Impact of the Use of Agricultural Phytosanitary Products on the Quality of Groundwater in the Feija South-East Zone of Morocco: Case of Pesticides

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***Abstract*—This study aims to assess the impact of phytosanitary products on the quality of surface and groundwater. The technique was established through an integrated methodology encompassing field analysis, water sampling, and surveys of agricultural producers and vendors. Laboratory analyses included the detection of pesticide residues (herbicides, fungicides, insecticides, and acaricides). This article describes a reliable and efficient analytical method for determining and detecting pesticides at 8 wells throughout 2022 to 2025, along with the scientific study of these wells. The researchers employed advanced statistical techniques to find out how pesticides affected the quality of water in the Feija area. The results showed that there were phytosanitary products in the water, such as fungicides, herbicides, acaricides, and insecticides. The results show the existence of a moderate relationship between pesticides and water quality; this relationship indicates that pesticides contribute to the degradation of water quality.**

***Keywords*—phytosanitary products, water resources, evaluation, protocol, sampling, heavy metals**

I. Introduction

Historically, agriculture relied on natural substances such as cattle and sheep manure to enrich soils [1]. Over time, agricultural practices have evolved with the introduction of poultry manure, sulfur-based treatments for foliar fungal diseases, and modern mechanized techniques for plowing, sowing, cultivation, and harvesting [2]. These developments, combined with the widespread use of irrigation and phytosanitary products, have significantly increased agricultural productivity. Phytosanitary products, commonly referred to as agricultural pesticides, are chemical substances used to protect crops from diseases and pests affecting roots, leaves, and stems [3]. They play a crucial role in ensuring the safety, regularity, and quality of agricultural production [4, 5]. A crop protection product typically contains one or more active molecules designed to protect plants against pests, inhibit their action, regulate plant growth processes, preserve harvested products, or eliminate weeds by hindering or stopping their growth. Despite their benefits, the intensive use of pesticides has raised growing concerns regarding environmental and public health impacts. Today, the use of pesticides is increasingly questioned in both agricultural systems and green spaces [6]. Several studies indicate that excessive and uncontrolled pesticide application can lead to soil degradation, contamination of surface and groundwater, and potential risks to human health. The present study aims to evaluate groundwater contamination by pesticides in the Feija Plain, located in southeastern Morocco, through a multiyear assessment combining field surveys and laboratory analyses. Farmers and retailers of phytosanitary products were interviewed to identify the most commonly used pesticides in the region, while groundwater samples from selected wells were analyzed to detect and quantify pesticide residues. This integrated approach allows for a better understanding of the relationship between agricultural practices and groundwater quality in the Feija area.

II. Literature Review

When it comes to chemicals used in agriculture, there are different types of nomenclature. The term “phytosanitary product” is the most frequently used in the scientific literature, followed by the terms “pharmacological product” and “pesticide” in everyday language. The use of chemicals plays a crucial role in enhancing agricultural productivity. Fertilizers, herbicides, insecticides, and fungicides are widely used, with the last 3 generally grouped under the generic term “pesticides” or “phytosanitary products” [6, 7].

Certain crops are exposed to diseases caused by microorganisms such as fungi, bacteria, or insects, which can degrade plant health and reduce yields. To protect crops, insecticides are used to eliminate harmful insects (for example, aphids), fungicides are applied to combat fungal diseases, and herbicides are used to control weeds. All these products are considered phytosanitary products [8]. Pesticides are small molecules composed of an active and toxic component and a secondary component that ensures the stability of the product [9].

Farmers use phytosanitary chemicals to protect crops and promote their growth, enabling them to generate greater revenue per hectare and meet the growing food demand of the population [10]. The absence of pesticides can lead to a significant reduction in yields due to pathogenic aggressions to which crops may be exposed, thereby negatively affecting farmers’ income. Although phytosanitary products are used unevenly worldwide, they reduce crop losses caused by pests by nearly half. As a result, agriculture can achieve up to 70% of its potential yields with plant protection products, compared with only 40% if no products are used [10]

Plant protection products are known to impact the environment, food quality, and potentially human well-being. In recent years, pesticides have been increasingly criticized for their effects on environmental health and food safety. Several risks have been identified, particularly regarding human health. Research indicates that certain illnesses are associated with excessive exposure to pesticides. These substances accumulate in plant and animal products intended for consumption, drinking water, and even in the air, representing a significant public health concern. Some active molecules have been identified as mutagenic, carcinogenic, and endocrine-disrupting [11].

Although chemicals are applied to eradicate weeds, fungi, or insect pests, they do not remain confined to their intended targets. There are also socioeconomic and political challenges associated with the use or non-use of plant protection products. Regulated agriculture aims to produce goods and services that meet societal needs while minimizing risks. The dangers are not limited to immediate damage but also include long-term environmental perturbations and a widespread loss of public confidence in the safety of phytosanitary products [12]. Conceptual analysis of pesticide use: the term “pesticide” is a generic expression derived from the Latin words caedere (to kill) and pestis (plague). According to the European Commission, pesticides are products used in agriculture to destroy, prevent, or control organisms that are harmful to plants or agricultural commodities.

After harvesting, crop protection products may also be applied to agricultural products to enhance their preservation over extended periods, particularly during storage and transportation, such as for cereals. Several categories of pesticides can be distinguished based on their target organisms. Herbicides, sometimes referred to as “weed killers”, are active ingredients designed to eliminate unwanted vegetation. Fungicides protect crops against pathogenic fungi, while insecticides target insect pests, their larvae, and eggs. These products act through one or more active molecules that interfere with the metabolism of pests or plants to cause their elimination [13].

Some pesticides are highly selective, targeting only specific species or varieties, whereas others have a broader spectrum of action. Glyphosate, for example, is a non-selective active substance capable of destroying all plants and is therefore classified as a total herbicide. Active ingredients in plant protection products may be chemically synthesized or derived from natural substances such as essential oils. Biopesticides are part of a broader approach to plant protection aimed at reducing ecosystem disturbances; however, they currently represent less than 10% of the global pesticide market.

Farmers have always faced climatic conditions that favor plant diseases and pests, which can severely affect crop yields. Globally, up to 40% of harvests are lost each year due to diseases and pests. Consequently, pesticides have been widely adopted as a means of ensuring agricultural production security by reducing the risk of major yield losses and postharvest deterioration [14].

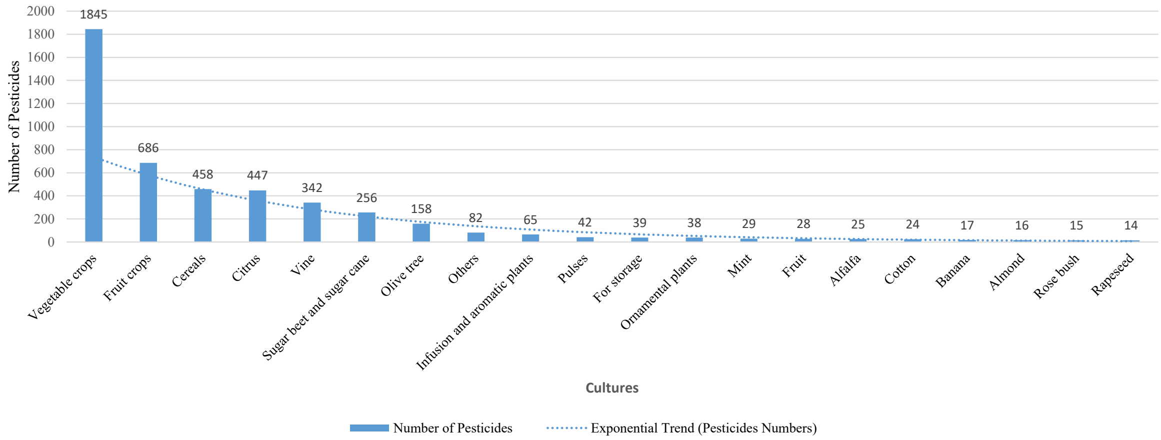

Fig. 1. Distribution of crops according to the number of pesticides used in Morocco in 2018.

