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ARTICLE

Groundwater Contamination in Semi-Arid Zones: Assessing Organophosphorus and Organochlorine Pesticide Risks from Agricultural Intensification in the Guir Watershed

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ABSTRACT

This study evaluates pesticide contamination in groundwater downstream of the Kaddoussa Dam (Guir watershed, Morocco) and investigates the influence of agricultural activities on water quality. Nine sampling stations were strategically selected during November 2023 (post-agricultural season) to analyze spatial patterns of 18 pesticide residues: 7 organophosphorus and 11 organochlorines. Identification and quantification were performed via gas chromatography method, targeting both compound classes. Key findings reveal moderate yet localized contamination. The total concentration of organophosphorus pesticides (∑POPs) ranged from 0 µg/L (S8) to 0.191 µg/L (S4), with peak concentrations at stations S3 (0.190 µg/L) and S4 (0.191 µg/L), correlating spatially with intensive agricultural zones. Otherwise, the total concentration of organochlorine pesticides (∑POCs) showed lower levels (0–0.060 µg/L), with maxima at S4 linked to endosulfan and HCH isomers. Notably, none of the detected organochlorine concentrations exceeded 0.06 µg/L, indicating relatively low levels of contamination. Central stations (S2–S6) exhibited co-occurrence of both pesticide groups, dominated by organophosphorus pesticides (0.135–0.191 µg/L), while peripheral sites (S1, S7, S8, S9) displayed negligible or undetectable residues. Despite sub-regulatory thresholds, the persistent detection of pesticides underscores ecological and public health risks, particularly in arid regions with heightened vulnerability due to limited healthcare access and water scarcity. Even at low concentrations,

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organophosphorus and organochlorine pesticides pose significant threats to aquatic ecosystems through bioaccumulation, while also presenting acute health risks to farmworkers and local communities dependent on contaminated groundwater. This study highlights the urgent need for integrated pesticide management strategies to mitigate long-term environmental and socio-economic impacts in agriculturally intensive, water-stressed regions.

Keywords: Pesticide Residues; Groundwater; Agricultural Activities; Human Health; Guir Watershed

1. Introduction

Water quantity and quality pose significant challenges for humanity in the 21st century[1, 2]. Agriculture stands as a primary contributor to the pollution of aquatic ecosystems, with nitrates stemming from agricultural activities emerging as the predominant groundwater contaminant globally[3, 4]. The expansive and intensified nature of agricultural endeavors, encompassing crop cultivation, livestock farming, and aquaculture, has been propelled by escalating food demands driven by population growth and evolving dietary preferences[5]. However, these agricultural practices impose substantial strains on water quality, exacerbating the degradation of aquatic environments[3].

Agriculture, which utilizes a staggering 70% of global water resources, emerges as a pivotal contributor to water contamination, releasing significant quantities of agrochemicals, organic matter, drug residues, sediments, and saline drainage into water bodies[4]. The escalating demand for food, coupled with population growth, has spurred the expansion of agriculture, intensifying pollution loads in water bodies through the unsustainable use of agrochemicals[6]. Consequently, agricultural areas serve as primary receptors of agrochemicals, gathering pollutants from nearby fields, thereby exacerbating environmental contamination[7]. Fertilizers and pesticides are the primary contaminants associated with agricultural practices[8, 9].

Pesticides, essential for managing pests, weeds, and crop diseases, have unquestionably enhanced agricultural efficiency[10]. However, alongside their undeniable contributions to food production, the indiscriminate application and inadequate oversight of pesticides have precipitated significant ecological ramifications, notably within aquatic ecosystems[3, 11]. Numerous scientific investigations have elucidated the adverse impacts of pesticides on aquatic environments[7, 12–15]. These chemicals can infiltrate water bodies through diverse pathways, including agricultural runoff, soil leaching into groundwater, and direct application in aquatic settings[16, 17]. Once introduced into water, pesticides exhibit remarkable persistence, posing enduring threats to aquatic organisms across multiple trophic levels[18, 19].

Studying the presence of pesticide residues in water and the environment is crucial for several reasons. First, pesticide residues in drinking water can pose significant health risks, including acute poisoning and long-term effects such as cancer, endocrine disruption, and reproductive issues[20–22]. Secondly, pesticides can have detrimental effects on ecosystems, harming non-target species like beneficial insects, aquatic life, birds, and mammals, which leads to biodiversity loss and ecosystem imbalance[12, 19]. Understanding pesticide contamination levels aids in devising strategies to mitigate these impacts[3]. Additionally, studying pesticide residues is essential for regulatory bodies to enforce laws and guidelines aimed at controlling pesticide use, ensuring that application does not exceed safe levels, thereby protecting both human health and the environment[23, 24]. Finally, studying pesticide residues contributes to the broader field of environmental science, enhancing our knowledge of pesticide behavior in various environmental matrices, including their degradation, mobility, and bioaccumulation, leading to better risk assessments and management practices[15, 25].

Studying the impact of pesticides on aquatic ecosystems in arid areas with developing agricultural activity is vital for safeguarding environmental health, protecting biodiversity, ensuring safe water and food supplies, and supporting sustainable socio-economic development. This research can inform better management practices and policies to mitigate risks and promote the sustainable use of pesticides, ensuring the long-term health and productivity of these vulnerable ecosystems[3].

However, the study area is one of the arid areas affected by the sudden development of agricultural activities after the installation of the Kaddoussa dam. Agricultural activities pose significant threats to the water quantity and quality in Boudnib. The expansion of agricultural activities in the region, especially in the date palm sector facilitated by the establishment of the Kaddoussa dam, has led to the excessive use of chemical fertilizers and pesticides. According to investigations conducted in the Boudnib area, several pesticides intended for treating various crops have been introduced in recent years. These findings have encouraged us to conduct a study on the potential risks posed by these products, given the rapidly growing agricultural activity in the region. As agriculture continues to expand, farmers are increasingly turning to pesticides to treat their crops, including fruit trees, vegetable crops, and cereals.

Monitoring pesticide residues in water and the environment is essential in arid areas like Boudnib, because these areas have scarce water resources, making any contamination more impactful. Pollutants, including pesticides, can accumulate more easily and reach higher concentrations, posing significant risks to the aquatic ecosystems and the communities that rely on them. Moreover, aquatic ecosystems in arid regions are often fragile and less resilient to disturbances. The introduction of pesticides can disrupt the delicate balance, leading to severe ecological consequences. In fact, pesticide contamination can compromise water quality, posing direct health risks to communities that depend on these water sources for drinking, irrigation, and livestock [26–28].

