Australian Journal of Crop Science

Article | https://doi.org/10.21475/ajcs.26.20.05.pne149 | 20(05):399-411 (2026)
Submitted: 06 October 2025 | Revised: 22 December 2025 | Accepted: 21 March 2026

Prioritization of pesticides used in sugar beet crop in a semi-arid region of Morocco

Majda ouhajjou[1]*, Mohamed Edahbi[2], Taoufik El Rasafi[3], Hanaa Hachimi[4], Abdelmajid Haddioui[1]

[1]Laboratory of Agro-Industrial and Medical Biotechnologies, Faculty of Science and Techniques, University of Sultan Moulay Slimane, Beni Mellal, Morocco
[2]Higher School of Technology (ESTFBS), Sultan Moulay Slimane University, Beni Mellal, Morocco.
[3]Health and Environment Laboratory, Faculty of Sciences Ain Chock, Hassan II University, Casablanca, B.P 5366, Maarif, Casablanca, Morocco
[4]Laboratory of Advanced Systems Engineering, National School of Applied Sciences ENSA, Ibn Tofail University Campus, Kenitra 14000, Morocco

***Corresponding author:** *Majda.ouhajjou@usms.ac.ma*

Abstract

Non-ecological and intensive agriculture is one of the main sources of drinking water contamination by pesticides. The impacts of pesticides on water quality are unknown for the majority of used pesticides and their detection is based on monitoring studies. However, these studies are confronted with the choice of pesticides to monitor in priority and the cost and time necessary to carry out such studies. This study aims to generate a list of priority pesticides for surface water and groundwater quality monitoring. To meet this objective, the pesticide prioritization approach adopted in this study is based on pesticide use data for sugar beet in the irrigated perimeter of Tadla in central Morocco, in combination with pesticide mobility and toxicity data accessible through the Pesticide Properties Database. Five indices are calculated to characterize and classify each pesticide from the initial list: quantity index, environmental exposure potential, toxicity potential, hazard potential, and weighted toxicity potential. This approach resulted in a final list of 16 pesticides. The ethofumesate, lenacil, et cyproconazole were identified as the pesticides with the most toxic effects on human health based on toxicity potential. Lenacil and metamitron are the pesticides with the highest risk based on hazard potential. The pesticides chlorpyrifos-ethyl, metamitron, lenacil, ethofumesate, phenmedipham and tefluthrin were identified with the highest weighted toxicity potential. The final list of priority pesticides obtained can serve as a basis for establishing a program to monitor pesticide residues in surface and groundwater in this intensive agricultural area.

Keywords: Priority pesticide, quantity, mobility, toxicity, irrigated perimeter of Tadla (IPT).

Introduction

The rapid increase in the world's population has led to a huge demand for food, which challenges farmers to increase food production (Tudi et al. 2021). Several solutions have been used to face this pressure, such as the application of modified seeds, precision agriculture technologies, agricultural robots and extensive use of pesticides against crop pests (Bongiovanni and Lowenberg-Deboer 2004; Reichenberger et al. 2007; Singh et al. 2020). However, uncontrolled pesticide use may lead to serious environmental problems. Pesticide residues are ubiquitous and can contaminate several compartments such as water, air, and soil or be transferred to the food chain (Vryzas 2018; Rasool et al. 2022), thus compromising the ecological balance and biodiversity (Mu et al. 2023; Vullo et al. 2023). Pesticide properties, climatic conditions, and management practices all influence the pathways of loss of pesticides and their potential for sorption, degradation, and dissipation in the environment (Farha et al. 2016). Moreover, pesticide mobility is affected by processes such as volatilization, plant uptake, and runoff and leaching, depending on soil type and environmental conditions (Farha et al. 2016).

Pesticide residues represent a major concern for human health in intensive agricultural areas (Guilpart et al. 2022). Their effects are cumulative and can be felt over the long term (Cedergreen 2014; Bjergager et al. 2017) depending on the type and pesticide dose (Kolakowski et al. 2020; Dcunha et al. 2023; An et al. 2023), the way of exposure (Kim et al. 2023), and the individual sensitivity (Huang et al. 2023). High levels of pesticides can cause severe health issues such as alteration of lipid and carbohydrate metabolism, disruption of the endocrine system (Wang et al. 2022), alteration of the neuronal metabolism (Huang et al. 2022) and disruption of liver function (Ojo et al. 2020). Moreover, several health problems (cancer, endocrine disorders, nervous system damage, and reproductive problems) observed in workers applying pesticides have been linked to exposure to pesticide residues (Joseph et al. 2022; de Graaf et al. 2022).

Serious efforts have been made to assess human health risks associated with pesticide exposure in water (Narita et al. 2014, 2021; Yu et al. 2019; Liu et al. 2022), and prioritization is one of the proposed methods. Prioritization of pesticides is generally based on their persistence and mobility (Dabrowski et al. 2014; Valcke et al. 2005), taking into consideration their toxicity and environmental risks (Narita et al. 2021). Moreover, the application history of pesticides, especially when no local monitoring data is available, is an essential indicator to compare their leaching and runoff risks and determine the most prioritized ones (Örtl 2019).

The Tadla Plain is located in central Morocco and has high agricultural importance. It is characterized by a semi-arid to arid climate and low rainfall. This zone is one of Morocco's oldest and largest irrigated perimeters, with more than 100,000 ha of irrigated land. The main irrigated crops include cereals, olives, citrus and sugar beet (Baite et al. 2021). For sugar beet, more than 12,500 ha are irrigated, ensuring the production of 880,000 tons, which is almost 25% of the national production of white sugar. This high white sugar production is associated with high use of various kinds of pesticides which may cause a severe contamination of soils, groundwater and surface water. To the best of our knowledge, pesticide residue monitoring has not been conducted previously, nor has a list of pesticides been generated to form the basis of any monitoring program in this region.

This work aims to identify and prioritize pesticides in order to develop a monitoring program for pesticide residues in surface water and groundwater within the area where sugar beet is grown in the irrigated perimeter of Tadla irrigation. The final list of priority pesticides will form the basis for planning pesticide residue monitoring programs in areas of sugar beet expansion and an assessment of its environmental impact at the same time.

Results

Prioritization of pesticides used in sugar beet cultivation

In this study, the approach adopted to prioritize the pesticides is based on a method that combines the properties of the pesticides (including the GUS index, toxicological effects) accessible through the phytosanitary database (PPDB, 2023), together with the data on pesticide use obtained from the previously conducted survey on sugar beet cultivation, covering a total area of 333 hectares in the rural commune of Sidi Jaber in the IPT. This approach allowed the generation of a list of prioritized pesticides used in sugar beet cultivation, through the calculation of four indices (Table 1): Quantity Index (QI), Toxicity Potential (TP), Hazard Potential (HP), and Weighted Hazard Potential (WHP) specific to each pesticide from the initial list. The generated priority pesticide list consists of 16 pesticides (Table 2).

Quantity Index (QI): The initial list of pesticides consisted of 28 pesticides with a total quantity of 1585.914 kg. The total quantity of the 16 priority pesticides according to the five four indices is 1526.347 kg. This represents more than 90% of the total quantity of pesticides reported in the survey. The top ten pesticides in the list of the QI are considered to be the most widely used pesticides in the surveyed area. Chlorpyrifos-ethyl alone accounts for more than 50% of the total amount of pesticides used. It is used in approximately 86.4% of the surveyed area. The most commonly used herbicides are metamitron, ethofumesate, phenmedipham and desmedipham. These herbicides were in use on over 90% of the sugar beet farms in the survey. Tefluthrin and bifenthrin are also in widespread use, but their areas of application are smaller. The areas of application of the pesticides lenacil, indoxacarb, cyproconazole and thiophanate-methyl are significant (62.04%, 38.63%, 26% and 23.13%, respectively) in relation to their relatively low application rates.

