03
Chlorobenzilate	0.020	1.394E-05	8.969E-06	6.968E-04	4.485E-04
DDD-p.p’	0.0005	1.134E-05	7.300E-06	2.269E-02	1.460E-02
DDE-p.p’	0.0005	1.550E-05	9.972E-06	3.099E-02	1.994E-02
DDT-o.p’	0.0005	1.205E-05	7.758E-06	2.411E-02	1.552E-02
DDT-p.p’	0.0005	1.431E-05	9.211E-06	2.862E-02	1.842E-02
Dichlofluanid	0.300	6.131E-05	3.945E-05	2.044E-04	1.315E-04
Ethofenprox	0.026	1.077E-04	6.931E-05	4.223E-03	2.718E-03
Flutriafol	0.010	6.593E-05	4.243E-05	6.593E-03	4.243E-03
Tau-fluvalinate L	0.005	8.681E-05	5.587E-05	1.736E-02	1.117E-02
Fonofos	0.002	1.281E-05	8.244E-06	6.405E-03	4.122E-03
Isazofos	NA	1.538E-05	9.901E-06	NA	NA

Pesticides	ADI (mg/kg-day)	Mean EDI children	Mean EDI adults	HQ children	HQ adults
Metazachlor	0.08	1.436E-04	9.240E-05	1.795E-03	1.155E-03
Methacrifos	0.006	4.524E-05	2.911E-05	7.540E-03	4.852E-03
Methoxychlor olefin	0.005	1.927E-05	1.240E-05	3.854E-03	2.480E-03
Methoxychlor. p.p’	0.005	1.648E-05	1.061E-05	3.297E-03	2.122E-03
Parathion-methyl	0.003	3.220E-05	2.072E-05	1.073E-02	6.908E-03
Pebulate	0.007	1.077E-04	6.931E-05	1.538E-02	9.901E-03
Pentachloroanisole	NA	1.263E-05	8.129E-06	NA	NA
Phorate	0.0007	1.408E-05	9.059E-06	2.011E-02	1.294E-02
Propachlor	0.013	1.096E-04	7.053E-05	8.430E-03	5.426E-03
Propargite	0.02	2.066E-04	1.330E-04	1.033E-02	6.648E-03
Propisochlor	0.025	5.240E-05	3.372E-05	2.096E-03	1.349E-03
Prothiofos	NA	4.066E-05	2.617E-05	NA	NA
Terbufos	0.002	1.112E-05	7.159E-06	5.562E-03	3.579E-03
Tetradifon	NA	2.729E-05	1.756E-05	NA	NA
Cumulative Hazard Index (HI)				**4.115E-01**	**2.634E-01**

The calculation of the cumulative Hazard Index (HI) shows that even the sum of HQs for the different pesticides remains below 1, with values of 0.411 for children and 0.263 for adults, confirming that combined exposure does not exceed the threshold considered safe for the studied populations. These results are consistent with other studies on pesticide health risks in agricultural coastal zones, where values ranged from 0.0072 to 0.3, i.e., levels significantly below the threshold, indicating acceptable risk in Yancheng Lake (Gu et al., 2024). Furthermore, a study conducted in China, evaluating risks associated with the consumption of crabs raised in rice-coculture systems for the pesticide chlorantraniliprole, showed that no significant risk was associated with their consumption (Song et al., 2019). When comparing our results with those obtained in fish, it is observed that non-carcinogenic risks associated

with organophosphorus and organochlorine compounds generally remain low, with hazard quotients below 1, suggesting negligible impact on human health (Habibullah-Al-Mamun et al., 2025; Olisah et al., 2023). However, certain studies on fish exposed to organochlorines have shown risk values exceeding 1, indicating potential hazard to consumers (Yohannes et al., 2014).

Thus, despite the presence of multiple residues in a single sample, the estimated dietary exposure does not appear to represent a significant non-carcinogenic risk to consumer health, while underscoring the necessity for regular monitoring and particular attention to persistent and bioaccumulable pesticides.

Carcinogenic Risk

The assessment of carcinogenic risk associated with the consumption of pesticide-contaminated crabs was conducted in order to estimate the probability of long-term carcinogenic effects in consumers. Among the 32 molecules identified, only 7 had cancer slope factors (CSF) available in the literature and were therefore retained for this analysis. The carcinogenic risk (CR) was calculated from estimated dietary exposure and compared to the generally accepted tolerance threshold (1×10^{-6}), enabling the identification of compounds likely to represent a risk to human health, particularly among the most vulnerable populations.

The seven pesticides identified as carcinogenic in crab samples exhibit varying oral slope factors (OSF), reflecting their distinct carcinogenic potentials (Table 4). Alachlor and biphenyl are distinguished by their lowest OSFs (0.056 and 0.008 mg/kg-day^{-1}, respectively), whereas organochlorine compounds (DDD-p,p', DDE-p,p', DDT-o,p', and DDT-p,p') present high values (0.24–0.34 mg/kg-day^{-1}), characteristic of their persistence and bioaccumulation in aquatic food webs. Propargite, an acaricide, occupies an intermediate position with an OSF of 0.192 mg/kg-day^{-1}.