Indeed, the primary objective of this study is to assess the presence of pesticide residues in groundwater and evaluate their potential impact on aquatic ecosystems to provide relevant recommendations to protect aquatic ecosystems in this arid area.

2. Materials and Methods

2.1. Study Area

The study area is located on the southeastern edge of Morocco, encompassing the Wadi Guir valley from the Kaddoussa Dam site downstream to the Sahli perimeter, spanning approximately 60 km in length. It is situated 60 km southeast of the city of Gourrama and 80 km east of the city of Errachidia. The area is accessible via the RN10 National Road, approximately 60 km from Errachidia toward Boudnib, and via the RR601 Regional Road, 40 km from Gourrama toward Tazougart. The study area includes seven oases (**Figure 1**). These oases, located downstream of the Kaddoussa Dam, cover a total area of 825 hectares.

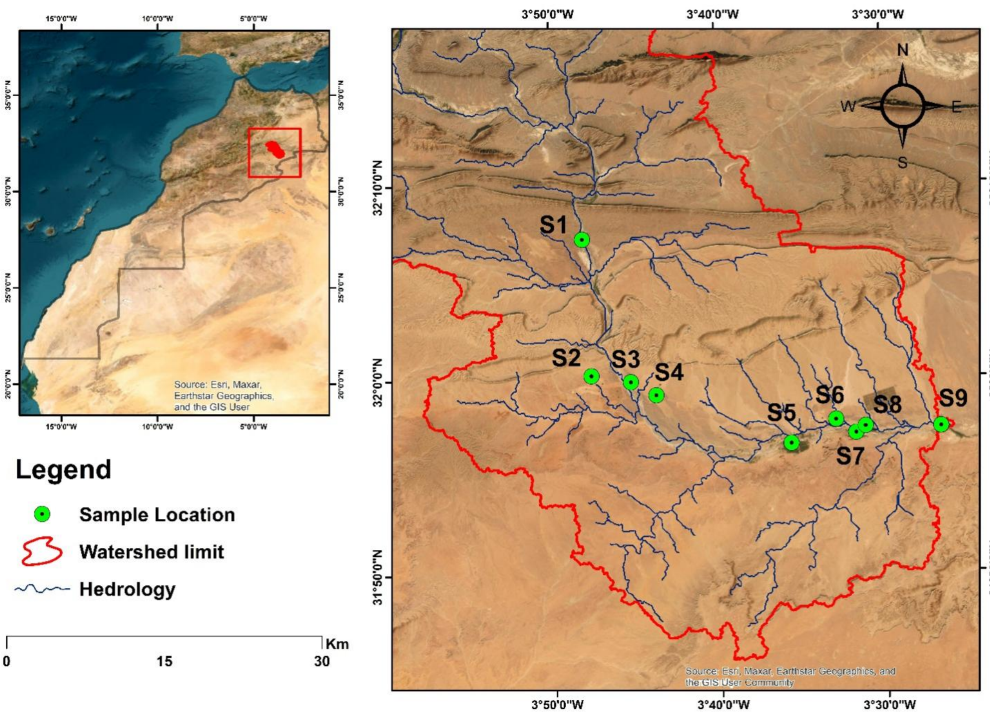

Figure 1. Geological Setting and Spatial Distribution of Sampling Stations Within the Study Area: Boudnib, Morocco (Scale: 1:750,000 (1 cm = 7.5 km)).

Source: Data Collected and Analyzed by the Authors.

The study area, corresponding to the Boudnib plain, is an integral part of the Guir watershed. It is connected to two major regional units: the Eastern High Atlas, characterized by a more rugged relief and lower elevations compared to other parts of the High Atlas, and the Cretaceous Errachidia-Boudnib sedimentary basin [29].

Specifically, the Quaternary aquifer of Boudnib is best described as a perched water table located in the upper levels overlaying the Senonian geological formation. These upper levels consist of poorly sorted or undifferentiated alluvial deposits from the early Quaternary period [29].

This complex aquifer system plays a vital role in water management in the region, providing regular recharge and helping regulate water levels, particularly during flood events [29]. Its perched nature and sedimentary composition contribute significantly to the vulnerability of groundwater to surface contaminants, including pesticides.

2.2. Historical Overview of Agricultural Activity in the Boudnib Extension Area

The settlement dynamics in Boudnib Assamer (extension area), situated west of the commune, are shaped by state-led agricultural initiatives organized into two distinct projects. The first, the PROMAR project (1998), allocated 45 hectares to 15 eligible youths (3 hectares each), targeting unemployed graduates in the Boudnib region. Selected from 120 applicants, beneficiaries received training in date palm cultivation, supported by state-funded 20-meter wells and irrigation infrastructure. However, prohibitive diesel costs stalled progress until the National Initiative for Human Development (NIHD) intervened, electrifying one well and later equipping a second with solar pumping to reduce operational expenses.

In 2014, a second adjacent project expanded land access, granting 5 hectares each to 11 farmers, with plans to eventually include 180 beneficiaries. Unlike PROMAR, this initiative relies on subsidies and supplier credits (e.g., for well drilling) rather than direct state funding. To date, 7 of 11 planned 60-meter-deep wells have been completed, strategically avoiding competition with existing groundwater resources.

These projects promote intensive, diversified farming inspired by traditional oasis systems, integrating vegetable crops for livestock, and arboriculture (olives, date palms). Leveraging pumping technology, farmers prioritize high-value summer crops and premium date varieties. However, this modernization has spurred heavy reliance on agrochemicals. A local phytobox operator reported monthly purchases of 10–15 liters of insecticides per farmer, exceeding fungicide use. Field surveys reveal annual pesticide expenditures of 2,500–3,000 MAD/hectare for smallholders, soaring to 9,000–10,000 MAD/hectare for commercial investors.

Cartographic and field data confirm rapid agricultural expansion: by 2015, 456 of 570 mapped hectares (80%) were actively cultivated. By 2024, this area surged to 5,000 hectares, intensifying concerns over unsustainable practices. Such growth risks creating a pesticide dependency cycle, where resistance prompts higher doses, exacerbating soil and water contamination, biodiversity loss, and health hazards from residue exposure [4]. This trajectory underscores the urgent need for integrated pest management and sustainable water-use policies to balance productivity with ecological and public health safeguards.