Toxicity Potential (TP): The toxicological data on endocrine disruption, neurotoxicity, developmental toxicity, carcinogenicity, and mutagenicity of the pesticides obtained from (PPDB, 2023) allowed the creation of the TP index for each the toxic effect, potentially capable of causing the toxic effect, not causing any toxic effect, or no current data to assess the pesticide's potential to cause the toxic effect. It should be noted that abamectin is not included in this radial diagram due to the unavailability of data for this pesticide in the database. The results obtained for this index allowed the classification of the following pesticides ethofumesate (TP=31), lenacil (TP=29), cyproconazole (TP=29), indoxacarb (TP=29), metamitron (TP=27), propaquizafop (TP=25), epoxiconazole (TP=25), tetraconazole (TP=25), chlorpyrifos-ethyl (TP=24), tefluthrin (TP=23) as the pesticides with the most toxic effects on human health. In fact, bifenthrin and metamitron are classified as endocrine disrupters (PPDB, 2023). Epoxiconazole is considered to be carcinogenic (PPDB, 2023). The pesticides chlorpyrifos-ethyl and tefluthrin are considered neurotoxic, as is indoxacarb. thiophanate-methyl, epoxiconazole, gamma-cyhalothrin, alpha-cyhalothrin, chlorpyrifos-ethyl, and desmedipham are classified as developmental toxicants, as is cycloxidim from the initial list. According to the Pesticide Properties Database, none of the pesticides are considered mutagenic (PPDB, 2023).

Environmental exposure potential (EEP): The EEP is an index that provides information on the potential of a pesticide to reach water resources through runoff or leaching. The EEP allowed to generate three categories of pesticides: those with high

Table 1. Initial list of pesticides classified according to their quantity index (QI), toxicity potential (TP), hazard potential (HP), and weighted hazard potential (WHP).

N°	Pesticides	QI	Pesticides	TP	Pesticides	HP	Pesticides	WHP
1	Chlorpyriphos-Ethyl	909.47	Ethofumesat	31	Lenacil	52	Chlorpyriphos-ethyl	9.17
2	Metamitron	242.15	Lenacil	29	Metamitron	44	Metamitron	6.72
3	Ethofumesat	85.57~~2~~	Cyproconazole	29	Indoxacarb	28	Lenacil	1.42
4	Phenmedipham	59.07~~3~~	Indoxacarb	29	Propaquizafop	26	Ethofumesat	1.13
5	Tefluthrine	46	Metamitron	27	Epoxiconazole	25	Phenmedipham ,	0.67
6	Lenacil	43.2	Propaquizafop	25	Thiophanate-methyl	25	Tefluthrine	0.64
7	Desmedipham	37.26	Epoxiconazole	25	Tefluthrine	22	Desmedipham	0.47
8	Clethodime	26.25	Tetraconazole	25	Bifenthrine	22	Bifenthrine	0.36
9	Bifenthrine	26	Chlorpyriphos-ethyl,	24	Cyproconazole	21	Thiophanate-methyl	0.19
10	Haloxyfop-R-methyl ester	14.51~~8~~	Tefluthrine	23	Ethofumesat	21	Epoxiconazole	0.15
11	Cypermethrin	13.11~~5~~	Bifenthrine	23	Alpha-cypermethrin	20	Cypermethrin	0.15
12	Thiophanate-methyl	11.93~~5~~	Alpha-cypermethrin	21	Desmedipham	20	Indoxacarb	0.11
13	Fluazifop-P-butyl	10.8	Lambda-cyhalothrin	20	Phenmedipham	18	Picoxystrobine	0.09
14	Epoxiconazole	9.69	Cypermethrin	19	Cycloxidime	18	Clethodim	0.07
15	Picoxystrobine	7.9	Zeta-cypermethrin	18	Cypermethrin	18	Difenoconazole	0.06
16	Methomyl	6.25	Gamma-cyhalothrin	18	Zeta-cypermethrin	18	Haloxyfop-R Methyl Ester	0.04
17	Difenoconazole	6.18~~5~~	Methomyl	18	Picoxystrobine	18	Cyproconazole	0.04
18	Indoxacarb	6.15	Phenmedipham	18	Tetraconazole	18	Tetraconazole	0.04
19	Lambda-cyhalothrin	5	Desmedipham	18	Chlorpyriphos-ethyl	16	Propaquizafop	0.04
20	Triflusulfuron-methyl	4.23	Haloxyfop-R Methyl Ester	18	Difenoconazole	15	Triflusulfuron-methyl	0.03
21	Tetraconazole	3.62~~5~~	Clethodim	15	Triflusulfuron-methyl	13	Methomyl	0.03
22	Cyproconazole	3.16	Triflusulfuron-methyl	14	Gamma-cyhalothrin	10	Cycloxidime	0.03
23	Cycloxydime	2.7	Fluazifop-p-butyl	12	Methomyl	8	Fluazifop-p-butyl	0.03
24	Propaquizafop	2.3	Cycloxidime	9	Lambda-cyhalothrin	6	Alpha-cypermethrin	0.02
25	Alpha-cypermethrin	1.57	Picoxystrobine	9	Haloxyfop-R Methyl Ester	5	Lambda-cyhalothrin	0.02
26	Zeta-cypermethrin	1.02	Difenoconazole	6	Clethodim	4	Zeta-cypermethrin	0.01
27	Abamectin	0.4	Thiophanate-methyl	15	Fluazifop-p-butyl	4	Gamma-cyhalothrin	0.002
28	Gamma-cyhalothrin	0.4	Abamectin	-	Abamectin	-	Abamectine	-

mobility (EEP=4), namely indoxacarb, lenacil, ethofumesate and cyproconazole; those with moderate mobility (EEP=2), such as metamitron and propaquizafop; and the remaining pesticides on the list are characterized by low mobility (EEP=1).

Hazard potential (HP): The hazard potential of the pesticides on the initial list is assessed using the HP index. This index takes into account both the toxicity of the pesticide to humans and its mobility potential, measured by its EEP index. Lenacil (HP=52) followed by metamitron (HP=44) are the pesticides with the highest risk. These results indicate that the HP index is strongly influenced by the TP index.

Table 2. Final list of priority pesticides.

N°	Pesticides	WHP	Mobility	Treated area from total surveyed area
1	Chlorpyriphos-Ethyl	9.17	Low	86.4%
2	Metamitron	6.72	Medium	81%
3	Lenacil	1.42	High	62.04%
4	Ethofumesate	1.13	High	99.69%
5	Phenmedipham	0.67	Low	90.09%
6	Tefluthrine	0.64	Low	18.4%
7	Desmedipham	0.47	Low	90.09%
8	Bifenthrine	0.36	Low	13.5%
9	Thiophanate-methyl	0.19	Low	23.13%
10	Epoxiconazole	0.15	Medium	29.4%
11	Indoxacarb	0.11	Low	38.63%
12	Clethodime	0.07	Low	69.51%
13	Haloxyfop-R-methyl	0.04	Low	69.84%
14	Cyproconazole	0.04	High	26%
15	Tetraconazole	0.04	Medium	13.43%
16	Propaquizafop	0.04	Medium	7.23%