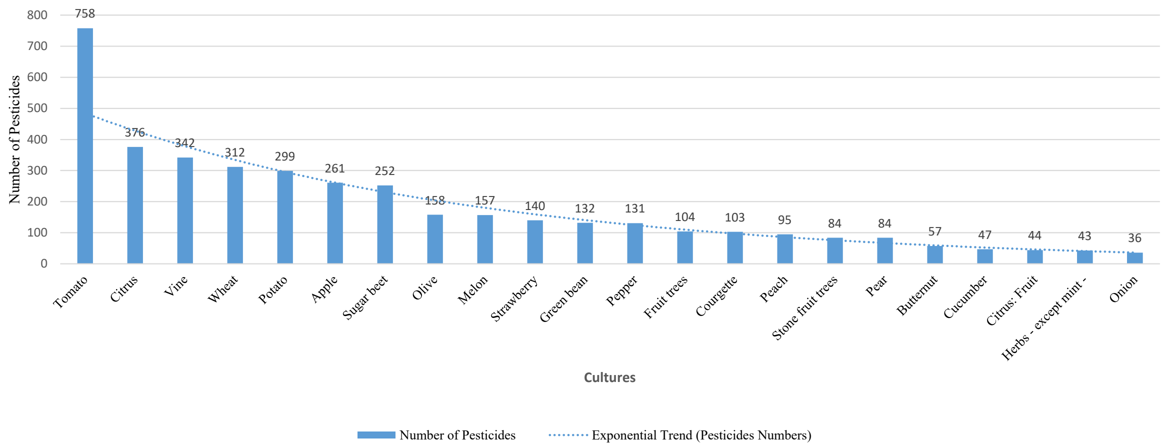

Fig. 2. Crops using more than 50 different pesticides in Morocco.

Since the second half of the twentieth century, synthetic pesticides have been extensively used in European and North American agriculture. Their use increased alongside farm specialization, mechanization, and the application of chemical fertilizers. Currently, more than 800 active substances are available on the market, and global pesticide consumption exceeds 3 million tons annually [15]. 4 major companies, Syngenta Group, Bayer, Corteva, and BASF, dominate the global pesticide market, accounting for approximately 70% of sales in 2018, with growth driven mainly by South America, Southeast Asia, and Africa. Farmers, agricultural workers, and rural populations are among the most vulnerable groups exposed to pesticides. Health effects may be immediate, such as skin irritation or respiratory problems, or chronic, manifesting over long-term exposure [16].

The chlordecone case illustrates the long-term consequences of pesticide misuse. This insecticide was applied for nearly 20 years in banana plantations in Martinique and Guadeloupe before being banned in 1993 due to its harmful effects on human health [17]. It caused permanent soil and water contamination, and decades later, the food chain and local populations remain affected. Epidemiological studies indicate a strong probability that pesticide exposure is linked to cancer and reproductive disorders, particularly among agricultural workers exposed to chlordecone [18]. Pesticides pose risks to the general population, although farmers remain the most exposed. Active substances can be transported by wind and water and persist in the environment for many years, contaminating soil, water, and food products. Countries such as France have implemented monitoring systems to control pesticide residues in food. In 2017, approximately 4% of inspections detected banned substances. While such control systems offer some consumer protection, they remain limited to known and monitored molecules [13].

In 2018, Morocco marketed 379 active substances, corresponding to 5179 commercial products and 1316 formulations. Fig. 1 presents the distribution of crops according to the number of pesticides used in Morocco during that year. Certain crops require a particularly high number of phytosanitary treatments, reflecting their susceptibility to pests and diseases.

Fig. 2 highlights crops that use more than 50 different pesticides, with tomato cultivation showing one of the highest levels of pesticide application. The intensive use of phytosanitary products in such cropping systems increases the risk of environmental contamination, particularly of soil and groundwater resources, and underscores the importance of monitoring pesticide use patterns at the national scale [13].

III. Materials and Methods

A. Presentation of the Study Area

The present study was conducted in the Feija Plain (see Fig. 3), located south of the town of Zagora on the right bank of the Oued Draa. The study area is characterized by a schistose bedrock valley extending approximately 80 km from west to east and bordered on both sides by mountainous areas [19]. The valley is between 8 and 12 km wide in its upper reaches and expands further eastward, opposite the town of Zagora, where it connects to the Oued Draa Valley, which drains this vast plain.

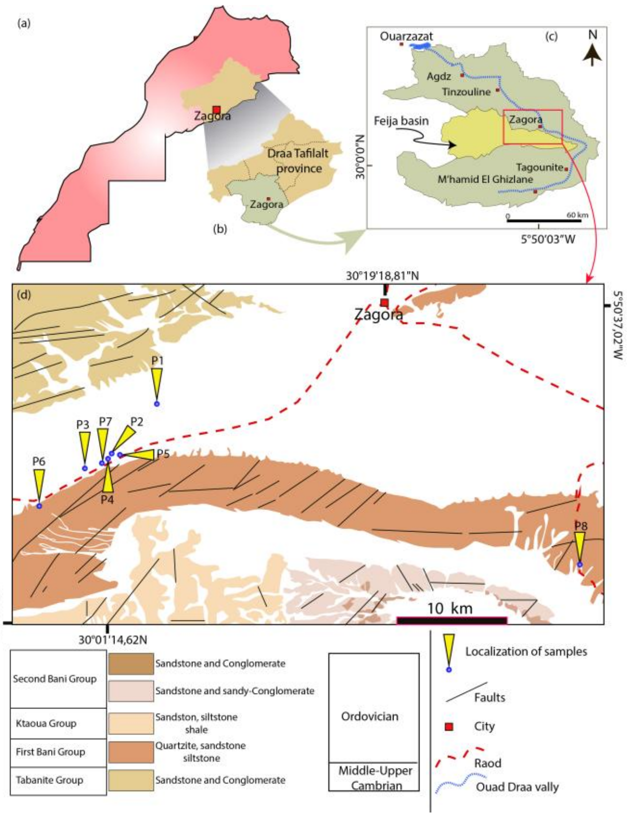

Fig. 3. Location and geological map of the study area

Phytosanitary products play a critical role in agricultural production and are considered indispensable in crop pest control programs. Intensive agricultural systems require a rational and targeted use of plant protection products to prevent environmental pollution and human contamination. When applying a crop protection product, the objective is to treat a specific plant cover, such as leaf surfaces and weeds in the case of herbicides, or infested plants in the case of fungicides and insecticides.

The effectiveness of a crop protection product depends on the ability of its active substance to control pests or weeds while minimizing unavoidable losses. Chemical application aims to maximize the quantity of product reaching the target while reducing dispersion onto non-target surfaces. To achieve effective field application, it is essential to comply with several.

B. Survey and Interview: Data Collection Methods

To assess the impact of phytosanitary product use on groundwater quality in the Feija area, 2 complementary approaches were adopted.

The first approach was based on the physicochemical analysis of groundwater samples collected from 8 wells located within the Feija Plain. These analyses were carried out at the CLIC LAB laboratory during the 2025 hydrological year.

The second approach consisted of a questionnaire-based survey conducted among agricultural stakeholders (Fig. 4). A total of 186 farmers and 35 resellers were surveyed regarding the use of chemical products, including herbicides, insecticides, and fungicides, during the 2025 agricultural season. Data were collected through in-depth, face-to-face interviews with farmers and retailers using a random sampling method to assess the impact of agricultural practices on groundwater quality in southeastern Morocco.

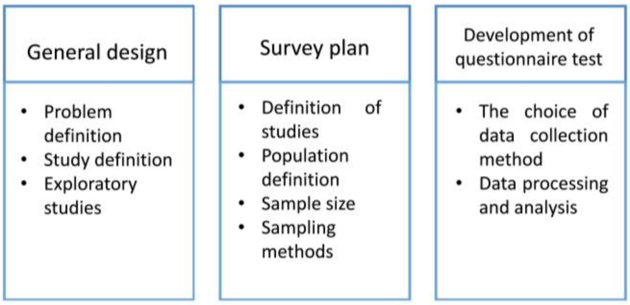

Fig. 4. Data collection methods.

The initial sample size was calculated using the following equation:

$$N = \frac{z2 \times (p) \times (1 - p)}{c2}$$

where z represents the confidence interval (95% or 99%), p is the estimated proportion (5%), and c is the margin of error (0.05).

The final sample consisted of 186 farmers (N_1) and 35 resellers (N_2).

The objective of this stage was to compare the conceptual model with field observations. By combining literature review and quantitative analysis, a research model was developed to illustrate the relationships between phytosanitary product use and groundwater quality in the Feija region. The model highlights correlations that are logical, coherent, and supported by empirical evidence, which was also collected to verify the effectiveness of the procedure [20].

Samples were collected in sterile bottles prepared in the laboratory. Care was taken to avoid contact between the bottleneck or cap and external surfaces. An air space was left in the bottle to facilitate sample mixing, except in anaerobic sampling conditions where oxidation of reduced chemical species or inhibition of anaerobic bacteria must be avoided [21].

C. Chemical Analysis: Gas Chromatography

Pesticide contamination was analyzed using gas chromatography, a technique suitable for compounds that become volatile when heated. In this method, the sample is injected, vaporized, and transported by a carrier gas through a column containing a stationary phase, allowing compound separation. Each compound migrates through the column at a specific rate, producing a detectable signal recorded and analyzed using computer software [13].