2.3. Climatic Characteristics

The region exhibits a semi-arid continental climate, characterized by low precipitation and significant seasonal and diurnal temperature fluctuations. Winter temperatures can drop to −5°C, while summer temperatures may peak at 50 °C. Precipitation is typically low and irregular, predominantly delivered through short-lived, localized thunderstorms. The wettest years on record include 2008/09 (403 mm, slightly more than double the mean annual precipitation), followed by 1995/96 (395 mm) and 1979/80 (305 mm). Conversely, the driest years were 1963/64 (43 mm, approximately one-quarter of the annual average), 1983/84 (75 mm), and 2000/01 (75 mm) [30].

2.4. Groundwater Sampling

Sampling was conducted in a single campaign during November 2023, with samples collected from nine wells and boreholes located in oases and modern farms. Notably, wells are shallower than boreholes. Sampling stations were strategically selected to ensure representative coverage of areas with significant agricultural activity. Collected samples were stored in 2L glass containers wrapped in aluminum foil. After collection, all samples were immediately preserved in coolers at 4 °C to maintain integrity before transportation to the laboratory for analysis.

Table 1 presents the location, specificity, and characteristics of the stations.

Table 1. Location, Specificity, and Characteristics of the Stations.

Station	Sample Type	Station Specifics	Geographic Coordinates
S1	Well water (Depth: 50 m–60 m)	Located between Tazougart Oasis and Kaddoussa. The area features significant agricultural activity, with expanding farms operated by local rights-holder farmers. Proximity to the Kaddoussa Dam increases exposure to surface water resurgence, which may influence groundwater recharge and pose potential contamination risks.	X: 650780.70 Y: 170331.56
S2	Borehole water (Depth: 80 m–100 m)	Modern farm (pesticide use).	X: 657865.66 Y: 155570.11
S3	Borehole water (Depth: 80 m–100 m)	Modern farm (pesticide use).	X: 674962 Y: 153361
S4	Borehole water (Depth: 80 m–100 m)	Modern farm (pesticide use).	X: 655444 Y: 156806
S5	Borehole water (Depth: 80 m–100 m)	Modern farm (pesticide use).	X: 651693 Y: 157376
S6	Well water (Depth: 20 m–25 m)	Located in Boudnib Oasis (Lghaba perimeter). The well irrigates agricultural plots in a highly dynamic farming area, marked by expansion of local rights-holder farms. Long-term agricultural intensification includes diversified vegetable crops, requiring enhanced phytosanitary protection (e.g., pesticide application).	X: 670728 Y: 151078
S7	Well water (Depth: 20 m–30 m)	Located in Oulad Ali Oasis. The well irrigates agricultural plots in a key farming hub, characterized by expanding rights-holder farms.	X: 676868 Y: 152127
S8	Well water (Depth: 20 m–30 m)	Located in Beni Ouziem Oasis. The well irrigates plots within the oasis, where agricultural activity is significant, with expanding rights-holder farms.	X: 677772 Y: 152767
S9	Well water (Depth: 50 m–60 m)	Located in Sahli Oasis. The well irrigates oasis plots. Proximity to surface water (fed by natural springs and accumulation thresholds) makes it strategic for agriculture. However, farming activity here remains moderate compared to other stations.	X: 684946.27 Y: 152815.69

Note. S: Station.

2.5. Organochlorine and Organophosphorus Pesticides Analysis

The choice to analyze organochlorine and organophosphorus pesticides is based on their fundamental differences in environmental behavior, toxicity, and persistence. Their combined inclusion in the analysis provides a comprehensive view of the impact of pesticides on ecosystems and human health while considering temporal dynamics (recent effects vs. persistent effects). Furthermore, this study serves as a valuable reference and a solid baseline (initial state) for future research.

2.5.1. Organophosphorus Pesticides Analysis

Liquid-liquid extraction was used to determine pesticide residues, in accordance with the procedure described by the Moroccan Institute for Standardization, as outlined in standard NM 03.7.201: *Determination of organophosphorus and organo-thiophosphorus pesticides – Gas chromatography method* [31].

After identifying the compounds present, the chromatographic peaks are quantified, and the concentrations are expressed in µg/L.

Seven organophosphorus pesticides were considered in this study: Diazinon, methyl-parathion, ethyl-parathion, dimethoate, fenitrothion, fonofos, and malathion.

2.5.2. Organochlorine Pesticides Analysis

Liquid-liquid extraction was employed to determine pesticide residues, in accordance with the procedure described by the Moroccan Institute for Standardization under standard NM 03.7.202: *Determination of Organochlorine Pesticides and Polychlorinated Biphenyls in Water – Gas Chromatography Method* [31]. Following compound identification, chromatographic peaks were quantified, and concentrations were expressed in µg/L.

Eleven organochlorine pesticides were analyzed in this study: aldrin, endosulfan, hexachlorocyclohexane (HCH), lindane, dieldrin, endrin, heptachlor, heptachlor epoxide, dichlorodiphenyltrichloroethane (DDT), dichlorodiphenyldichloroethane (DDD), and methoxychlor.

2.6. Statistical Analysis

For the statistical analysis of this study, data processing was carried out using OriginLab V24 and Microsoft Excel 2013.

3. Results and Discussion

3.1. Organochlorine and Organophosphorus Pesticides Analysis

The results organochlorine and organophosphorus pesticides analysis are summarized in **Table 2**.

3.1.1. Organophosphorus Pesticides

Analyses of organophosphorus pesticide concentrations revealed values exceeding the detection limit (0.05 µg/L) at multiple stations, with significant spatial variability. The lowest concentration was 0.055 µg/L (malathion, S1 and diazinon, S6) and the highest reached 0.07 µg/L (parathion-methyl, S3 and malathion, S6). Diazinon ranged from undetectable in seven stations to 0.063 µg/L (S4), while parathion-methyl varied between 0.056 µg/L (S7) and 0.07 µg/L (S3). Other pesticides like parathion-ethyl, dimethoate, fenitrothion, and malathion showed concentrations spanning from 0.055 µg/L to 0.07 µg/L, with fonofos being undetected. Notably, S3, S4, and S6 exhibited the highest pesticide levels, while S8 had no detectable residues, and S1 had lower concentrations. The spatial heterogeneity observed is likely due to localized agricultural practices, particularly in intensive farming zones such as S3 and S4. Cumulative pesticide loads at S3 and S4 were 0.190 µg/L and 0.191 µg/L, respectively, raising concerns about chronic exposure risks.