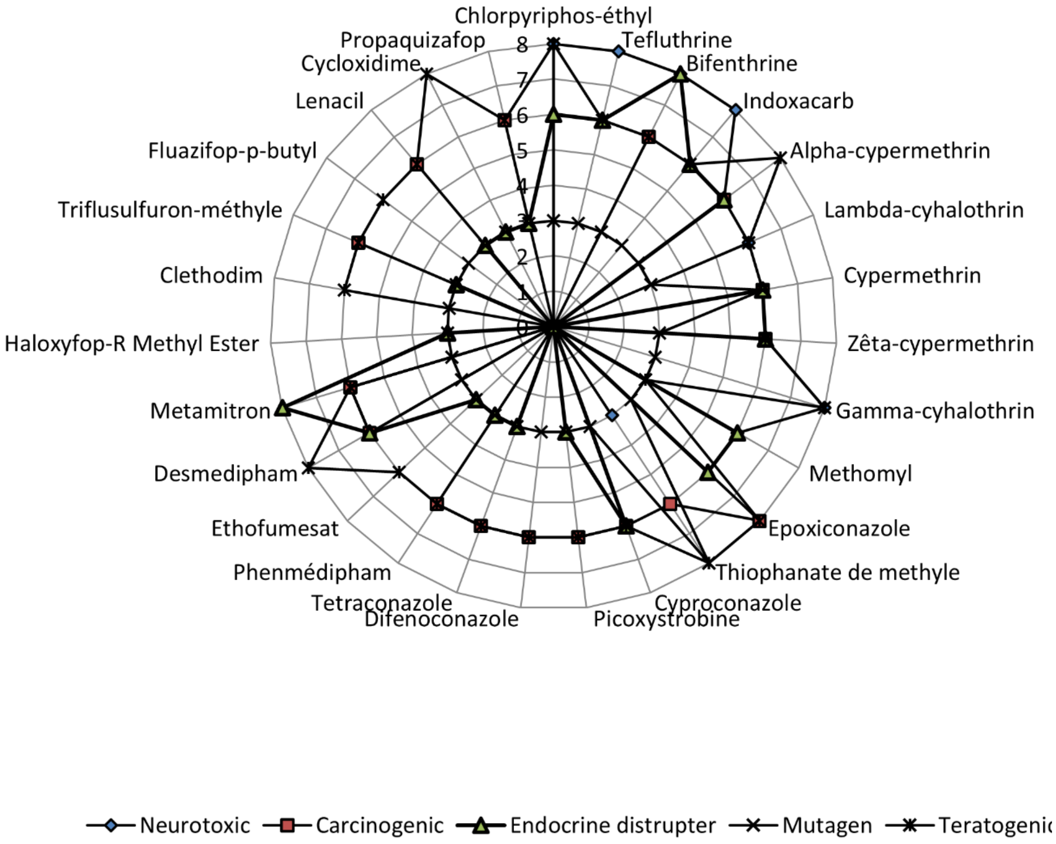

Fig. 1. Radial diagram of the scores for the five toxic effects used to rate each of the 28 pesticides in the initial pesticide list.

Weighted toxicity potential (WHP): This approach is also based on calculating the Weighted Hazard Potential (WHP), which is determined by combining the indices: QI, TP, HP, and EEP. It ranks pesticides according to their contribution to contamination, based on the total amount of all pesticides used (Q_{Total}). The pesticides with the highest weighted risk potential are chlorpyrifos-ethyl (WHP = 9.17), followed by metamitron (WHP = 6.72), lenacil (WHP = 1.42), ethofumesate (WHP = 1.13), phenmedipham (WHP = 0.67) and tefluthrin (WHP = 0.64), all of which are heavily used according to their QI indices.

Principal Component Analysis

A Principal Component Analysis is designed to convert the original variables, namely the four index scores: QI, TP, HP and WHP for each pesticide, into new variables called principal components (Figure 2). The program extracted two principal components that explain 85.33% of the total variance in the five original variables. The first component is strongly associated with the QI and WHP variables, while the second component combines the HP and TP variables. The principal components explain 69.6%, 97.8%, 78.3%, and 95.6% of the variance of the TP, QI, HP, and WHP variables, respectively. QI and WHP are very close to the x-axis representing the first component. These two variables are strongly associated with this component, which explains 53.23% of the variation. On the other hand, the TP and HP variables are close to the y-axis and are therefore strongly associated with the second component, which explains an additional 32% of the variation.

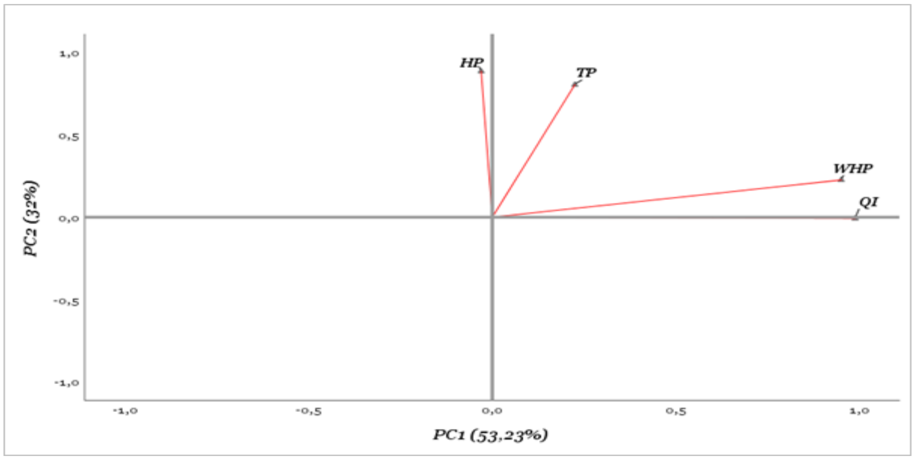

Fig. 2. Principal components.

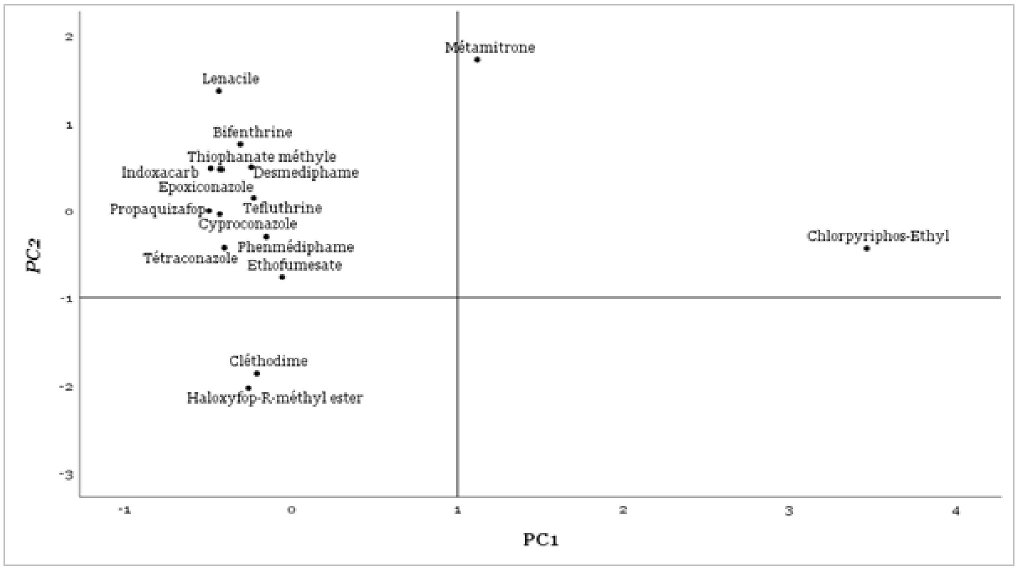

Fig. 3. Distribution of pesticides relative to the two principal components.

mobility (EEP=4), namely indoxacarb, lenacil, ethofumesate and cyproconazole; those with moderate mobility (EEP=2), such as metamitron and propaquizafop; and the remaining pesticides on the list are characterized by low mobility (EEP=1).