Identification and quantification of compounds were achieved by comparing retention times and mass spectra with those of standard solutions and reference databases. The injection volume ranged from 1 to 10 µL using a micro syringe, with rapid injection to prevent peak broadening. Both split and splitless injection modes were employed depending on sample concentration [14].

In this study, pesticide analyses were performed using an Agilent 7890B gas chromatograph equipped with a multimode injector and coupled to an Agilent 7000C triple quadrupole mass spectrometer. Separation was achieved using a fused-silica DB-5MS capillary column (30 m length, 0.25 mm internal diameter, 0.25 µm film thickness). Helium (purity 5.0) was used as the carrier gas.

The injection was performed in splitless mode with an injection volume of 1 µL at 250 °C. The oven temperature was initially set to 60 °C for 1 min, then increased at a rate of 10 °C per minute to 300 °C. The ion source temperature was set to 175 °C, and the transfer line temperature was maintained at 275 °C. Ionization was carried out by electron impact at 70 eV in positive mode.

Pesticide identification relied on spectral databases containing approximately 7000 reference spectra. The results revealed the presence of various pesticides in groundwater samples from the Feija Plain, indicating diffuse contamination associated with local agricultural practices and intensive use of phytosanitary products [13].

IV. Results and Discussion

A. Descriptive Analysis

1) Survey for the farmers

Fig. 5 illustrates the distribution of respondents by frequency and percentage of respondents who use or do not use pesticides and fertilizers on their land.

It is noted that a very large number of farmers apply agricultural phytosanitary products and fertilizers at the plot level. The graph shows the distribution of respondents by pesticide use, distinguishing between absolute frequencies and relative percentages. The results indicate that the majority of respondents report using pesticides, representing 83.9% of the total sample, compared to only 16.1% who state not using them. This strong predominance of the use of chemical inputs highlights a marked dependence of agricultural practices on pesticides. Frequency analysis confirms that the use of these products is a widespread practice, suggesting that they are perceived by farmers as essential factors to improve yields and secure production.

Moreover, the exponential trend curves reinforce this observation by illustrating a high concentration of responses in the 'Yes' modality, while the 'No' modality remains marginal. This configuration reveals an unbalanced structure of agricultural practices, likely to have significant environmental and health implications, particularly in terms of soil degradation, water resource pollution and risks for human health.

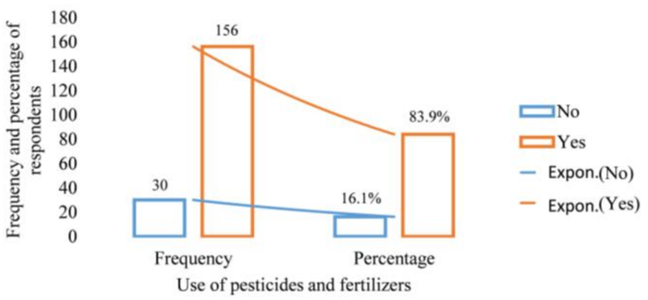

Fig. 5. Distribution of respondents by frequency and percentage: Use or not of pesticides and fertilizers within crops.

Fig. 6 illustrates the frequency and percentage of use of different types of pesticides by respondents. It is noted that farmers would apply much more insecticides followed by acaricides and ultimately by fungicides and herbicides to their farms. The graph shows the distribution of respondents by type of pesticide used, distinguishing absolute frequencies and relative percentages for 4 categories: acaricides, fungicides, herbicides and insecticides. The results show a differentiated use of pesticides according to their agronomic function.

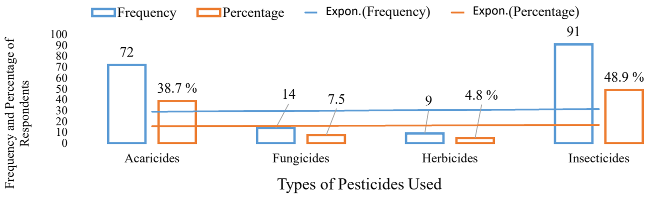

Fig. 6. The frequency and percentage of use of different types of pesticides by farmers.

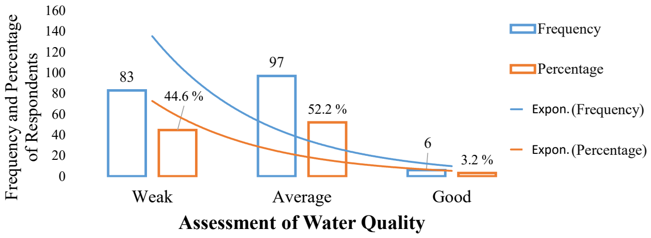

Fig. 7. The frequency and percentage of age of use of different types of pesticides by farmers.

Insecticides appear as the most widely used products, representing 48.9% of the sample. This predominance is explained by the strong pressure exerted by pest insects on crops, prompting farmers to prioritize treatments that directly target yield losses.

Acaricides occupy the second position, at 38.7%. Their relatively high use indicates a significant presence of harmful mites in the agricultural systems studied, requiring regular chemical interventions. This low proportion may reflect either lower phytosanitary pressure from fungal diseases and weeds, or the use of alternative methods, such as mechanical weeding or adapted cultural practices.

The trend lines for frequencies and percentages confirm a marked concentration of use on insecticides and acaricides, revealing an asymmetric structure in phytosanitary practices. This distribution highlights a targeted dependence on certain types of pesticides, which may have environmental implications, particularly for soil and water resource contamination.

Thus, these results highlight the need for integrated pest management to rationalize pesticide use and promote sustainable agricultural strategies.

This representation makes it possible to analyze the overall perception of the state of water resources in the studied area.

Fig. 7 illustrates the overall perception of water resource quality within the study area The results indicate that the majority of respondents rate water quality as average, representing 52.2% of the sample. This predominance suggests that, although water is considered usable, it nevertheless has certain limitations that may affect its agricultural or domestic use, particularly in terms of salinity, pollution, or chemical contamination. The relatively high proportion reflects a worrying perception of water resource degradation, which may be associated with anthropogenic pressures such as intensive use of pesticides and fertilizers, agricultural runoff, or inadequate management of discharges. On the other hand, only a minority of respondents, 6 respondents corresponding to 3.2%, consider that the quality of water is good. This low proportion highlights the rarity of situations where water is perceived as healthy and of good quality, confirming the existence of significant environmental constraints. Thus, these results highlight the need to strengthen policies for the protection of water resources, notably through more rational management of agricultural inputs and the promotion of sustainable practices, in order to sustainably improve water quality.

Fig. 8 illustrates the distribution of frequency and percentage of respondents based on their knowledge of the biological effects of pesticides. It is noted that almost 92% of farmers do not know the biological effects of pesticides and the remaining 8% know their effects. The graph shows the frequency and percentage of pesticide use according to different application periods during the agricultural production cycle. 4 modalities are distinguished: pesticides used from planting to fruiting, once a month, once a semester, and once a year.

The results show a very marked predominance of continuous use of pesticides from planting to fruiting, with a sample size of 183 respondents, representing 98.4% of the sample. This extremely high proportion indicates that almost all farmers surveyed apply pesticides regularly throughout the crop cycle, reflecting a strong reliance on chemical inputs for crop protection.

On the other hand, the other terms of use appear marginal. The application once a month, once a semester, and once a year concerns each 1.05% of respondents, which corresponds to a very small proportion of the sample. This distribution suggests that one-time or limited treatment strategies remain poorly adopted in the studied context.

The exponential trend lines associated with frequencies and percentages illustrate a rapid decrease in pesticide use when the frequency of application decreases. This dynamic confirms the existence of an intensive use model, dominated by repeated and continuous applications.

From an environmental perspective, such intensity of use is likely to increase the risks of contamination of soil and water resources, as well as negative effects on biodiversity and human health. These results thus highlight the urgency of promoting integrated pest management practices and rational use of pesticides in order to reduce the environmental impacts associated with their excessive use.

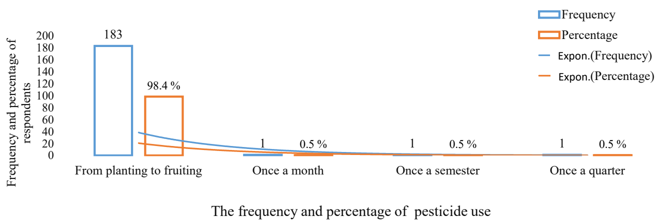

Fig. 8. Distribution of respondents according to their experience in using pesticides.

Fig. 9 illustrates the distribution of respondents by their knowledge of the biological effects of pesticides and grains, showing frequency and percentage. The graph presents the level of knowledge of respondents regarding the biological effects of pesticides and grains, distinguishing absolute frequencies and relative percentages according to 2 modalities: Yes (knowledge) and No (lack of knowledge). This representation makes it possible to evaluate the degree of awareness among agricultural actors about the biological impacts related to pesticide use.