The results highlight that the majority of analyzed pesticides exceed the conventional tolerance threshold of 1×10^{-6}, indicating a potential risk to human health. Propargite appears as the most concerning compound, with CR values reaching 3.97×10^{-5} in children and 2.55×10^{-5} in adults, i.e., well above the acceptable threshold. Similarly, persistent organochlorine residues, notably DDE-p,p', DDT-p,p', DDT-o,p', and DDD-p,p', present significant risk levels (2.722×10^{-6} – 5.268×10^{-6}), reflecting the impact of historical contaminations. Alachlor also shows exceedance of the threshold, suggesting a contribution from current agricultural inputs. Conversely, biphenyl constitutes the sole exception, with CR values below the critical threshold at 1.689×10^{-7} (children) and 1.087×10^{-7} (adults), indicating a negligible risk.

Table 4
Carcinogenic risk assessment of pesticides detected in crabs for children and adults

Pesticides	Oral Slope Factor (mg/kg-day)	Mean EDI children	Mean EDI adults	CR children	CR children
Alachlor	0.056	1.825E-05	1.175E-05	1.022E-06	6.578E-07
Biphenyl	0.008	2.111E-05	1.359E-05	1.689E-07	1.087E-07
DDD-p.p’	0.24	1.134E-05	7.300E-06	2.722E-06	1.752E-06
DDE-p.p’	0.34	1.550E-05	9.972E-06	5.268E-06	3.391E-06
DDT-o.p’	0.34	1.205E-05	7.758E-06	4.099E-06	2.638E-06
DDT-p.p’	0.34	1.431E-05	9.211E-06	4.866E-06	3.132E-06
Propargite	0.192	2.066E-04	1.330E-04	3.967E-05	2.553E-05

Overall, these results highlight a chronic risk associated with the consumption of crabs contaminated by carcinogenic compounds, particularly concerning in children. The analysis reveals that six of the seven detected pesticides exceed the conventionally accepted carcinogenic tolerance threshold of 1×10^{-6}, indicating significant and persistent exposure of the consuming population. This concern is heightened in children, whose calculated risks are systematically higher than those of adults—with ratios ranging from 1.5 to 1.6 depending on the molecules—due to their lower body mass, immature metabolism, and increased developmental vulnerability to the effects of endocrine disruptors and carcinogens. These values, although concerning, remain below the regulatory action thresholds (1×10^{-4}) established by the US EPA for general populations.

Our results are consistent with those reported by Xie et al. (2025) in the Pearl River Delta, China, showing that carcinogenic risks associated with the consumption of aquatic products generally range between 10^{-6} and 10^{-5}, indicating a non-negligible dietary risk but below the critical threshold of 1×10^{-4}. Similarly, in the Bay of Bengal, high concentrations of organochlorines led to carcinogenic risks exceeding this threshold, particularly for aldrin (1.89×10^{-4}), dieldrin (1.90×10^{-4} to 2.72×10^{-4}), and heptachlor, highlighting a significant long-term health risk (Habibullah-Al-Mamun et al., 2025). Furthermore, a study conducted in Nigeria showed that the carcinogenic risk associated with heptachlor in infants also exceeded the tolerable threshold of 1×10^{-4}, whereas it remained below this threshold in adults and children (Olanrewaju et al., 2025). By comparison, the risk levels observed in the Loukkos coastal area remain lower, suggesting less critical exposure, although not negligible.

Collectively, these results demonstrate chronic exposure to potentially carcinogenic contaminants, which, despite remaining below regulatory action thresholds, justify the necessity of implementing management and surveillance measures aimed at limiting contamination sources, reducing consumer exposure, and preventing any aggravation of health risk.

4. Conclusion

This study highlights multi-residue contamination of crabs from the Loukkos basin, characterized by the co-occurrence of recent pesticides and persistent organochlorine compounds. The observed contamination profiles reflect chronic and multi-source exposure, resulting from both current agricultural inputs and historical contaminations, with marked interspecific variability and significant bioaccumulation potential in certain species, notably *C. sapidus*.

The health risk assessment shows that non-carcinogenic risks remain generally below safety thresholds for adults and children, suggesting limited short-term impact. Conversely, the analysis of carcinogenic risks reveals that several pesticides exceed the reference threshold of 1×10^{-6}, indicating non-negligible chronic exposure, although observed levels remain below the regulatory action threshold of 1×10^{-4}. These results underscore particular concern for vulnerable populations and highlight the importance of considering long-term effects.

Overall, this study emphasizes that agriculturally influenced coastal ecosystems, such as the Loukkos basin, are subjected to significant anthropogenic pressure, likely to affect both ecological sustainability and the sanitary safety of fishery resources. It demonstrates the necessity of strengthening surveillance programs, better controlling pesticide use, and developing integrated management strategies in order to reduce contamination sources and protect both aquatic ecosystems and human health.

Declarations

5. Conflict of Interest

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

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7. Author Contributions

Y D: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Validation, Resources.

A H: Supervision, Writing – review & editing, Validation.

A B: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Validation, Resources.

I Q: Methodology, Resources, Writing – original draft.