Hazard potential (HP): The hazard potential of the pesticides on the initial list is assessed using the HP index. This index takes into account both the toxicity of the pesticide to humans and its mobility potential, measured by its EEP index. Lenacil (HP=52) followed by metamitron (HP=44) are the pesticides with the highest risk. These results indicate that the HP index is strongly influenced by the TP index.

The QI and WHP indices are positively correlated, with their arrows pointing in the same direction. This indicates that the pesticides used the most often have a high WHP index (Figure 3). Therefore, the pesticides plotted to the right of the graph, in the direction of the QI and WHP arrows, are characterized by high use (chlorpyrifos-ethyl has the highest use) and high WHP, compared to those plotted to the left, in the opposite direction of the arrows (clethodim, haloxyfop-R-methyl, epoxiconazole and indoxacarb), which have low use levels (Figure 3). Similarly, the arrows for TP and HP provide information on the toxicity and exposure potential of the pesticides, highlighting metamitron and lenacil as the most toxic, with medium to high exposure potential. The fact that these two arrows are so closely aligned indicates a strong correlation between the TP and HP indices of the pesticides. In general, high toxicity and high exposure potential are characteristic of the pesticides shown at the top of the graph of figure 3. There are some pesticides that have both high toxicity and high use, such as metamitron.

Discussion

The pesticide ranking approach presented in this study to classify pesticides likely to pollute groundwater and surface water in the IPT area is based on the QI, TP, HP, EEP and WHP indices. It is a modified version of the approach presented by (Dabrowski et al. 2014), with a specific focus on sugar beet cultivation. According to this approach, the quantity applied is a key factor for including pesticides in the prioritized list. All the data on the use of pesticides were obtained from a survey carried out among 148 sugar beet growers in the rural commune of Sidi Jaber.

The mobility potential of these pesticides (estimated using their EEP index) and their toxic effects (estimated using their TP) were combined in the calculation of the hazard potential (HP) to estimate the risk of the exposure to these pesticides through the consumption of contaminated water. In this study, the WHP index ranks pesticides based on their individual contribution to the contamination generated by the total number of pesticides applied to sugar beet in the study area. Using PCA, this index showed a positive correlation with the QI index, as well as a positive correlation between the TP and HP indices. The approach resulted in a final list of 16 priority pesticides, from an initial list of 28, to monitor the water resources in sugar beet expanding areas in the irrigated perimeter of Tadla. The representativeness of the area treated with sugar beet by most of these pesticides is significant, making them prime candidates for water monitoring in the irrigated perimeter of Tadla. These pesticides have been detected in various compartments such as soil (Cuevas et al. 2008; Tata et al. 2016; Cheng et al. 2023), surface water and groundwater (Pennington et al. 2014; Gula et al. 2015; Lefrancq et al. 2017; Đurović et al. 2018; Saraiva et al. 2018; Park et al. 2020; Hall and Anderson 2020; Wang et al. 2021), and plant matrices (Zhou et al. 2021; Cheng et al. 2024) within agricultural ecosystems. This distribution within the ecosystem, in combination with their toxicity to humans and living organisms, highlights the importance of monitoring these priority pesticides in both surface and groundwater in sugar beet expansion areas within the Tadla irrigated perimeter.

Pesticide residue monitoring provides information on groundwater and surface water contamination levels (Baran et al. 2021). Some of the pesticides on the priority list have been detected in both groundwater and surface water, such as chlorpyrifos, metamitron and haloxyfop-R-methyl. This indicates their potential to reach these resources in the IPT area through leaching or run-off. Chlorpyrifos remains the most widely used pesticide according to its QI. Studies in India have shown that it can leach into groundwater, especially when applied at high doses (Gula et al. 2015). It has also been found in rivers and lakes, and even in soil and sediments in some studies (Postigo and Barceló 2015; John and Shaike 2015; Huang et al. 2020; Ambreen and Yasmin 2021). Metamitron is often found in both surface and groundwater. This is due to its high solubility in water (1.70 g/L) and low sorption to soil particles (Đurović et al. 2018; Wang et al. 2021). Tetraconazole is active against a wide range of pathogens and its residues are also frequently found in surface waters, especially in areas where agriculture is practiced (Lefrancq et al. 2017). Its concentrations may be at peak levels during rainfall events due to run-off (Alam et al. 2013). Haloxyfop R-methyl has a half-life of a few hours and is rapidly hydrolysed in soil to haloxyfop acid (Poiger et al. 2015). However, it has been reported to occur in groundwater (Park et al. 2020). Other pesticides, such as bifenthrin and tefluthrin, do not migrate to groundwater. However, they have often been found in surface water due to agricultural run-off and weather events (Hall and Anderson, 2020; Wang et al., 2022; Pennington et al., 2014). Cyproconazole, a very mobile triazole fungicide according to the EEP index, which is often used for the control of wheat diseases such as rust and powdery mildew (Bajya et al. 2015), has been detected in surface waters with concentrations up to 49.05 µg/L (Saraiva et al. 2018). Other pesticides, such as lenacil, indoxacarb and propaquizafop, are not clearly detectable in surface water or groundwater, limiting their risk of contaminating these water reservoirs (Cuevas et al. 2008; Cheng et al. 2023). However, their detection in the surface layers of soils and their properties suggest that they may migrate and affect aquatic ecosystems. Lenacil, for example, which is highly mobile according to the EEP index, is known for its persistence in the soil and has a lower sorption and a higher sorption reversibility, which leads to its detection in larger quantities and at greater depths in the soil profile (Cuevas et al. 2008). The detection of these pesticides in surface water, groundwater and even in the soil raises crucial questions about their impact on the environment and health, and requires regular monitoring in areas where sugar beet cultivation is expanding within the irrigated perimeter of Tadla.

Pesticides have a detrimental effect on the health of humans (Kalyabina et al. 2021). Chlorpyrifos is one of the least toxic pesticides on the priority list. However, it has been confirmed to cause health complications such as neurological dysfunction, endocrine disruption, cardiovascular disease, developmental toxicity and immunotoxicity (Ubaid ur Rahman et al. 2021; Al-Janabi and Hashim 2021). Bifenthrin may cause sublethal toxic effects such as neurobehavioural toxicity, oxidative damage, immunotoxicity and endocrine disruption (Yang et al. 2018; Ullah et al. 2022; Sung et al. 2023). Tefluthrin is considered to be endocrine disrupting (Wu et al. 2009). It has also been shown that exposure to tefluthrin causes nerve damage leading to deficits in learning and memory, spatial exploration and autonomic motor functions in rats (Wang et al. 2023). Methyl-thiophanate is a suspected carcinogen. It has been shown to induce oxidative stress, DNA damage and mitochondrial dysfunction in human cells (Liu et al. 2021). Finally, there have been reports of epoxiconazole poisoning in humans, the most common manifestation of which is methaemoglobinaemia (Wu et al. 2010). Although this information on the toxicity of pesticides is very specific to only a few pesticides and not to all pesticides on the priority list, it helps to inform about the potential risks of these pollutants and therefore the need to monitor them to prevent their adverse effects on health.

The present approach to pesticide prioritization is based on simple data to generate a priority list of pesticides. This list should be dynamic and reflect the quantities of pesticides used in each agricultural campaign. One limitation in keeping the list up to date is the unavailability of such data on an annual basis. However, this approach remains useful. It provides a simple means of assessing the environmental impact of pesticides and ranking them in relation to each other. By prioritizing the top 10 pesticides in each of the five indices used in this approach, we were able to reduce the number of chemicals from the initial list reported in the study to 16 high-priority pesticides. Although the information on the occurrence of these pesticides in different compartments of the agroecosystem is limited, it provides a partial insight into the fate of these chemicals in the agroecosystem and their toxicity helps us to understand their impact on human health and environmental quality. This underlines the need to monitor them in surface and groundwater within the sugar beet extension areas of the IPT. The hazardous nature of some of these priority list pesticides, such as chlorpyrifos, cyproconazole, ethofumesate, methyl-thiophanate, epoxiconazole and tetraconazole, is further confirmed by their permanent withdrawal from the market in several countries, including Morocco. Due to their proven toxicity, these pesticides require continuous monitoring in all compartments of the agro-ecosystem. In particular, surface and groundwater in the Tadla irrigation area should be monitored.