3.1.2. Organochlorine Pesticides

Analyses revealed localized contamination with pronounced spatial variability, with concentrations not exceeding 0.06 µg/L. Endosulfan (0.031 µg/L, S5), HCH (0.03 µg/L, S4), and lindane (0.024 µg/L, S2) were detected, while aldrin, dieldrin, endrin, heptachlor, heptachlor epoxide, and methoxychlore remained undetectable. DDT and its metabolite DDD (0.019–0.024 µg/L) were found only in S1 and S6, suggesting historical rather than recent use. Stations S4 (0.06 µg/L), S2 (0.053 µg/L), and S3 (0.046 µg/L) showed the highest cumulative loads, linked to legacy agricultural practices or environmental persistence, while S7–S9 had no detectable OCPs. Despite low concentrations, persistent compounds such as DDT and endosulfan pose long-term bioaccumulation risks, particularly in aquatic ecosystems. Proactive monitoring of critical zones (S2–S4) and mitigation measures are recommended to address legacy contamination and prevent ecological degradation.

3.1.3. Total Concentrations of Organophosphorus and Organochlorine Pesticides

The total concentration of organophosphorus pesticides (∑POPs) ranges from 0 µg/L (S8) to 0.191 µg/L (S4), reflecting moderate but localized contamination. Stations S3 (0.190 µg/L) and S4 (0.191 µg/L) exhibit the highest total loads, likely linked to intensive agricultural practices.

The total concentration of organochlorine pesticides (∑POCs) varies between 0 µg/L (S7, S8, S9) and 0.060 µg/L at S4, with overall levels lower than those of ∑POPs. Contrary to the initial hypothesis, no station exceeds 0.06 µg/L for organochlorines, and the highest concentrations are primarily associated with endosulfan and HCH.

The central stations (S2, S3, S4, S5, S6) combine both types of pesticides, with dominant ∑POPs (0.135–0.191 µg/L), while peripheral stations (S1, S7, S8, S9) show negligible or undetectable concentrations.

Figure 2 illustrates the total concentrations observed at each station.

Table 2. Mean Concentration of Organochlorine and Organophosphorus Pesticide Residues (µg/L) in Groundwater.

Pesticides Analysis																		
	Organophosphorus Pesticides							**Organochlorine Pesticides**										
ID	**Diazinon**	**Methyl Parathion**	**Ethyl Parathion**	**Dimethoate**	**Fenitrothion**	**Fonofos**	**Malathion**	**Aldrin**	**Endosulfan**	**HCH**	**Lindane**	**Dieldrin**	**Endrin**	**Heptachlor**	**Heptachlor Epoxide**	**DDT**	**DDD**	**Methoxychlor**
Unit	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**
Analysis method	NM 03.7.201	NM 03.7.201	NM 03.7.201	NM 03.7.201	NM 03.7.201	NM 03.7.201	NM 03.7.201	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202	NM 03.7.202
S1	-	-	-	-	0.058	-	0.055	-	-	-	-	-	-	-	-	0.019	0.022	-
S2	-	-	-	0.066	0.06	-	0.06	-	0.029	-	0.024	-	-	-	-	-	-	-
S3	-	0.07	0.058	-	-	-	0.062	-	-	0.026	0.02	-	-	-	-	-	-	-
S4	0.063	-	-	0.064	-	-	0.064	-	0.03	0.03	-	-	-	-	-	-	-	-
S5	-	-	0.066	0.069	-	-	-	-	0.031	-	-	-	-	-	-	-	-	-
S6	0.055	-	-	-	0.057	-	0.07	-	-	-	-	-	-	-	-	0.02	0.024	-
S7	-	0.056	-	-	0.061	-	-	-	-	-	-	-	-	-	-	-	-	-
S8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S9	-	-	-	-	0.059	-	0.057	-	-	-	-	-	-	-	-	-	-	-

Note. All abbreviations used in this article are defined below.
HCH (Hexachlorocyclohexane); DDT (Dichlorodiphenyltrichloroethane); DDD (dichlorodiphenyldichloroethane);
S (Station); (-) (Not detected).

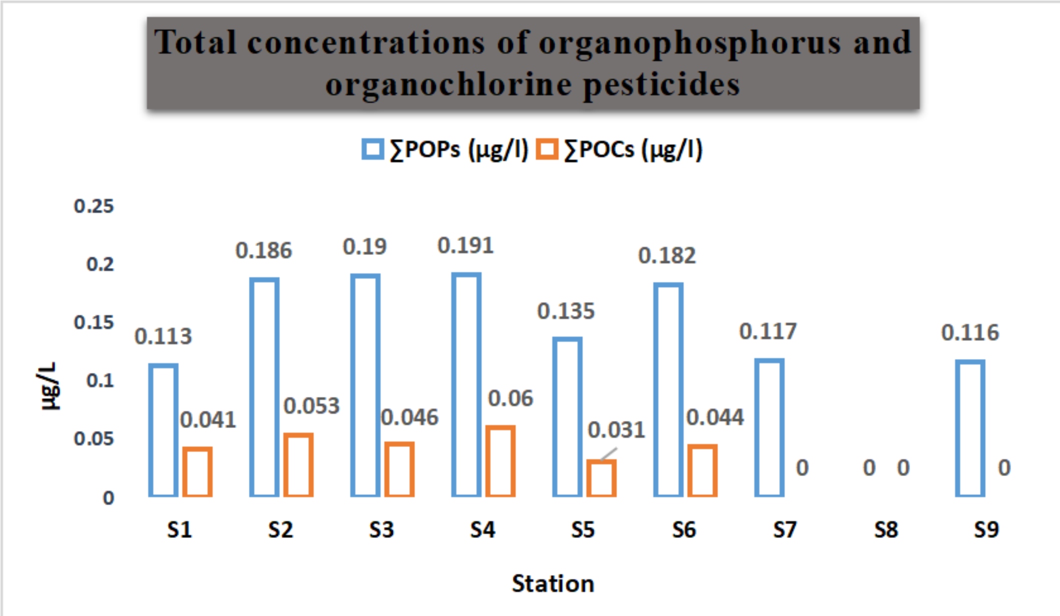

Figure 2. Total Concentrations of Organophosphorus and Organochlorine Pesticides.

3.1.4. Correlation Between Pesticide Concentrations and Well/Borehole Depths

The correlation analysis revealed distinct patterns between pesticide concentrations and well or borehole depths, offering important insights into pesticide mobility and aquifer vulnerability (**Figure 3**).