M E: Conceptualization, Supervision, Writing – review & editing, Validation.

8. Ethical Approval

9. Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

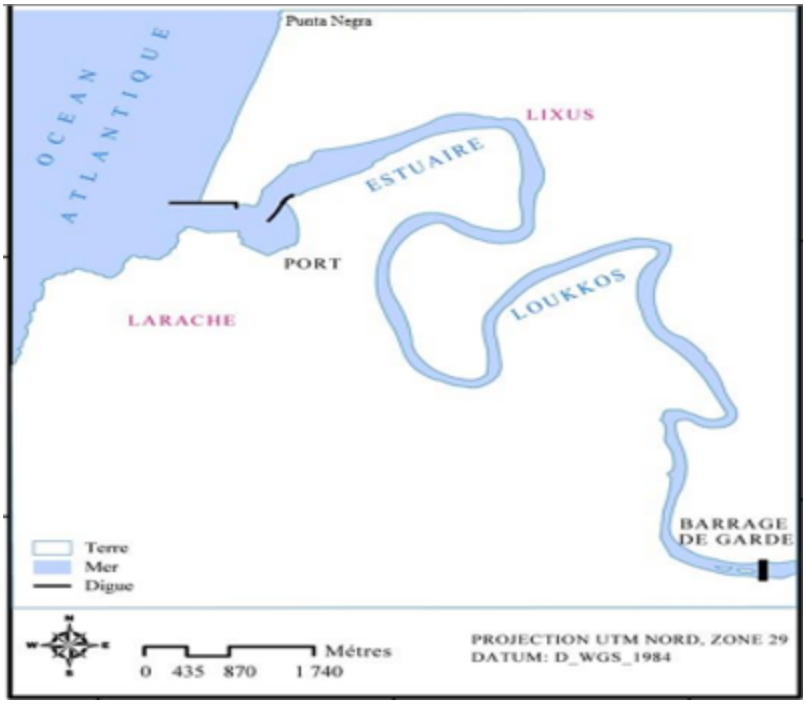


Figure 1

Larache coastal zones



Figure 2

Geographical location of crab sampling sites in Larache.

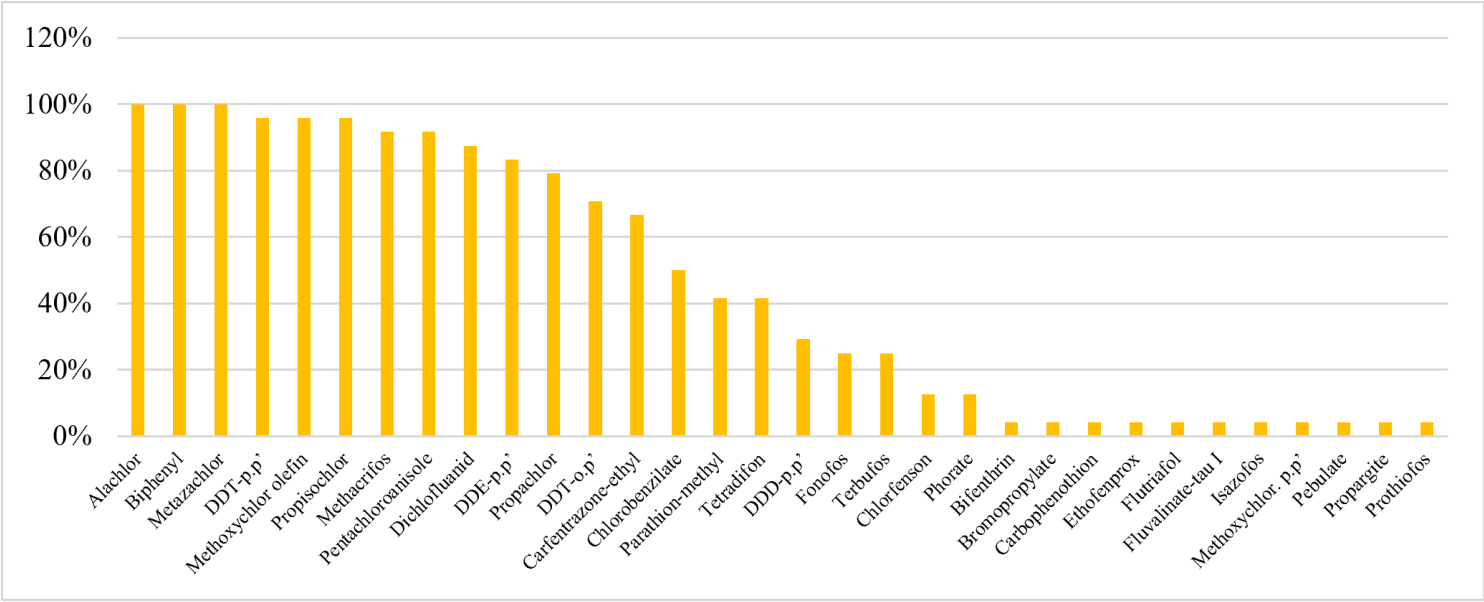


Figure 3

Detection frequency of pesticides in crab samples.

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