Materials and methods

Description of the study area and sampling sites

The study was conducted in the irrigated perimeter of Tadla (Figure 4). The soil in the region is generally fertile and consists of subtropical brown and chestnut soils (83% of the plain's surface). The region's climate is semi-arid to arid, with an average annual precipitation of 373.8 mm and temperature varying from 3.32 °C to 24.86 °C (Ouhajjou et al. 2024). The region is generally an agricultural zone with high production of crops such as cereals, olives, citrus and sugar beet. The region, located in the Oum Erbia basin, suffered for several years from a severe period of drought and irregular precipitation, which decreased the water reserves of the main dams in the region (Bin El Ouidan and Ahmed El Hansali). This severely affects the cultivated area of sugar beet in the region, being reduced from 10,000 ha during 2020-2021 to 1000 ha during 2021-2022 (MARDMF, 2020).

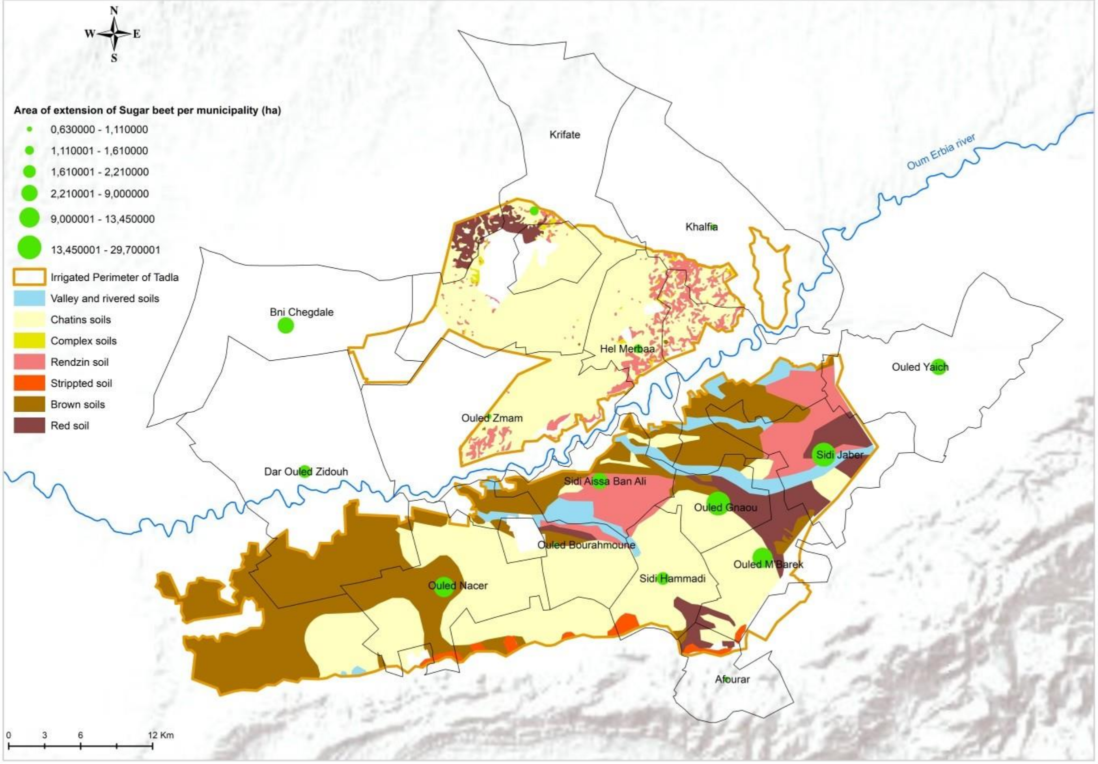

Fig. 4. Area of extension of sugar beet crop in the irrigated perimeter of Tadla.

This study was conducted in the province of Beni Mellal, municipality of Sidi Jaber. The approach for prioritizing pesticides adopted in this study is based on data related to the use of pesticides in the studied locality, in addition to data on the properties of these pesticides, in particular their physicochemical properties and their toxicological effects such as carcinogenicity, endocrine disruption, neurotoxicity, teratogenicity and immunotoxicity. The data on the use of pesticides were obtained from the results of a previous survey (Ouhajjou et al. 2024). The survey involved 148 farmers, who covered 92.5 % of the cultivated area (333 ha) of sugar beet in the municipality of Sidi Jaber during the 2020 – 2021 agricultural campaign. The farmers, selected on the basis of their willingness to participate and their experience in growing sugar beet, were asked about the types and amounts of pesticides used from sowing to harvest. The results are summarized in Table 3. Specifically, each pesticide from the survey is presented in terms of the total amount applied, the area treated with the pesticide, and the percentage of this area relative to the total area of 333 hectares of sugar beet farms included in the survey.

Pesticide properties were obtained from the database maintained by the Agriculture and Environment Research Unit at the University of Hertfordshire (PPDB, 2023).

Table 3. Initial list of pesticides reported by sugar beet growers surveyed at Sidi Jaber rural community, along with the area treated by the active substance and the percentage of this area relative to the total surveyed area.

N°	Pesticides	Area Treated (ha)	Treated area from total surveyed area
1	Chlorpyriphos-ethyl	287.7	86.4%
2	Tefluthrine	61.2	18.4%
3	Bifenthrine	44.95	13.5%
4	Metamitron	270.08	81%
5	Ethofumesat	332	99.69%
6	Phenmedipham	300	90.09%
7	Clethodime	231.05	69.51%
8	Desmedipham	300	90.09%
9	Haloxyfop-R Methyl Ester	232.6	69.84%
10	Lambda-cyhalothrin	190.6	57.08%
11	Cypermethrin	110.7	33.24%
12	Fluazifop-p-butyl	58.95	17.70%
13	Epoxiconazole	98.05	29.4%
14	Difenoconazole	74.2	2.22%
15	Lenacil	206.6	62.04%
16	Indoxacarb	128.65	38.63%
17	Methomyl	14.8	4.44%
18	Tetraconazole	44.75	13.43%
19	Picoxystrobine	86.45	26%
20	Cycloxidime	27.6	8.28%
21	Propaquizafop	24.1	7.23%
22	Gamma-cyhalothrin	46	13.81%
23	Alpha-cypermethrin	77	23.12%
24	Cyproconazole	86.45	26%
25	Zeta-cypermethrin	25.2	7.6%
26	Triflusulfuron-methyl	213.3	64.05%
27	Thiophanate-méthyl	77.05	23.13%
28	Abamectin	39.9	11.98%

Indexing approach for prioritization of pesticides used in sugar beet cultivation

The prioritization approach used in this study ranks pesticides according to their amount of use, mobility, and of their toxicity to human health, by calculating five indices (Dabrowski et al. 2014): Quantity index (QI), Environmental exposure potential of pesticide (EEP), Toxicity potential (TP), Hazard potential (HP) and Weighted hazard potential (WHP) specific to each pesticide. Each index ranks pesticides separately from other indices and generates a separate list of pesticides except for the Environmental exposure potential of pesticide. The first 10 pesticides from each list of the four indices (QI, TP, HP, and WHP) are aggregated to generate a final prioritized list of pesticides for the sugar beet crop in IPT.