In **Figure 3A**, several organophosphorus pesticides displayed significant positive correlations with depth, most notably Dimethoate (r = 0.72), Malathion (r = 0.61), and Ethyl Parathion (r = 0.54), suggesting their increased presence in deeper groundwater layers. These findings indicate a strong leaching potential and possible long-term persistence of these compounds in subsurface environments. In contrast, Fenitrothion showed a moderate negative correlation (r = −0.39), implying a higher prevalence in shallow wells, which may reflect its lower mobility or different degradation behavior.

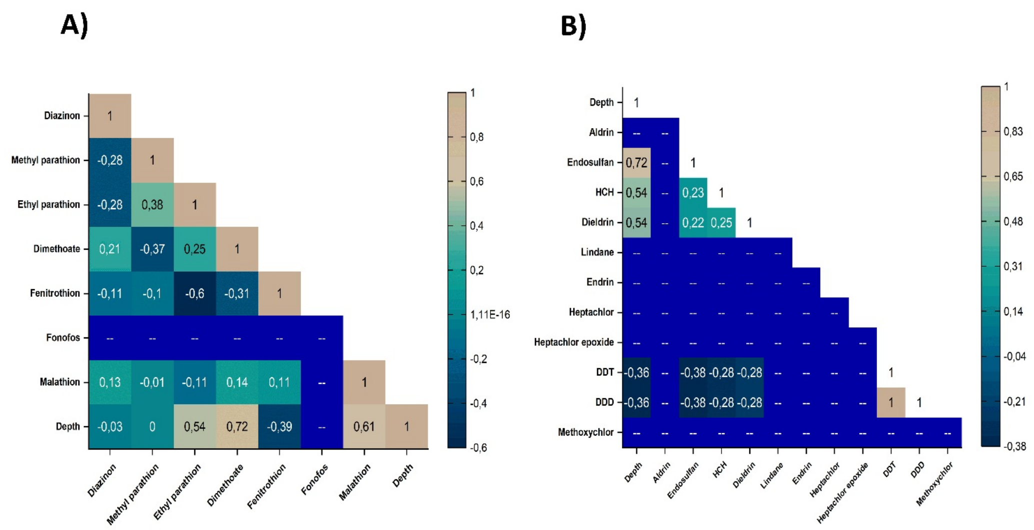

Figure 3. Correlation Matrices Between Well/Borehole Depth, Organophosphorus, and Organochlorine Pesticides Concentrations. (**A**) Organophosphorus Pesticides. (**B**) Organochlorine Pesticides.

Figure 3B, representing organochlorine pesticides, revealed a similarly varied trend. Endosulfan ($r = 0.72$), HCH, and Dieldrin ($r = 0.54$ each) exhibited strong to moderate positive correlations with depth, while DDT and its metabolite DDD were negatively correlated ($r = –0.36$). This pattern suggests that while certain organochlorines are capable of migrating to deeper zones, others like DDT remain near the surface, possibly due to their long-standing historical use and strong soil adsorption characteristics. These correlations underscore the importance of pesticide-specific behavior in groundwater contamination studies and highlight the necessity for depth-targeted monitoring strategies in pesticide-affected regions.

3.2. Discussion

According to the European Environment Agency, the EU Groundwater Directive (2006) establishes a preventive quality standard of 0.1 µg/L for pesticides to assess the chemical status of groundwater, reflecting a commitment to minimizing pesticide concentrations and safeguarding water quality, environmental health, and human safety [32]. Results indicate that stations S2, S3, S4, and S5 exceed this threshold for cumulative organophosphorus pesticides, necessitating urgent attention. Stations S1, S6, S7, and S9 exhibit pesticide levels slightly above or below the standard, warranting ongoing monitoring despite no significant exceedance. In contrast, station S8 shows no detectable pesticide contamination.

The detection of organophosphorus and organochlorine pesticide residues in the sampled waters is frequently linked to agricultural activities, both current and historical, involving pesticide use within the study area. These residues may also originate from preventive or curative pest control measures, such as applications targeting the Moroccan locust (*Dociostaurus maroccanus*) and other invasive species. This underscores the critical need for sustained monitoring to assess contamination trends and mitigate risks posed by these pollutants. Proactive surveillance is essential to safeguard water quality, limit ecological disruption, and protect public health in regions impacted by intensive agricultural practices.

In recent years, there has been increasing attention to studies focused on monitoring pesticide residues in food, water, groundwater, and soil, along with their quantitative health risk assessments [33]. A study conducted on the groundwater of the Saïss plain in Morocco revealed contamination with both banned and non-banned pesticides. Additionally, the concentrations of certain pesticides surpassed 0.1 µg/L [34]. Similarly, in a separate study focusing on the assessment of contamination by organochlorine pesticides and polychlorinated biphenyls in the water of Oualidia lagoon in Morocco, researchers observed the presence of organochlorines in the lagoon, with increasing enrichment observed from downstream to upstream areas. The concentrations ranged between 0.001 µg/L and 0.025 µg/L [35]. Expanding the geographical scope within Morocco, an integrated assessment of groundwater quality in the rural area of R'mel, located in Northwest Morocco, detected nine pesticides across four sites. These included Atrazine, Trietazine, Terbutryn, Chlorpyrifos ethyl, Endosulfan sulfate, Endosulfan alpha, Endosulfan beta, Metribuzin, and Metolachlor. However, none of these pesticides exceeded the European Union's standard limit of 0.1 µg/L [36]. Beyond Morocco, in Egypt, a study aimed at evaluating persistent organic pollutants in the aquatic ecosystem at the Rosetta Nile branch estuary, where it flows into the Mediterranean Sea in the northern Delta, revealed that α-HCH, p,p′-DDE, and polychlorinated biphenyls were the most prevalent compounds found, with concentrations ranging from 0.54 to 4.90 ng/L in the water. Further north, in Lebanon, a study conducted to evaluate pesticide contamination in Akkar groundwater revealed significant levels of organochlorine pesticides. The findings indicated substantial contamination, with concentrations reaching as high as 58.9 µg/L [37]. Lastly, a study undertaken to evaluate pesticide residues in the groundwater and soils of agricultural regions within the Águeda River Basin, spanning both Spain and Portugal, showed that during the summer, up to 80% of groundwater samples from the Spanish side and 70% from the Portuguese side exceeded the quality standard of 0.1 µg/L for one or more individual compounds [38].