The results show that the vast majority of respondents state that they are not aware of the biological effects of pesticides and grains. Indeed, 171 respondents, or 91.9%, are in the "no" category. This very high proportion reveals a significant lack of information and awareness about the biological and health risks associated with pesticide exposure.

Conversely, only a minority of respondents, corresponding to 15 respondents and representing 8% of the sample, claim to have knowledge of the biological effects of these substances. This low proportion indicates that training, extension and information dissemination efforts are still insufficient to reach all the actors concerned.

The exponential trend lines associated with frequencies and percentages illustrate a clear dominance of the 'no' modality, confirming the concentration of responses around the absence of knowledge. This structure highlights an increased vulnerability of farmers to health and environmental risks, due to the intensive use of pesticides combined with a low perception of their biological effects.

Thus, these results highlight the urgent need to strengthen awareness programs, training, and technical support for farmers, in order to improve their level of knowledge and promote safer and sustainable agricultural practices.

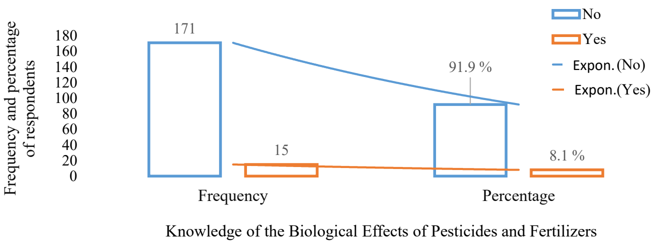

Fig. 9. Frequency distribution and percentage of respondents based on their knowledge of the biological effects of pesticides.

Fig. 10 illustrates the frequency and percentage distribution of respondents by their knowledge of, or lack thereof, different types of fertilizers and pesticides. We notice that 88.2% of farmers do not know the different types of fertilizers and pesticides, and only 11.8% manage to know the latter.

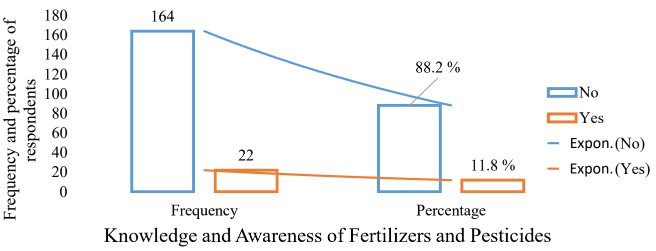

Fig. 10. The frequency and percentage of respondents' distribution according to their response to the water quality assessment.

The results show that the majority of respondents state that they do not have sufficient knowledge regarding fertilizers and pesticides. Indeed, 164 respondents, or 88.2% of the sample, are in the "No" category. This high proportion highlights a significant lack of technical and scientific knowledge related to agricultural inputs, despite their intensive use.

On the other hand, only 22 respondents, representing 11.8%, state that they have adequate knowledge of fertilizers and pesticides. This low proportion suggests that access to information, training, and technical support remains limited for a large part of the farmers surveyed.

The exponential trend curves associated with frequencies and percentages confirm the dominance of the "no" modality, reflecting a strongly unbalanced structure in favor of the absence of knowledge. This imbalance is of particular concern in a context where pesticide use is frequent and continuous, as shown by previous results.

Thus, these findings highlight the need to strengthen agricultural training, extension and awareness mechanisms in order to improve farmers' technical culture and promote a more rational and sustainable use of fertilizers and pesticides, thus contributing to the protection of the environment and public health.

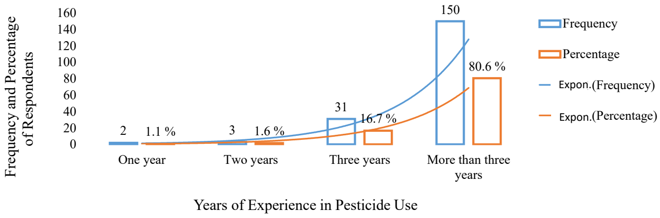

Fig. 11. The frequency and percentage of respondents' distribution according to their response to the water quality assessment.

Fig. 11 illustrates the frequency and percentage of distribution of respondents according to their water quality assessment responses. After analyzing the graph, we can say that 3% of farmers say that well water is of good quality; however, 52% think that the water quality is average, and the rest respond that the well water in this region is of poor quality. The graph shows the distribution of respondents by duration of experience with pesticide use, expressed in both absolute frequencies and relative percentages. 4 categories are distinguished: 1 year, 2 years, 3 years, and more than 3 years. This variable allows us to understand the level of seniority of practices related to the use of pesticides. The results show that the overwhelming majority of respondents have more than 3 years' experience in pesticide use, or 80.6% of the sample. This high proportion indicates that the use of pesticides is part of longstanding and sustainable agricultural practices, reflecting a standardization of their use over time.

Respondents with 3 years of experience represent 31 individuals, or 16.7%, reflecting an intermediate phase of adoption and consolidation of phytosanitary practices. On the other hand, the categories corresponding to 2 years and 1 year of experience remain marginal, with 1.6% and 1.1% of respondents, respectively. This low representation suggests that few farmers are recently engaged in pesticide use.

The exponential trend curves associated with frequencies and percentages highlight a very marked increase in the number of people with the duration of experience, confirming the concentration of practices around an old and prolonged use. This configuration reinforces the hypothesis of a structural dependence on pesticides in the agricultural systems studied. Thus, these results highlight that the longevity of experience in pesticide use, combined with a low level of knowledge and a high frequency of use, constitutes an aggravating factor for environmental and health risks, notably in terms of soil degradation and water resource pollution.

Fig. 12 presents the frequency and percentage of use of active commercial products by farmers during the 2024/2025 agricultural season. It is noted that the most used agricultural phytosanitary products are in descending order of percentage: Tractor 25ec, Romectine, Acramite, Allerte 10% EC, Santri, Karate 5 EC, Malyphos, and finally the Bazooka 200 g. The graph shows the distribution of respondents by commercial pesticide products used, distinguishing between absolute frequencies and relative percentages for each product. This analysis makes it possible to identify the substances most commonly used in agricultural practices and to evaluate the diversity of plant protection products used.

The results show a marked variability in the use of commercial products. Some pesticides record relatively high frequencies, indicating an increased preference or availability of these products in the local market. Conversely, other products have lower frequencies, reflecting more limited or occasional use.

The distribution of percentages confirms this heterogeneity, with values generally between low and moderate levels. This dispersal suggests that farmers are not using a single product, but rather a combination of several commercial pesticides, probably depending on the type of crop, the stage of plant development, and pest pressure.

The exponential trend lines associated with frequencies and percentages indicate an overall trend of increasing use of certain products, reflecting a gradual increase in the use of commercial pesticides. This dynamic can be interpreted as the result of an adaptation of farmers to phytosanitary constraints, but also as a sign of a growing dependence on chemical solutions.

From an environmental and health point of view, the diversity and intensity of use of these commercial products raise major concerns, particularly in terms of soil contamination, water resource pollution and chronic exposure of rural populations.

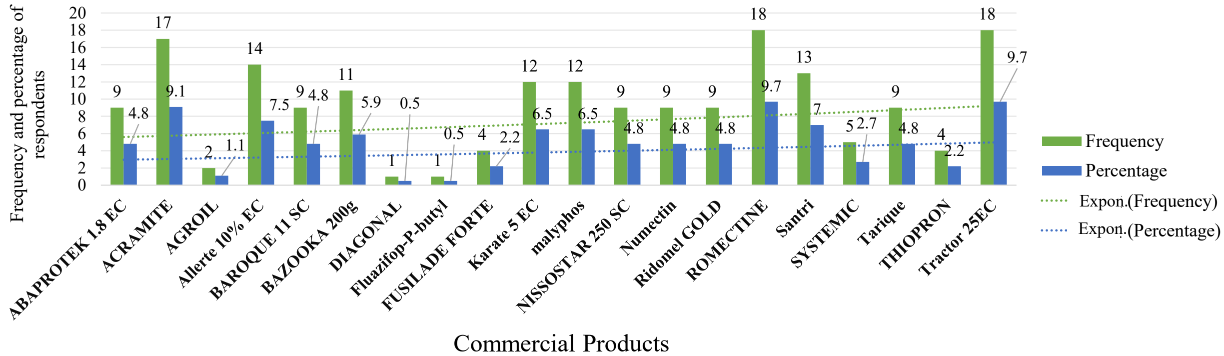

Fig. 12. Frequency and percentage of active use of commercial products by farmers during the 2024/2025 agricultural season.