Quantity index (QI): All the pesticides obtained from the survey results were kept as an initial list for the prioritization of pesticides. The method used in this work considers all pesticides reported in the survey of sugar beet growers. It does not make an initial selection based on quantities used. Although the quantity applied is an important factor in prioritizing pesticides, it is important to consider their toxicity, which, even when used in small quantities, can have irreversibly damaging effects on human health and biodiversity. The initial list consists of 28 pesticides which have been applied in a total quantity of 1585.914 kg (Ouhajjou et al. 2024). The quantity index of each pesticide corresponds to the amount used of that pesticide applied as reported in the survey.

Toxicity potential (TP): Five toxic effects were used to score each pesticide (endocrine disrupting potential, carcinogenicity, developmental toxicity, neurotoxicity, and mutagenicity). Each toxic effect was categorized into one of four different endpoint categories, namely 'Yes' (there is definitive evidence that the chemical causes the toxic effect), 'Possible' (the chemical may cause the toxic effect), 'No data' (no studies have been conducted to confirm whether or not the pesticide causes the toxic effect) and 'No' (there is definitive evidence that the chemical does not cause the toxic effect). Data for each toxic effect were obtained from the Plant Protection Database (PPBD) performed by the Agriculture and Environment Research Unit (AERU) at the University of Hertfordshire (PPDB, 2023). The scores for each toxic effect were weighted according to an adapted scoring system modified from that developed by (Dabrowski et al. 2014). Scores for each of the toxic effects (carcinogenicity, developmental toxicity, mutagenicity, neurotoxicity, and endocrine disruption), were weighted equally, with scores of 8, 6, 3, and 0 beings respectively attributed to the answers 'Yes', 'Possible', 'No data' and 'No'.

Effects for which no data were available were assigned a higher value than for those for which there was absolutely no effect as a precautionary measure. The score was lower than that given for a possible effect because it is assumed that there is a higher probability that more serious effects have been identified. For all toxic effects, a value of zero was assigned when the literature reported no effects. The TP was obtained by adding the scores assigned to each of the five toxic effects for each pesticide, except for abamectin, a pesticide that was not found in the database.

Environmental exposure potential (EEP): The approach used in this work is based on the GUS index to assess the mobility of the substance to groundwater. In (Dabrowski et al. 2014), a system for annotating the GUS index (Table 4) was developed to generate the EEP for all pesticides included in the initial list.

Table 4. GUS mobility score annotation system for calculating the environmental exposure potential of pesticides in the initial list.

Environmental exposure potential	GUS Score	Assigned value
High	GUS > 2.8	4
Medium	2.8 > GUS > 1.8	2
Low	GUS < 1.8	1
No data	No K_{OC} or DT_{50} value	1.5

Hazard potential (HP): The HP calculates the hazard rating of pesticides on the initial list. The HP is the product of two indices according to the formula (1):

HP= TP * EEP (1)

Where TP is the toxicity potential of the pesticide and EEP representing the environmental exposure potential of the pesticide.

Weighted toxicity potential (WHP): The approach is based on the use of a so-called WHP index which is calculated according to the formula (2):

$WHP = HP * QI/Q_{Total}$ (2)

Where HP is hazard potential, QI represents the quantity index of pesticides, and Q_{Total} represents the total quantity of all pesticides used, as reported by the survey (1585.914 kg).

Principal Component Analysis

To highlight the indices that contributed to the inclusion of pesticides in the priority list, as well as the correlations that exist between the indices selected for the prioritization of pesticides, a principal components analysis was performed using the SPSS statistical software.

Conclusion

The pesticide prioritization approach adopted in this study focused on pesticide use data from a 333ha sugar beet area, together with physico-chemical and toxicity data, to produce a list of 16 priority pesticides. This list will be of great use in the establishment of a groundwater and surface water monitoring program in the Tadla area, particularly in the sugar beet expansion zone. It will be possible to identify other pesticides that have an environmental impact on water resources and are harmful to the rural population of the perimeter by having data on pesticide use throughout the sugar beet growing area of the Tadla irrigated perimeter. Prioritizing pesticides for water monitoring program could also be improved by focusing on classifying pesticides used on other characteristic crops in the perimeter, such as citrus, to identify the highest priority pesticides for each dominant crop. A comparison of the environmental impact of the crops within the perimeter would also be beneficial in order to encourage the development of more environmentally friendly control practices. However, accessing data on pesticides used is a major constraint to implementing this approach. The annual collection of plant protection product use data for the different crops in the catchment area would enable the development of a comprehensive list of priority plant protection products for the IPT, which would greatly assist in the development of a groundwater monitoring program in the Tadla perimeter.

Acknowledgment

The authors would like to express their sincere gratitude to their respective universities for providing the knowledge and expertise that have been invaluable to the development of this work.

Ethical statement: In the case of this study no permits or approvals were required

Funding: The present research did not receive any financial support.

Statement of Contributions: Majda Ouhajjou: Conceptualization and investigation process, Methodology, Validation, Writing-Review and Editing; Mohamed Edahbi: Conceptualization and investigation process, Writing-Review and Editing; Taoufik El

Rasafi: Methodology, Validation, Writing-Review and Editing; Hanaa Hachimi: Writing-Review and Editing; Abdelmajid Haddioui: Validation, Writing-Review and Editing.

Conflict of interest: The authors declare that there is not any conflict of interests regarding the publication of this manuscript.

References

Alam S, Sengupta D, Kole RK, Bhattacharyya A (2013) Dissipation kinetics of tetraconazole in three types of soil and water under laboratory condition. Environ Monit Assess 185:9819–9824. https://doi.org/10.1007/s10661-013-3294-0

Al-Janabi AOH, Hashim HS (2021) Efficiency of Pseudomonas putida in bioremediation of chlorpyrifos toxicity. IOP Conf Ser: Earth Environ Sci 722:012040. https://doi.org/10.1088/1755-1315/722/1/012040

Ambreen S, Yasmin A (2021) Novel degradation pathways for Chlorpyrifos and 3, 5, 6-Trichloro-2-pyridinol degradation by bacterial strain *Bacillus thuringiensis* MB497 isolated from agricultural fields of Mianwali, Pakistan. Pesticide Biochemistry and Physiology 172:104750. https://doi.org/10.1016/j.pestbp.2020.104750

An R, Li B, Zhong S, et al (2023) Distribution, source identification, and health risk of emerging organic contaminants in groundwater of Xiong'an New Area, Northern China. Science of The Total Environment 893:164786. https://doi.org/10.1016/j.scitotenv.2023.164786

Baite W, Boukdir A, Baite M (2021) Integrated management of irrigation water in the irrigated perimeter of Tadla (Morocco) and involvement of farmers in the aquifer contract. AIP Conference Proceedings 2345:020043. https://doi.org/10.1063/5.0049663

Bajya D, Chilana P, Lakharan MC (2015) Evaluation and dose standardization of newly combination fungicide Amistar Xtra 280 SC (Azoxystrobin 18.2% + Cyproconazole 7.3%) for control of wheat diseases. 39:50–54

Baran N, Surdyk N, Auterives C (2021) Pesticides in groundwater at a national scale (France): Impact of regulations, molecular properties, uses, hydrogeology and climatic conditions. Science of The Total Environment 791:148137. https://doi.org/10.1016/j.scitotenv.2021.148137

Bjergager MBA, Dalhoff K, Kretschmann A, et al (2017) Determining lower threshold concentrations for synergistic effects. Aquatic Toxicology 182:79–90. https://doi.org/10.1016/j.aquatox.2016.10.020