According to the report by the National Food Safety Office published in 2018, the distribution of agricultural production in Morocco based on the number of registered pesticides shows varied usage depending on the type of crop: Vegetable crops: 1845 registered pesticides; Fruit crops: 686 registered pesticides; Cereals: 458 registered pesticides; Citrus: 447 registered pesticides. With 1845 registered pesticides, vegetable crops represent the category most treated with pesticides. This could be due to the diversity of vegetables grown and the need to manage a wide range of pests and diseases [39]. The same report also highlights that vegetables and fruits are classified as the primary users of highly dangerous pesticides.

Morocco has taken significant steps to enhance agricultural safety and environmental protection by withdrawing several highly hazardous pesticides from use. The list of banned active materials includes Methyl parathion, Ethyl parathion, Aldrin, Endosulfan, HCH, DDT, DDD, DDE, Endrin, and Heptachlor. These substances are notorious for their persistence in the environment, potential to bioaccumulate, and harmful effects on human health and wildlife. By eliminating these dangerous chemicals, Morocco aims to reduce the risk of contamination in food and water supplies, protect biodiversity, and promote sustainable agricultural practices. This proactive measure reflects a commitment to safer and more environmentally friendly farming methods, aligning with global efforts to phase out the most toxic pesticides and safeguard public health and the ecosystem [39].

In Morocco, the phytosanitary market is predominantly private, with 90% of it being controlled by well-known multinational companies, either operating through their subsidiaries or via local Moroccan distribution firms. The domestic production of phytosanitary products is minimal, with 95% of these products being imported in a ready-to-use state, and only a small portion formulated locally. Additionally, 35% to 45% of the imported products are repackaged into smaller, more convenient packaging to meet the needs of small-scale users [40]. In 2015, the Moroccan Ministry of Agriculture, in collaboration with the FAO, initiated a project aimed at eliminating obsolete pesticides, including Persistent Organic Pollutants (POPs), and associated waste, totaling approximately 800 tonnes. This four-year project focuses on eradicating the identified stocks of obsolete pesticides and establishing a program to prevent future accumulations of expired stocks in Morocco. Additionally, the project aims to implement a management system for empty pesticide packaging and promote the development of integrated pest management strategies to reduce the reliance on chemical pesticides [40].

3.3. Organochlorine and Organophosphorus Pesticides Toxicity

3.3.1. Contamination Pathways

Pesticide contamination in water pathways is a significant environmental concern [3]. Pesticides enter aquatic ecosystems through various pathways, including:

a. **Runoff:** After pesticides are applied to agricultural fields, lawns, or other areas, rainfall or irrigation can cause these chemicals to run off the land surface and enter nearby water bodies, such as rivers, lakes, and streams.

b. **Leaching:** Pesticides can percolate through the soil and reach the groundwater. This process is known as leaching. Factors affecting leaching include soil type, pesticide properties (e.g., solubility and persistence), and the amount of water moving through the soil.

c. **Drift:** Spraying can cause pesticides to drift into water bodies (**Figure 4**) [41].

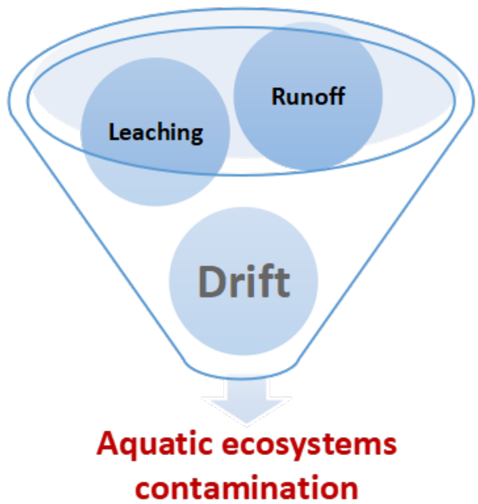

Figure 4. Pesticides Contamination Pathways.

A range of factors that can be broadly categorized into environmental and physicochemical influences the infiltration of pesticides into surface water and groundwater. Environmental factors depend on soil type and texture (soil characteristics such as texture, structure, permeability and organic matter), topography and climate and weather conditions (precipitation intensity and frequency). On the other hand, physicochemical factors depend mostly on pesticide Properties (solubility, degradation rate, adsorption coefficient, volatility, and persistence). Moreover, application methods and agricultural practices can significantly influence a pesticide's potential to leach through the soil profile [42, 43].

These factors do not operate in isolation but interact in complex ways to influence pesticide behavior in the environment. For example, the adsorption coefficient and organic matter content of the soil can interact to determine how much pesticide remains in the soil versus how much leaches into groundwater. Similarly, climate conditions such as heavy rainfall can amplify the effects of soil texture on pesticide runoff[42, 43].

3.3.2. Organophosphorus Pesticides

a. Diazinon

Diazinon, a widely used organophosphorus pesticide, is highly effective against a broad spectrum of agricultural pests. However, its persistent use has led to substantial ecological and biological concerns. Diazinon is often detected in groundwater, drinking water, and surface water, highlighting its pervasive environmental presence. The residual diazinon in these environments can adversely impact non-target organisms through various pathways, including air, water, soil, and the food chain[44, 45]. Numerous studies have demonstrated diazinon's negative effects on non-target organisms (**Table 3**). Diazinon alters the behavior of zebrafish embryos and larvae[46]. Additionally, diazinon can affect the vital organs of fish (Ctenopharyngodon idella), and lead to death[45]. Moreover, a study showed that diazinon influences the blood, gill, liver, and kidney of the freshwater fish Capoeta damascina[47]. Diazinon has been detected in drinking water, posing significant risks to human health[48]. In 2000, the United States Environmental Protection Agency (U.S. EPA) reached an agreement with diazinon registrants to terminate all residential uses of the pesticide. Consequently, indoor applications were discontinued in 2002, followed by the cancellation of outdoor uses in 2004. This decision restricted diazinon usage exclusively to agricultural purposes[44].

Table 3. Toxicity of Diazinon to Non-Target Species.