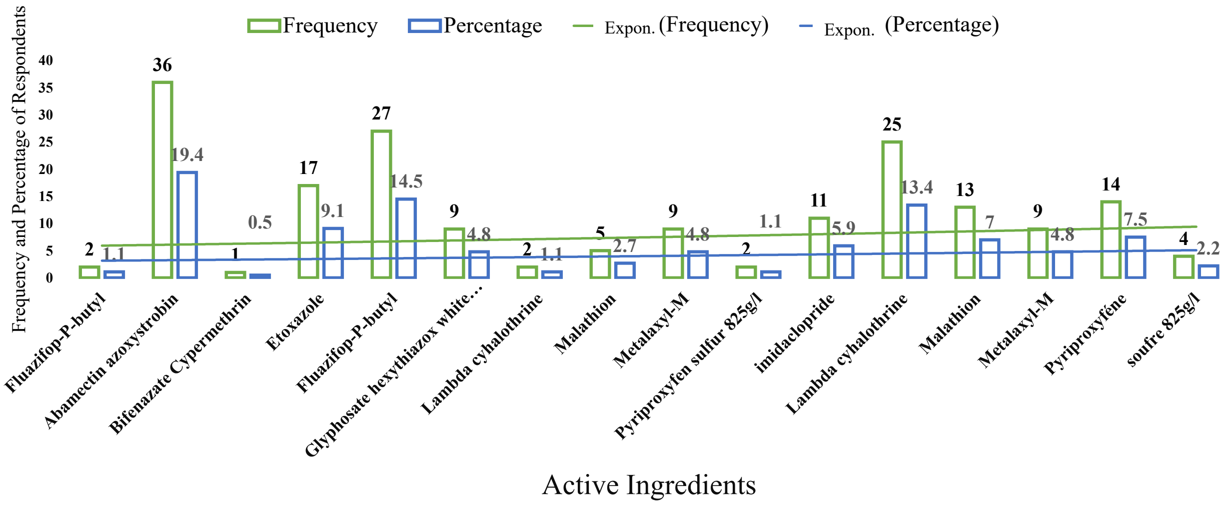

Fig. 13. Frequency and percentage of use of active molecules by farmers during the 2024/2025 season.

Fig. 13 illustrates the frequency and percentage of use of pesticide active molecules by farmers during the agricultural season 2024/2025. It is noted that the most used active ingredients in descending order of the percentage of use by farmers are: Abamectin, Azoxystrobin, Fluazifop-p-butyl, Lambda-clothespins and finally Etoxazole during the 2024/2025 agricultural season.

The results show a notable heterogeneity in the use of active molecules. Some substances have relatively high frequencies, reflecting the frequent use of widely distributed molecules perceived as effective against targeted pests or diseases. These dominant molecules often reflect choices guided by agronomic efficiency, commercial availability, and informal technical recommendations.

Other active molecules have lower frequencies and percentages, indicating a more limited or specific use, possibly related to particular crops, at specific stages of the crop cycle, or regulatory and economic constraints. This dispersion of values suggests that farmers use a diverse basket of active substances, rather than a single molecule.

The exponential trend curves associated with frequencies and percentages indicate a global trend towards the gradual increase in the use of certain active molecules, which can reflect an intensification of phytosanitary pressure and a continuous adaptation of agricultural practices in the face of pest resistance.

From an environmental and health perspective, the diversity and frequency of use of these active molecules raise significant concerns, particularly in terms of cumulative toxicity, residues in soil and water, and risks to human health. These results highlight the need to strengthen the control of the use of active molecules, promote less harmful alternatives, and encourage integrated pest management strategies.

Fig. 14 presents the quantity purchased by farmers in tons per year during the 2024/2025 season. The results indicate that the total quantity of pesticides purchased per year reached 728.5 tons, revealing a high level of consumption of chemical inputs in the studied area. Among the categories analyzed, fungicides occupy the first place with 255.8 tons, reflecting a strong pressure of fungal diseases on crops and an intensive use of these products to ensure phytosanitary protection.

Herbicides are the second most consumed category, with 231.3 tons, reflecting the importance of chemical weed control in the agricultural systems studied. Acaricides account for 135.9 tons, while insecticides have the lowest amount at 105.5 tons. This distribution highlights a prioritization of uses according to the dominant phytosanitary constraints. The exponential trend curve associated with purchased quantities shows a gradual increase in the volume of pesticides, highlighting an overall intensification of their use. This trend is consistent with previous results on frequency of use, duration of experience and low level of knowledge about the biological effects of pesticides.

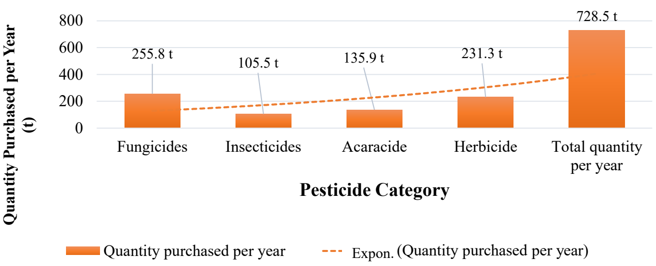

Fig. 14. Quantity purchased by farmers in tons per year during the 2024/2025 agricultural season.

From an environmental perspective, such volumes of pesticides are likely to result in high risks of soil and water resource contamination, as well as negative impacts on biodiversity and human health. These results highlight the urgent need to promote a more rational management of pesticides, based on the reduction of quantities used, the adoption of alternative practices and the strengthening of awareness-raising and control mechanisms.

2) Interview with the resellers

Fig. 15 illustrates the frequency and percentage of pesticide delivery by resellers during the 2024/2025 agricultural season. It is noted that insecticides are the most delivered, followed by herbicides, acaricides, and fungicides. The graph shows the distribution of respondents by type of pesticide used, distinguishing between absolute frequencies and relative percentages for 4 main categories: Acaricides, Fungicides, Herbicides and Insecticides.

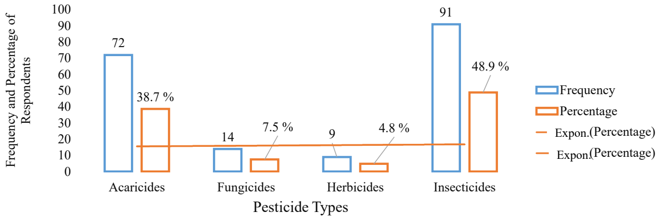

Fig. 15. The frequency and percentage of pesticide delivery by resellers during the 2024/2025 agricultural season.

The results show that insecticides constitute the most used category, representing 48.9% of the sample. This high proportion reflects a significant pressure from insect pests on crops, encouraging farmers to prioritize the use of this type of pesticide in order to preserve agricultural yields.

Acaricides occupy the second position, at 38.7%. Their relatively high use suggests a significant presence of harmful mites in production systems, requiring specific and regular treatments.

On the other hand, fungicides and herbicides are significantly less used, corresponding to 7.5%, while herbicides are not used, representing 4.8% of the sample. This low proportion can be explained by a lower phytosanitary pressure related to fungal diseases and weeds, or by the adoption of alternative cultural practices such as manual or mechanical weeding.

The exponential trend curves associated with frequencies and percentages confirm a marked concentration of pesticide use around insecticides and acaricides, revealing an asymmetric structure of phytosanitary practices. This distribution highlights a targeted dependence on certain types of pesticides, which may lead to environmental and health impacts, particularly in terms of soil and water resource pollution.

Thus, these results highlight the importance of promoting integrated pest management and more rational use of pesticides in order to reduce the risks associated with their excessive use while maintaining agricultural productivity.

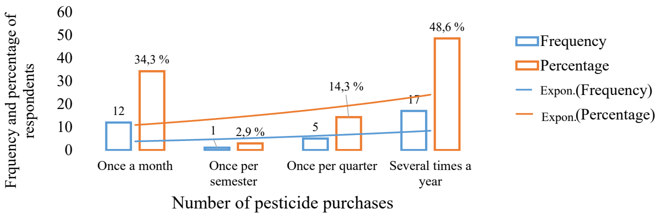

Fig. 16. The frequency and percentage of the number of times of pesticide purchases from monthly to annual by farmers from Zagora resellers during the 2024/2025 agricultural season.

Fig. 16 gives the frequency and percentage of the number of times from monthly to annual pesticide purchases by farmers from Zagora resellers. It is noted that farmers' purchases of pesticides are mainly annual, followed by monthly, then quarterly, and at the end of the semester. The graph shows the distribution of respondents by number of pesticide purchases per year, distinguishing between absolute frequencies and relative percentages. Four methods are identified: a purchase per month, a purchase per semester, a purchase per year, and several purchases per year. This variable allows the analysis of farmers' pesticide supply behavior.