Bongiovanni R, Lowenberg-Deboer J (2004) Precision Agriculture and Sustainability. Precision Agriculture 5:359–387. https://doi.org/10.1023/B:PRAG.0000040806.39604.aa

Cedergreen N (2014) Quantifying Synergy: A Systematic Review of Mixture Toxicity Studies within Environmental Toxicology. PLOS ONE 9:e96580. https://doi.org/10.1371/journal.pone.0096580

Cheng Z, Gao H, Xiong Y, et al (2024a) Dissipation behaviours, residues, and health risk of six herbicides in sugar beets under field conditions. Ecotoxicology and Environmental Safety 274:116199. https://doi.org/10.1016/j.ecoenv.2024.116199

Cheng Z, Hou Z, Han H, et al (2023) Adsorption, mobility, and degradation of the pesticide propaquizafop in five agricultural soils in China. Sci Rep 13:5814. https://doi.org/10.1038/s41598-023-32771-6

Cheng Z, Xiong Y, Ma T, et al (2024b) Dissipation and Risk Assessment of Propaquizafop in Ginseng under Field Conditions. J Agric Food Chem 72:6613–6624. https://doi.org/10.1021/acs.jafc.3c07832

Cuevas MV, Cox L, Calderón MJ, et al (2008) Chloridazon and lenacil dissipation in a clayey soil of the Guadalquivir river marshes (southwest Spain). Agriculture, Ecosystems & Environment 124:245–251. https://doi.org/10.1016/j.agee.2007.10.003

Dabrowski JM, Shadung JM, Wepener V (2014) Prioritizing agricultural pesticides used in South Africa based on their environmental mobility and potential human health effects. Environment International 62:31–40. https://doi.org/10.1016/j.envint.2013.10.001

Dcunha R, Kumari S, Najar MA, et al (2023) High doses of clethodim-based herbicide GrassOut Max poses reproductive hazard by affecting male reproductive function and early embryogenesis in Swiss albino mice. Chemosphere 336:139215. https://doi.org/10.1016/j.chemosphere.2023.139215

de Graaf L, Boulanger M, Bureau M, et al (2022) Occupational pesticide exposure, cancer and chronic neurological disorders: A systematic review of epidemiological studies in greenspace workers. Environmental Research 203:111822. https://doi.org/10.1016/j.envres.2021.111822

Đurović A, Stojanović Z, Kravić S, et al (2018) Novel electrochemical procedure for the determination of metamitron. International Journal of Environmental Analytical Chemistry 98:369–385. https://doi.org/10.1080/03067319.2018.1469625

Farha W, Abd El-Aty AM, Rahman MdM, et al (2016) An overview on common aspects influencing the dissipation pattern of pesticides: a review. Environ Monit Assess 188:693. https://doi.org/10.1007/s10661-016-5709-1

Guilpart N, Bertin I, Valantin-Morison M, Barbu CM (2022) How much agricultural land is there close to residential areas? An assessment at the national scale in France. Building and Environment 226:109662. https://doi.org/10.1016/j.buildenv.2022.109662

Gula K, Thakur S, Kumar A, et al (2015) A Lysimeter Study to Access the Risk of Chlorpyrifos Con- taminated Groundwater in a Sandy Loam Soil With Differ- ent pH. 352:15–35

Hall LW, Anderson RD (2020) An Eighteen Year Temporal Trends Analysis of Bifenthrin Sediment Concentrations in California Waterbodies. Water 12:2402. https://doi.org/10.3390/w12092402

Huang L, Guo X, Liu P, et al (2022) Correlation between acute brain injury and brain metabonomics in dichlorvos-poisoned broilers. Journal of Hazardous Materials 422:126849. https://doi.org/10.1016/j.jhazmat.2021.126849

Huang P, Liu SS, Wang ZJ, et al (2023) Study on the characterization of pesticide modes of action similarity and the multi-endpoint combined toxicity of pesticide mixtures to Caenorhabditis elegans. Science of The Total Environment 893:164918. https://doi.org/10.1016/j.scitotenv.2023.164918

Huang X, Cui H, Duan W (2020) Ecotoxicity of chlorpyrifos to aquatic organisms: A review. Ecotoxicology and Environmental Safety 200:110731. https://doi.org/10.1016/j.ecoenv.2020.110731

John EM, Shaike JM (2015) Chlorpyrifos: pollution and remediation. Environ Chem Lett 13:269–291. https://doi.org/10.1007/s10311-015-0513-7

Joseph N, Propper CR, Goebel M, et al (2022) Investigation of Relationships Between the Geospatial Distribution of Cancer Incidence and Estimated Pesticide Use in the U.S. West. GeoHealth 6:e2021GH000544. https://doi.org/10.1029/2021GH000544

Kalyabina VP, Esimbekova EN, Kopylova KV, Kratasyuk VA (2021) Pesticides: formulants, distribution pathways and effects on human health – a review. Toxicology Reports 8:1179–1192. https://doi.org/10.1016/j.toxrep.2021.06.004

Kim D-H, Ait Bamai Y, Belova L, et al (2023) Human exposure to persistent and mobile chemicals: A review of sources, internal levels and health implications. Science of The Total Environment 893:164764. https://doi.org/10.1016/j.scitotenv.2023.164764

Kolakowski BM, Miller L, Murray A, et al (2020) Analysis of Glyphosate Residues in Foods from the Canadian Retail Markets between 2015 and 2017. J Agric Food Chem 68:5201–5211. https://doi.org/10.1021/acs.jafc.9b07819

Lefrancq M, Jadas-Hécart A, La Jeunesse I, et al (2017) High frequency monitoring of pesticides in runoff water to improve understanding of their transport and environmental impacts. Science of The Total Environment 587–588:75–86. https://doi.org/10.1016/j.scitotenv.2017.02.022

Liu Y, Yu J, Sun H, et al (2022) Screening and prioritizing substances in groundwater in the Beijing–Tianjin–Hebei region of the North China Plain based on exposure and hazard assessments. Journal of Hazardous Materials 423:127142. https://doi.org/10.1016/j.jhazmat.2021.127142

Liu Z, Chen Y, Han J, et al (2021) Determination, dissipation dynamics, terminal residues and dietary risk assessment of thiophanate-methyl and its metabolite carbendazim in cowpeas collected from different locations in China under field conditions. Journal of the Science of Food and Agriculture 101:5498–5507. https://doi.org/10.1002/jsfa.11198

MARDMF. 2020. Monographie de la région Béni Mellal - Khénifra. Béni Mellal: Regional Directorate of Agriculture, Ministry of Agriculture, Rural Development and Maritime Fisheries

Mu H, Yang X, Wang K, et al (2023) Ecological risk assessment of pesticides on soil biota: An integrated field-modelling approach. Chemosphere 326:138428. https://doi.org/10.1016/j.chemosphere.2023.138428

Narita K, Matsui Y, Iwao K, et al (2014) Selecting pesticides for inclusion in drinking water quality guidelines on the basis of detection probability and ranking. Environment International 63:114–120. https://doi.org/10.1016/j.envint.2013.10.019

Narita K, Matsui Y, Matsushita T, Shirasaki N (2021) Selection of priority pesticides in Japanese drinking water quality regulation: Validity, limitations, and evolution of a risk prediction method. Science of The Total Environment 751:141636. https://doi.org/10.1016/j.scitotenv.2020.141636

Ojo AF, Peng C, Ng JC (2020) Combined effects and toxicological interactions of perfluoroalkyl and polyfluoroalkyl substances mixtures in human liver cells (HepG2). Environmental Pollution 263:114182. https://doi.org/10.1016/j.envpol.2020.114182

Örtl E (2019) Protecting the sources of our drinking water: The criteria for identifying persistent, mobile and toxic (PMT) substances and very persistent and very mobile (vPvM) substances under EU Regulation REACH (EC) No 1907/2006. Umweltbundesamt