Toxicity to Non-Target Species	Toxicity Level	Description of Toxic Effects on Non-Target Species
Fish or daphnia	Extremely	Diazinon is extremely toxic to freshwater fish and invertebrates. Its main metabolite, oxypyrimidine, is weakly toxic in fish and freshwater invertebrates (in Daphnia magna)[49].
Rats	Long-term effects	Exposure to diazinon has been previously demonstrated to result in long-term neurobehavioral changes in rats[50].
Birds	Extremely	Diazinon is extremely toxic in birds exposed orally. It is also extremely toxic in birds exposed through food[51, 52].
Bees	High	This insecticide is highly toxic to bees with an acute contact LD_{50} of 0.22 µg/bee[53, 54].
Human	Long-term effects	Research highlighted that chronic exposure to diazinon can lead to cancer, lung lesions, and cytogenetic abnormalities, suggesting potential long-term health impacts[55, 56].

b. Methyl parathion

Methyl parathion is an organophosphorus insecticide known for its insecticidal properties, which are due to its inhibition of acetylcholinesterase (AChE). This mechanism also accounts for its high toxicity in humans. The primary route of human exposure is inhalation, though dermal contact and accidental ingestion can also be significant. Classified by the World Health Organization (WHO) as Category Ia (extremely toxic) and by the United States Environmental Protection Agency (EPA) as Toxicity Category I (most toxic), methyl parathion is approved for outdoor use only[57, 58]. Methyl parathion poses significant threats to the ecosystem by contaminating air, soil, and water, creating a toxic environment for humans, birds, freshwater fish, aquatic organisms, and marine life. Its use as an insecticide is widely recognized as a serious environmental hazard[59–61]. Studies have shown that methyl parathion induces many negative effects on fish[59, 62–64]. It can also cause damage to Wistar rats[65]. Moreover, methyl parathion can be dangerous to human health by different pathways[66, 67].

c. Malathion

Malathion, an organophosphate insecticide, has been extensively used since its introduction in the 1950s for agricultural, residential, and public health applications, particularly for mosquito control. Despite its lower acute toxicity compared to other organophosphates, malathion still poses significant risks to human health and aquatic ecosystems [68, 69]. Numerous studies have demonstrated malathion's negative effects on non-target organisms. For instance, it induces hematoxicity in Barbonymus gonionotus [70], causes genotoxic effects in Daphnia magna [71], and leads to oxidative damage and neurotoxicity in zebrafish [72]. Additionally, malathion alters gene expression in embryonic zebrafish [73], and causes liver and kidney toxicity in rats [74]. Malathion leads to the death of many species of fish, *Colossoma macropomum* [75], *Labeo rohita* [76]. It also exhibits genotoxic effects on human lymphocytes [77, 78].

3.3.3. Organochlorine Pesticides

a. DDT (Dichlorodiphenyltrichloroethane)

DDT (dichloro-diphenyl-trichloroethane), introduced in the 1940s, was the pioneering modern synthetic insecticide. It was highly effective against malaria, typhus, and other insect-transmitted diseases. However, DDT's chemical properties, particularly its long half-life of up to 30 years, led to significant health and environmental issues. Its persistence in the environment and tendency to biomagnify in organisms caused various problems [79–81]. DDD (Dichlorodiphenyldichloroethane) and DDE (Dichlorodiphenyldichloroethylene) are both metabolites of DDT (Dichlorodiphenyltrichloroethane) [82, 83]. DDD was also produced and used as an insecticide, though its use was much less prevalent compared to DDT. DDE, on the other hand, is not commercially produced but can form through the dehydrochlorination of DDT in alkaline environments. In many environmental samples, DDE is detected at higher concentrations than DDT [82, 83].

Studies have demonstrated that DDT induces numerous negative effects on fish [84–86]. DDT and its metabolites pose significant threats to various bird species, as confirmed by research on California condors [87], pelicans [88], and house sparrows (Passer domesticus) [89]. Moreover, DDT has been shown to have direct effects on bees, with its metabolites being detectable in honey [90, 91]. These findings underscore the pervasive and long-lasting impact of DDT on both aquatic and terrestrial ecosystems.

DDT, historically used for malaria control and agricultural pest management, poses significant risks to human health despite its effectiveness:

(1) **Endocrine disruption:** DDT can interfere with hormone systems, leading to reproductive issues such as reduced fertility and developmental problems in offspring [92, 93].

(2) **Carcinogenicity**: DDT is classified as a possible human carcinogen. Studies have linked DDT exposure to cancers like breast cancer, pancreatic cancer, and liver cancer [94–96].

(3) **Neurotoxicity**: Chronic exposure to DDT can affect the nervous system, leading to neurotoxicity [97].

(4) **Liver damage**: DDT has been associated with liver enlargement and damage, which can impair liver function over time [98].

(5) **Immune system impairment**: Exposure to DDT can weaken the immune system, making individuals more susceptible to infections [92, 99].

b. Endosulfan

Endosulfan is an organochlorine insecticide that has been extensively used in agriculture since the 1950s to control a variety of pests on crops such as cotton, tea, fruits, and vegetables. Its high efficacy and broad-spectrum activity have made endosulfan a popular choice among farmers. However, its persistence in the environment and toxic effects on non-target organisms have led to increasing concerns and regulatory actions worldwide. Due to its significant environmental and health risks, endosulfan has been banned or severely restricted in over 80 countries, including those in the European Union, the United States, and India. It is listed under the Stockholm Convention on Persistent Organic Pollutants, which aims to eliminate or restrict the production and use of persistent organic pollutants [100–103].

Endosulfan can leach into the soil and contaminate groundwater, posing a risk to aquatic ecosystems. It has been frequently detected in surface water bodies, where it affects a wide range of aquatic organisms. Endosulfan is highly toxic to fish and aquatic invertebrates; even at low concentrations, it can cause significant mortality and sublethal effects such as behavioral changes and reproductive impairments [104–106].

Studies have shown that endosulfan can lead to many negative effects on various aspects of fish (**Table 4**).

Table 4. Toxicity of Endosulfan to Various Aspects of Fish.

Toxicity	**Studies**
Genotoxicity	Previous experiments have demonstrated the harmful effects of endosulfan on various aspects of fish health, including the induction of genotoxic damage [107, 108]. A study evaluating the genotoxic effects of a mixture of endosulfan and deltamethrin on the African sharptooth catfish found significant genotoxicity [109].
Endocrine effects	Endosulfan is known to have significant endocrine-disrupting properties, affecting fish hormonal balance. Endosulfan has been demonstrated to disrupt gonadal steroidogenesis in the cichlid fish Cichlasoma dimerus [110]. Larval fish exposed to 0.1 μg/L of endosulfan exhibited a reduced GnRH signal and an enlarged nuclear area in FSH beta-positive cells [111].
Neurotoxic effects	Endosulfan has been shown to have significant neurotoxic effects on fish. These effects primarily stem from its ability to interfere with the normal functioning of the nervous system, particularly through the disruption of neurotransmitter systems and neuronal development [112]. A study demonstrated an exacerbation of neurotoxic effects induced by endosulfan in the seluang fish [113]. Endosulfan has shown developmental neurotoxicity in zebrafish [114].
Reproductive effects	Endosulfan has been found to exert significant negative effects on the reproductive health of fish. Endosulfan poses reproductive toxicity to male freshwater fish, specifically Cyprinion watsoni [115]. Furthermore, Endosulfan diminishes fertilization success and induces abnormal embryo development in zebrafish [116].