The results show that the category "several purchases per year" is the most represented, representing 48.6% of the sample. This high proportion indicates a frequent use of pesticide purchases, reflecting regular and continuous use of chemical inputs throughout the agricultural year.

The "one purchase per month" method comes second, corresponding to 34.3%. This monthly purchase frequency suggests a particularly high intensity of use, often associated with crops requiring repeated treatments or strong pest pressure.

On the other hand, more spaced purchases remain marginal, at 14.3%, while those declaring a purchase per semester correspond to 2.9%. These low proportions indicate that ad procurement strategies are not widely adopted.

The exponential trend lines associated with frequencies and percentages show a marked increase in the number of respondents with the intensity of purchase frequency. This dynamic confirms the existence of a model of intensive use of pesticides, consistent with previous results related to frequency of use and duration of experience.

Thus, these results highlight a strong dependence of farmers on pesticides, stressing the need to promote more sustainable agricultural practices and rationalize supply strategies in order to limit the environmental and health impacts associated with their intensive use.

Fig. 17 presents the quantity sold by resellers in tons per year during the 2024/2025 agricultural season. We notice that resellers say that 1/3 of their sale would be fungicides, followed by herbicides, and acaricides and finally insecticides. The graph shows the distribution of respondents by quantity of pesticides applied per hectare, expressed in litres per hectare (l/ha), distinguishing between absolute frequencies and relative percentages. 4 dose classes are considered: 1 l/ha, 2–3 l/ha, 4 l/ha and 8 l/ha. This analysis allows the evaluation of the intensity of phytosanitary practices at farm level.

The results indicate that the dose of 4 L/ha is the most commonly used, representing 45.7% of the sample. This high proportion suggests that this dose constitutes an empirical standard widely adopted by farmers, probably perceived as a compromise between agronomic efficiency and cost control. Category 8 L/ha comes second, or 25.7%. This high dose reflects a significant increase in the use of pesticides on certain farms, which may be associated with increased phytosanitary pressure or an insufficient perception of the risks related to overdose.

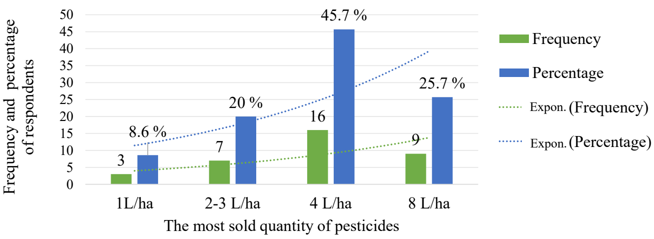

Fig. 17. The distribution of respondents by the quantity of pesticides sold is presented, including the frequency and percentage.

Fig. 18 illustrates the distribution of respondents by their knowledge of the biological effects of pesticides and grains. The graph presents the level of knowledge of respondents regarding the biological effects of pesticides and grains, distinguishing absolute frequencies and relative percentages according to 2 modalities: Yes (knowledge) and No (lack of knowledge). This variable makes it possible to evaluate the degree of awareness among farmers of the biological and health impacts related to the use of pesticides.

The results show that almost all respondents state they are not aware of the biological effects of pesticides and grains. Indeed, 97.1% of the sample are in the "No" modality. This extremely high proportion highlights a major lack of information and training on the biological risks associated with pesticide exposure.

Conversely, only 2.9% claim to have knowledge of the biological effects of these substances. This originality highlights the inadequacy of awareness-raising and scientific dissemination actions among farmers.

The exponential trend curve associated with the "No" modality illustrates an overwhelming domination of the absence of knowledge, confirming the concentration of responses around this category. This situation is particularly worrying in a context characterized by a high frequency of pesticide use, significant doses per hectare and a long period of experience in these practices.

Thus, these results highlight the urgency to implement targeted training, information and technical support programs in order to improve farmers' level of knowledge and reduce environmental and health risks related to intensive pesticide use.

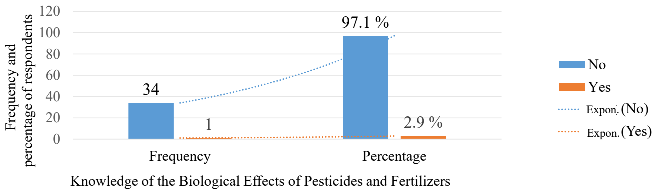

Fig. 18. The frequency and percentage of the number of times of monthly to annual pesticide purchases by farmers from Zagora resellers during the 2024/2025 agricultural season.

Fig. 19 shows the quantity sold by resellers in tons per year during the 2024/2025 agricultural season. We note that resellers indicate that one third of their sales correspond to fungicides, followed by herbicides and acaricides, and finally insecticides. The graph shows the distribution of respondents by level of experience in pesticide and industrial grain sales, distinguishing between absolute frequencies and relative percentages for 2 categories: more than 3 years of experience and 3 years of experience. This variable makes it possible to evaluate the degree of maturity and seniority of the actors involved in the marketing of agricultural inputs.

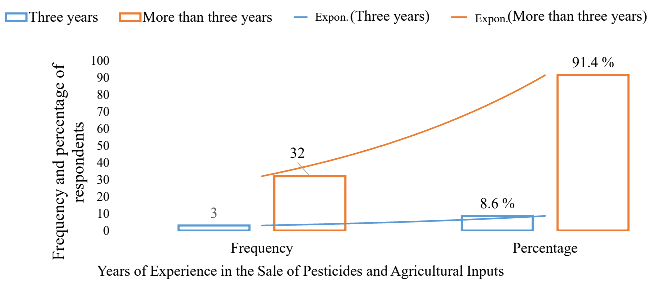

Fig. 19. Frequency distribution and percentage of resellers based on their knowledge of the biological effects of pesticides and fertilizers.

The results show that the vast majority of respondents have more than 3 years' experience in selling pesticides and industrial grains. This category includes 32 respondents, or 91.4% of the sample. This very high proportion indicates that the sales activity of these products is mainly carried out by experienced actors, whose practices are sustainably installed over time.

In contrast, respondents with three years of experience represent only 3 individuals, or 8.6% of the sample. This low proportion suggests a limited entry of new players into the sector, which may reflect either barriers to entry or structural stability in the local market for pesticides and industrial grains. The exponential trend curve associated with the category "more than 3 years" illustrates a marked increase in the concentration of respondents in this modality, confirming the dominance of experienced profiles. This configuration is particularly significant when related to previous results showing a high intensity of pesticide use and a low level of knowledge of their biological effects.

Fig. 20 illustrates the frequency and percentage of sales of commercial pesticides by resellers during the 2024/2025 agricultural season in Zagora. It is noted that the most sold commercial pesticides are Bazooka 200, followed by Strong Shooting, then Tractor 25, Systemic, Tarique, Romectine, and others. The graph shows the distribution of respondents by commercial pesticide products used, distinguishing between absolute frequencies and relative percentages for each product. This analysis aims to identify the most commonly used products and to appreciate the diversity of pesticides marketed and used in the studied area.

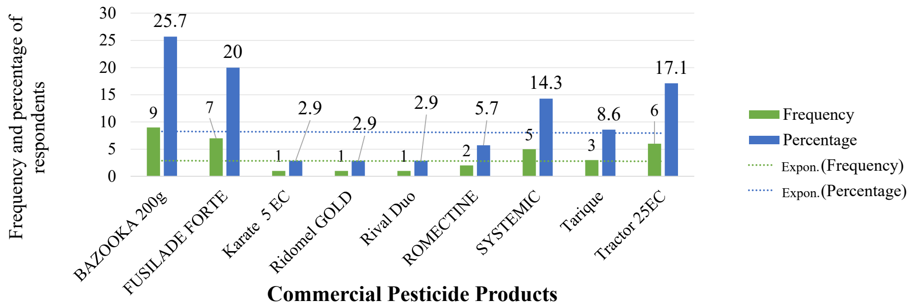

Fig. 20. Frequency and percentage of sales of commercial pesticide products by dealers during the 2024/2025 season.

The results indicate a marked heterogeneity in the use of commercial products. Some products are distinguished by relatively high levels of use. In particular, Bazzoka 200 g appears as the most frequently used, with respective percentages of 25.7% and 20%, reflecting a strong user preference for these formulations. This predominance can be explained by their perceived effectiveness, their availability on the market, or their adaptation to dominant cultures.

Other products, such as Systemic and Tractor, have intermediate use levels, with percentages ranging from 14.3% to 17.1%. These values suggest regular but less widespread use, probably linked to specific phytosanitary needs or to particular stages of the crop cycle.

On the other hand, some products have frequencies and low percentages, below 6%, indicating a marginal or occasional use. This low adoption can be attributed to economic constraints, limited efficiency, or preferences for other commercial alternatives.