Ouhajjou M, Bouazzama B, Edahbi M, Hachimi H (2024) Diagnosis of agrochemical inputs in sugar beet (Beta vulgaris L.) fields in the irrigated perimeter of Tadla, Morocco. Mediterranean Journal of Chemistry 14:20–32. https://doi.org/10.13171/mjc02401171756ouhajjou

Park S, Lee JY, Park H, et al (2020) Haloxyfop-*P*-methyl induces developmental defects in zebrafish embryos through oxidative stress and anti-vasculogenesis. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 233:108761. https://doi.org/10.1016/j.cbpc.2020.108761

Pennington PL, Harper-Laux H, Sapozhnikova Y, Fulton MH (2014) Environmental effects and fate of the insecticide bifenthrin in a salt-marsh mesocosm. Chemosphere 112:18–25. https://doi.org/10.1016/j.chemosphere.2014.03.047

Poiger T, Müller MD, Buser HR, Buerge IJ (2015) Environmental Behavior of the Chiral Herbicide Haloxyfop. 1. Rapid and Preferential Interconversion of the Enantiomers in Soil. J Agric Food Chem 63:2583–2590. https://doi.org/10.1021/jf505241t

Postigo C, Barceló D (2015) Synthetic organic compounds and their transformation products in groundwater: Occurrence, fate and mitigation. Science of The Total Environment 503–504:32–47. https://doi.org/10.1016/j.scitotenv.2014.06.019

Rasool S, Rasool T, Gani KM (2022) A review of interactions of pesticides within various interfaces of intrinsic and organic residue amended soil environment. Chemical Engineering Journal Advances 11:100301. https://doi.org/10.1016/j.ceja.2022.100301

Reichenberger S, Bach M, Skitschak A, Frede H-G (2007) Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; A review. Science of The Total Environment 384:1–35. https://doi.org/10.1016/j.scitotenv.2007.04.046

Saraiva AS, Sarmento RA, Golovko O, et al (2018) Lethal and sub-lethal effects of cyproconazole on freshwater organisms: a case study with Chironomus riparius and Dugesia tigrina. Environ Sci Pollut Res 25:12169–12176. https://doi.org/10.1007/s11356-017-1180-y

Singh A, Dhiman N, Kar AK, et al (2020) Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. Journal of Hazardous Materials 385:121525. https://doi.org/10.1016/j.jhazmat.2019.121525

Spomer N, Ramble ST, Coffelt M, Scherer C (2011) Movement of Chlorantraniliprole and Indoxacarb Termiticides in Sandy Loam and Silty Clay Loam Soil Columns Used Against Subterranean Termites (Isoptera: Rhinotermitidae). Sociobiology 57:201–213

Sung E, Park J, Lee H, et al (2023) Bifenthrin induces cell death in bovine mammary epithelial cells via ROS generation, calcium ion homeostasis disruption, and MAPK signaling cascade alteration. Pesticide Biochemistry and Physiology 196:105637. https://doi.org/10.1016/j.pestbp.2023.105637

Tata R, Madhavi M, Maddela Y (2016) Dissipation and Persistence of Propaquizafop in Soil, Plant and Rhizomes in Turmeric and its Effect on Soil Properties. 15:

Tudi M, Daniel Ruan H, Wang L, et al (2021) Agriculture Development, Pesticide Application and Its Impact on the Environment. International Journal of Environmental Research and Public Health 18:1112. https://doi.org/10.3390/ijerph18031112

Ubaid ur Rahman H, Asghar W, Nazir W, et al (2021) A comprehensive review on chlorpyrifos toxicity with special reference to endocrine disruption: Evidence of mechanisms, exposures and mitigation strategies. Science of The Total Environment 755:142649. https://doi.org/10.1016/j.scitotenv.2020.142649

Ullah S, Ahmad S, Altaf Y, et al (2022) Bifenthrin induced toxicity in *Ctenopharyngodon idella* at an acute concentration: A multi-biomarkers based study. Journal of King Saud University - Science 34:101752. https://doi.org/10.1016/j.jksus.2021.101752

Valcke M, Chaverri F, Monge P, et al (2005) Pesticide prioritization for a case–control study on childhood leukemia in Costa Rica: a simple stepwise approach. Environmental Research 97:335–347. https://doi.org/10.1016/j.envres.2004.05.011

Vryzas Z (2018) Pesticide fate in soil-sediment-water environment in relation to contamination preventing actions. Current Opinion in Environmental Science & Health 4:5–9. https://doi.org/10.1016/j.coesh.2018.03.001

Vullo AI, Vullo DL, Basack SB (2023) Assessment of intensive periurban agriculture soil quality applying biomarkers in earthworms. Journal of Environmental Management 344:118535. https://doi.org/10.1016/j.jenvman.2023.118535

Wang H, Xu W, Li L (2023) Tefluthrin induced toxicities in zebrafish: Focusing on enantioselectivity. Pesticide Biochemistry and Physiology 195:105572. https://doi.org/10.1016/j.pestbp.2023.105572

Wang S, Miltner A, Muskus AM, Nowak KM (2021) Microbial activity and metamitron degrading microbial communities differ between soil and water-sediment systems. Journal of Hazardous Materials 408:124293. https://doi.org/10.1016/j.jhazmat.2020.124293

Wang Y, Ning X, Li G, Sang N (2022) New insights into potential estrogen agonistic activity of triazole fungicides and coupled metabolic disturbance. Journal of Hazardous Materials 424:127479. https://doi.org/10.1016/j.jhazmat.2021.127479

Wang Y, Teng M, Wang D, et al (2017) Enantioselective bioaccumulation following exposure of adult zebrafish (*Danio rerio*) to epoxiconazole and its effects on metabolomic profile as well as genes expression. Environmental Pollution 229:264–271. https://doi.org/10.1016/j.envpol.2017.05.087

Wu SN, Wu YH, Chen BS, et al (2009) Underlying mechanism of actions of tefluthrin, a pyrethroid insecticide, on voltage-gated ion currents and on action currents in pituitary tumor (GH3) cells and GnRH-secreting (GT1-7) neurons. Toxicology 258:70–77. https://doi.org/10.1016/j.tox.2009.01.009

Wu YJ, Lin YL, Huang HY, Hsu BG (2010) Methemoglobinemia induced by indoxacarb intoxication. Clinical Toxicology 48:766–767. https://doi.org/10.3109/15563650.2010.503657

Xiong G, Zou L, Deng Y, et al (2019) Clethodim exposure induces developmental immunotoxicity and neurobehavioral dysfunction in zebrafish embryos. Fish & Shellfish Immunology 86:549–558. https://doi.org/10.1016/j.fsi.2018.12.002

Yang Y, Wu N, Wang C (2018) Toxicity of the pyrethroid bifenthrin insecticide. Environ Chem Lett 16:1377–1391. https://doi.org/10.1007/s10311-018-0765-0

Yu Y, Yu Z, Xiang M, et al (2019) Screening and prioritization of chemical hazards for deriving human health ambient water quality criteria in China. Journal of Environmental Management 245:223–229. https://doi.org/10.1016/j.jenvman.2019.05.076

Zhou Q, Liu Z, Liu F, et al (2021) Determination of desmedipham residue in 21 foods by HPLC-MS/MS combined with a modified QuEChERS and mixed-mode SPE clean-up method. Journal of Food Composition and Analysis 102:104004. https://doi.org/10.1016/j.jfca.2021.104004

IUPAC PPDB Search. https://sitem.herts.ac.uk/aeru/iupac/search.htm. Accessed 9 June 2023

Australian Journal of Crop Science | 20(05):399-412 (2026)