Pesticides such as endosulfan pose a significant global risk to human health [117]. Elevated levels of endosulfan can disrupt the hormone estrogen, leading to reproductive and developmental harm in both humans and animals [117, 118]. The central nervous system is particularly vulnerable to endosulfan toxicity, and exposure can also result in liver damage [119]. In addition, studies show that endosulfan acts as a neurotoxic factor [120]. These diverse toxicological properties highlight the broad-ranging health risks associated with endosulfan exposure.

c. Lindane (gamma-HCH)

Lindane, a chlorinated hydrocarbon insecticide, has been extensively studied for its toxicity to aquatic life in recent scientific research. Studies indicate that lindane poses significant risks to aquatic organisms due to its persistence in aquatic environments and bioaccumulative properties in the food chain [121, 122].

Recent studies have highlighted the profound impacts of lindane, an insecticide, on various organisms, particularly emphasizing its toxicity to fish. Research on grass carp (Ctenopharyngodon idella) exposed to sublethal concentrations of lindane reveals significant histological effects on intestinal tissues, even at low doses [121]. Furthermore, lindane's toxicity extends beyond fish, playing a crucial role in inducing harmful effects in nematodes and causing oxidative stress and intestinal damage in Caenorhabditis elegans. Chronic exposure to 100 ng/L of lindane has been shown to markedly affect Caenorhabditis elegans, resulting in detrimental physiological effects including increased ROS production, lipofuscin accumulation, and the presence of germ cell corpses [123].

In vitro studies have demonstrated that lindane induces dose-dependent damage to granulosa cells, further highlighting its detrimental effects on reproductive health [124].

Based on multiple studies, lindane has been classified as a potential human carcinogen, with research indicating an increased incidence of thyroid cancer in the United States linked to its exposure [125, 126]. Adverse pregnancy and birth outcomes have been attributed to disruptions in meiotic spindle formation, polar body extrusion, and embryonic development [126, 127]. The extensive use and persistent environmental toxicity of lindane underscore the urgent need for its removal from ecosystems [128].

3.4. Challenges of Pesticide Use in Arid Areas

The Boudnib extension, located in an arid region, has experienced significant agricultural expansion from 570 hectares in 2015 to nearly 5,000 hectares by 2024. This increase indicates substantial development in an area where agriculture is typically challenged by limited water resources and harsh climatic conditions. The transformation of such a vast area into cultivated land in an arid region is remarkable and underscores the intensive efforts to boost agricultural productivity. The challenges of pesticide use in arid areas can be summarized in four key points:

(1) **Increased reliance on pesticides**: In arid regions, the harsh environmental conditions often lead to greater pest

pressure, as the limited biodiversity can result in pests finding fewer natural predators. This scenario can drive farmers to rely heavily on pesticides to protect their crops, exacerbating the issues related to pesticide resistance and environmental contamination.

(2) **Water scarcity and contamination**: Water is a precious resource in arid areas. The contamination of groundwater with pesticides, even at low concentrations, is particularly concerning as water sources are limited and heavily relied upon. The presence of organophosphorus and organochlorine pesticides in groundwater samples from Boudnib highlights the risk of water pollution, which can have dire consequences for both human consumption and irrigation.

(3) **Soil health and fertility**: Arid soils are often less fertile and more prone to degradation. The excessive use of pesticides can further deteriorate soil health by disrupting microbial communities and reducing soil fertility. Maintaining soil quality is crucial in arid areas to sustain agricultural productivity over the long term.

(4) **Human health risks**: In arid regions, communities are often more vulnerable due to limited access to healthcare and clean water. Pesticide residues on crops and in water sources can pose significant health risks, particularly for farm workers and local populations who may have limited means to mitigate exposure.

4. Conclusions

The rapid agricultural expansion in the Boudnib region, an arid zone, presents both significant opportunities and pressing challenges for sustainable farming. As highlighted by our study of pesticide contamination in groundwater downstream of the Kaddoussa Dam (Guir watershed, Morocco), the widespread use of pesticides, particularly organophosphorus and organochlorines, presents long-term risks to water quality, non-target species, and human health. Although pesticide residues were found at levels below regulatory thresholds, their persistent presence in groundwater, particularly in areas with intensive agricultural activity, poses a serious ecological threat. Even at low concentrations, these chemicals can accumulate in the environment and pose direct risks to aquatic ecosystems, farmworkers, and local communities who rely on contaminated groundwater sources.

In the face of these challenges, it is clear that sustainable agricultural practices and ongoing environmental monitoring are crucial. This includes the adoption of integrated pest management (IPM) practices, more efficient water management strategies, and active community engagement in mitigating pesticide use. By promoting these sustainable practices, it is possible to balance agricultural productivity with environmental protection, ensuring food security and safeguarding the health of future generations.

Moreover, given the ongoing agricultural intensification in Boudnib and its associated risks, further studies are urgently needed. These should focus on monitoring the evolution of pesticide contamination and its long-term impacts on both the environment and public health. Additionally, such research is essential for guiding policy decisions and refining farming practices to foster the sustainable development of agriculture in water-stressed regions like Boudnib. Through comprehensive studies and the implementation of integrated management strategies, we can mitigate the adverse effects of pesticide use and promote more sustainable farming in arid environments.

Author Contributions

Conceptualization, E.M.A., A.E.M., and A.A.; methodology, E.M.A., A.E.M., A.A., and A.A.B.; software, E.M.A., A.E.M., and A.A.; validation, E.M.A., A.E.M., A.A., and A.A.B.; formal analysis, E.M.A., A.A.B.; investigation, E.M.A.; resources, E.M.A., A.E.M., and A.A.; data curation, E.M.A.; writing—original draft preparation, E.M.A.; writing—review and editing, E.M.A., A.E.M., A.A., and A.A.B.; visualization, E.M.A., A.A.B.; supervision, E.M.A., A.A.B.; project administration, E.M.A., A.A.B. All authors have read and agreed to the published version of the manuscript.

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The data that support the findings of this study are available from the corresponding author upon reasonable request. All relevant data are included in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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