The exponential trend lines associated with frequencies and percentages highlight an overall trend towards concentration of use around a few dominant products, while others remain poorly used. This configuration reveals a dependence on a limited number of commercial pesticides, which can increase the risks of pest resistance and environmental impacts.

The commercial profile of active substances in the Zagora region (Fig. 21) underscores an intensive chemical dependency, primarily driven by imidacloprid (25.7%). The prevalence of this systemic neonicotinoid is intrinsically linked to the protection of high-value crops, such as watermelon, against viral vectors. Furthermore, the significant market share of fluazifop-P-butyl (20%) and glyphosate (11.4%) highlights the critical pressure of weed management in the Feija irrigated perimeters.

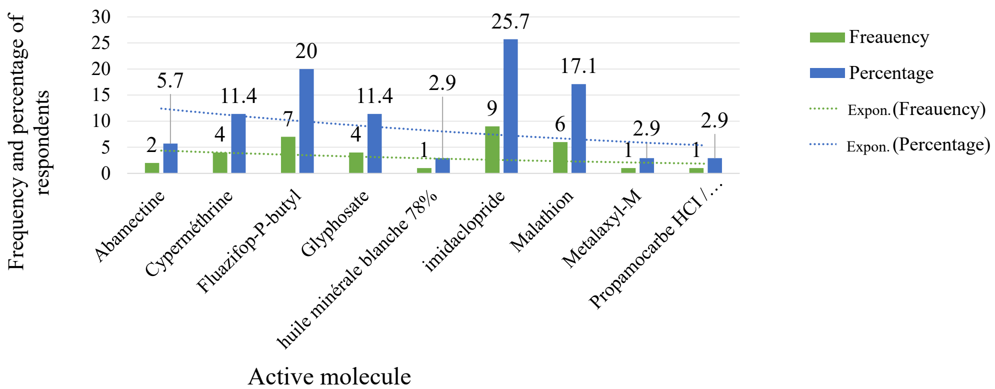

Fig. 21. The distribution of frequency and percentage of sales of commercial pesticides by resellers during the 2024/2025 agricultural season in Zagora.

Fig. 22 illustrates the annual tonnage of chemical inputs marketed, categorized by major functional classes. During the 2024/2025 agricultural campaign, the total volume of pesticide transactions reached 214.9 tons, indicating a substantial chemical pressure within the study area. Structural analysis of these sales reveals a marked predominance of fungicides, which represent the largest share at 76.5 tons. This dominance reflects an intensive management strategy against fungal pathogens affecting local crops. Herbicides and acaricides follow with respective volumes of 62.5 tons and 58.3 tons, confirming the critical role of chemical weeding and mite control in regional cultivation protocols. Conversely, insecticides exhibit the lowest physical tonnage (17.6 tons).

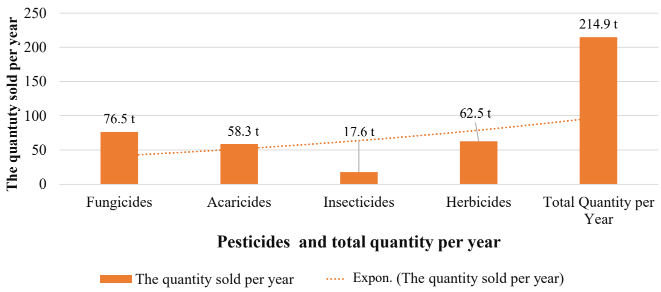

Fig. 22. Quantity sold by resellers in tons per year during the 2024/2025 agricultural season.

The results show a significant diversity of active molecules, with a notable concentration around certain substances. The molecule imidacloprid appears as the most used, corresponding to 25.7% of the sample. Malathion ranks second, at 17.1%, reflecting a still significant use despite concerns about its toxicity. Other molecules, such as cypermethrin, chlorpyrifos, fipronil and diazinon, have intermediate levels of use, with percentages approaching 11.4% and 20%, indicating a relatively frequent use of these substances. On the other hand, some active molecules display very low frequencies, of the order of 2.9%, revealing a marginal or occasional use. This dispersion reflects a heterogeneity of practices and an adaptation of chemical choices to specific crop constraints and local phytosanitary pressures. The exponential trend curves associated with frequencies and percentages indicate an overall trend towards the concentration of use around a few dominant molecules, suggesting increased dependence on certain active ingredients. Thus, these results highlight the need to strengthen the control and regulation of the use of active molecules, to promote less toxic alternatives and encourage integrated pest management strategies in order to reduce the negative impacts associated with the repeated use of certain pesticides with a notable concentration around certain substances.

The graph shows the quantity of pesticides sold per year, expressed in tons, according to the main product categories, namely fungicides, acaricides, insecticides and herbicides, as well as the total quantity sold per year. This analysis makes it possible to evaluate the extent of pesticide marketing and the relative contribution of each category to overall sales volume. The results show that the total quantity of pesticides sold per year reached 214.9 tons, reflecting a high level of marketing of chemical inputs in the studied area. Among the different categories, fungicides constitute the largest share with 76.5 tons, which reflects a strong demand related to the control of fungal diseases affecting crops. Acaricides is the second largest with 58.3 tons, indicating a significant use of these products for pest mite control. Herbicides represent 62.5 tons, which highlights the importance of chemical weeding in the agricultural systems analyzed. On the other hand, insecticides show the lowest quantity sold, with 17.6 tons. This relatively low value can be interpreted in the light of previous results showing a targeted but frequent use of insecticides, involving lower unit doses or a higher concentration of certain formulations. The exponential trend curve associated with quantities sold indicates a gradual increase in volumes, suggesting an overall intensification of pesticide marketing. This trend is consistent with the strong experience of sales players and the high frequency of purchase observed in previous results. Thus, these results highlight the magnitude of pesticide flows in the agricultural system studied and emphasize the need to strengthen the mechanisms for regulation, control, and monitoring of sales.

B. Explanatory Analysis

Researchers chose multinomial logistic regression as the regression method. This choice was made because the variables were nominal. Table 1 presents information on the estimated model. The final model predicts "204.739" of the variance in the probability of using groundwater quality for pesticide use, indicating that the model is effective.

Table 1. Information on the model (Multinomial logistic regression)

Model	Model Fit Criteria Likelihood Ratio Tests			
	Log-likelihood-2	Chi-squared	Ddl	Sig.
Constant only	248.327	-	-	-
Final	204.739	43.588	88	1.000

Table 2 presents the likelihood ratio test. The model explains 26% of the variability in water quality. This reflects a moderate explanatory capacity; it has a moderately positive relationship between water quality and the use of pesticides. A value of 0.145 indicates a good model fit, which confirms that the use of pesticides is a relevant explanatory factor for water quality.

Table 2. Pseudo R2 values for the multinomial logistic regression model

Category	Values (µg/L)
Cox et Snell	0.209
Nagelkerke	0.260
Mcfadden	0.145

A detailed examination of the Likelihood Ratio Tests (Table 3) reveals that the environmental fate of pesticides in the Feija aquifer is fundamentally governed by application intensity. The extreme Chi-squared value for 'quantity used' (6.417) indicates a direct linear correlation between input volumes and groundwater degradation.

Furthermore, the statistical significance of 'farmer experience' suggests that traditional pest management habits in Zagora may be misaligned with modern ecotoxicological standards. Conversely, the lack of significance for variables related to 'knowledge of ingredients' or 'biological effects' highlights a behavioral gap: awareness of pesticide risks does not necessarily translate into reduced chemical usage. This suggests that the pollution in the P1–P8 wells is a structural issue of the local agricultural model, where the maximization of watermelon yields justifies excessive chemical inputs, regardless of the farmer's level of technical awareness.

Table 3. Likelihood ratio tests for model effects

Effect	Model Fit Criteria Likelihood Ratio Tests			
	Log of likelihood-2 of the Reduced Model (µg/L)	Chi-squared	Ddl	Sig.
Constant	204.739	0.000	0	-
Do you heavily use pesticides and engrains within your land?	204.93	0.200	2	0.905
How many times do you use its pesticides and engrains?	210.33	5.590	6	0.471
According to you, what is the most used pesticide?	204.81	0.077	2	0.962
What is the quantity of its pesticides used?	621.89	6.417	10	0.000
How many experiences do you have with the use of these pesticides?	312.37	107.63	6	0.000
Do you know the biological effects of its pesticides and its engrains?	204.54	-	2	-
Do you have the culture of knowing the ingredients of its pesticides?	208.47	3.740	2	0.154
According to you, what phytosanitary products do you buy frequently?	205.25	0.517	10	1.000
According to you, what quantity do you buy per year?	170.38	-	18	-
Active ingredient	204.65	-	2	-

C. Multi-Year Analysis

Table 4 presents the results of analyses of the concentrations of pesticides detected in groundwater during the period 2022–2025. It allows identifying the types of pesticides, the active molecule, and the concentrations (its evolution over time).

Table 4. The results of analyses of the concentrations of pesticides detected in groundwater during the period 2022–2025

Years	Pesticides	Molecule Active	Concentrations (µg/L)
2022	Insecticides	Cyperméthrine	0.034
2022	Insecticides	Cyperméthrine	0.0125
2022	Insecticides	Imidaclopride 200	0.0122
2022	Insecticides	Cyperméthrine 25%	0.035
2022	Insecticides	Malathion	0.012
2022	Acaricides	Abamectine 18	0.022
2022	Acaricides	Bifenazate 480	0.032
2022	Herbicides	Glyphosate-sel d isopropylamine	0.0115
2023	Fungicide	Métalaxyl-m 20	0.038
2023	Insecticides	Cyperméthrine	0.0112
2023	Insecticides	Imidaclopride 200	0.0131
2023	Insecticides	Cyperméthrine 25%	0.022
2023	Insecticides	Malathion	0.0126
2023	Acaricides	Abamectine 18	0.024
2023	Insecticides	Bifenazate 480	0.032
2023	Herbicides	Glyphosatesel d isopropylamine	0.0115
2024	Fongicide	Métalaxylm 20	0.037
2024	Insecticides	Cyperméthrine	0.0104
2024	Insecticides	Imidaclopride 200	0.0123
2024	Insecticides	Cyperméthrine 25%	0.025
2024	Insecticides	Malathion	0.011
2024	Insecticides	Cyperméthrine	0.023
2024	Insecticides	Cyperméthrine	0.03
2024	Herbicides	Glyphosatesel d isopropylamine	0.0116
2025	Fungicide	Métalaxyl-m 20	0.034
2025	Insecticides	Cyperméthrine	0.0123
2025	Insecticides	Imidaclopride 200	0.0121
2025	Insecticides	Cyperméthrine 25%	0.024
2025	Insecticides	Malathion	0.0121
2025	Acaricides	Abamectine 18	0.023
2025	Acaricides	Bifenazate 480	0.033
2025	Herbicides	Glyphosate-sel d isopropylamine	0.0117

The results indicate chronic contamination of the environment by pesticide residues, with the recurring presence of active molecules on the 2022–2025 campaign. These results show a continuous and diversified use of agricultural pesticides.

1) Analysis of temporal trends

Table 5 presents Descriptive statistical analysis: This describes the average level of concentration of pesticides in groundwater over the entire period 2022–2025.

Table 5. Descriptive statistic

Descriptive Statistic	Average Concentrations (µg/L)
Mean	0.0241
Median	0.0212
Minimum	0.020
Stdev	0.0066
Skewness	1.1277
Kurtosis	2.3133
Jarque-berra	0.9254
Probability	0.6295
Sum	0.09640
Sum sq. Dev	0.000132
Observations	4

2) Temporal distribution and linear trend of pesticide concentrations

To assess temporal behavior, the measurement-level pesticide concentrations reported in Table 4 were plotted against sampling year for the 2022–2025 period.

Fig. 23 presents the resulting point cloud together with a single ordinary least-squares linear regression line. Each point represents one pesticide concentration measured in groundwater (µg/L); the horizontal axis corresponds to sampling year and the vertical axis to pesticide concentration. A small horizontal jitter was applied only to improve the separation of observations recorded in the same year, whereas the regression was fitted using the exact year values.

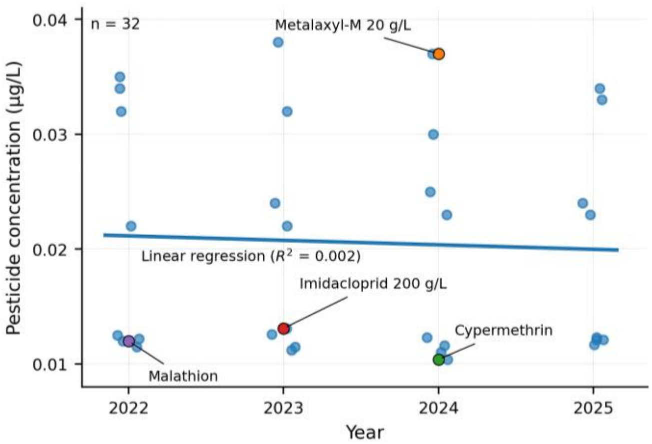

Fig. 23. Scatter plot of pesticide concentrations detected in groundwater from 2022 to 2025 with a single linear regression fit.

The fitted line is nearly horizontal ($R^2 = 0.002$), indicating no meaningful linear temporal association across the pooled observations. The dispersion around the line reflects substantial between-molecule variability. For example, Metalaxyl-M 20 g/L (0.037 µg/L in 2024) lies well above the fitted trend, whereas Cypermethrin (0.0104 µg/L in 2024) lies below it. Accordingly, the figure should be interpreted as evidence of heterogeneous concentrations over time rather than a strong monotonic increase or decrease.

Thus, this graph highlights a global relationship between the active molecules of pesticides and the variable studied, while highlighting the existence of substantial variations between substances.

According to the results cited on the graph, we can notice an initial decrease between 2022 and 2025, followed by a stabilization and then a slight increase in concentrations in 2022 (Table 6), this evolution suggests a variation over time in pesticide contaminations. This dynamic suggests an initial reduction in contaminants, probably related to changes in agricultural practices, then a moderate recovery.

Table 6. Relation between years and average pesticide concentration in groundwater

Year	Average Concentration (µg/L)
2022	0.0248
2023	0.0231
2024	0.0224
2025	0.0251

Cypermethrin is gradually decreasing and continues over the entire 2022–2025 period, indicating a reduction in pesticide use. Cypermethrin 25%, a relative increase at the beginning, then a marked drop until 2022, followed by stabilization at a low level. Imidacloprid presents a low level, a slight rebound in 2023, then stabilization. Metalaxyl-M represents relatively stable values, reflecting a limited presence for more controlled use. These results show the continuation of a multi-year monitoring, as well as an agricultural analysis in order to prevent any lasting increase in contamination levels.

A multi-year analysis conducted using EViews, based on panel data covering the period from 2022 to 2025, reveals a multi-year fluctuation in average pesticide concentrations. Descriptive statistics highlight variations in levels across years, while graphical analysis indicates a temporal trend [increasing/decreasing/stable]. The econometric analyses carried out attest to the [statistically significant] nature of these variations, which suggests a measurable evolution in contamination during the period considered.

3) Environmental risk assessment

The ecological risk assessment, which is necessary for authorizing the placing on the market of plant protection products, applies to the formulation and each active substance contained in it. This analysis is carried out in 3 distinct phases for various categories of environmental organisms or compartments: (i) the exposure assessment, (ii) the effects assessment, (iii) the risk assessment, which consists of a comparison between ecotoxic effects and potential exposures. The tools used to characterize the fate of substances and evaluate effects range from laboratory tests to tests conducted on simplified ecosystems.

Pesticides are defined as the active chemical substances present in plant protection products or phytosanitary products intended for plant protection, as well as biocides, such as disinfectants, insecticides, rodenticides or wood preservatives. These substances have a general or targeted action on harmful organisms, including plants (weeds), animals (insects, mites, molluscs, etc.), fungi or bacteria.

The European Union requires the assessment of potential environmental risks of pesticides before they are approved for use within its territory. Environmental Risk Assessments (ERAs) of pesticides are used to estimate their risks by analyzing their environmental fate and ecotoxicity. The environmental fate of a pesticide refers to the evolution of its physicochemical characteristics and its distribution after its dispersion in the surrounding environment. For example, it is the process of degradation of a pesticide, its potential accumulation in soil, and/or its transformation into different chemical compounds. Ecotoxicology examines the impact of a pesticide on various living organisms, including birds, mammals, plants, insects, and fish. These assessments identify and define the risk of potential adverse effects of pesticides on non-target organisms, ecosystems, and biodiversity.

Table 7. Risk assessment concentration data for each insecticide detected in 2018

Insecticide	Ec50 (mg/l)	Lc50 (mg/l)	Kd (l/kg)	Log koc	Log kow	Koc [mg/L]	Foc	Pnec (mg/L)
Abamectine	6.300	180.000	53.300	4.325	4.400	1.400	38.071	0.006
Aldrine	0.028	0.006	0.245	6.390	6.500	17.500	0.014	0.000
Bifenazate	0.500	0.058	23.100	3.342	3.400	1.778	12.992	0.001
Cadusafos	0.001	0.040	4.800	3.785	3.850	0.227	21.145	0.000
Chlorpyrifos-ethyl	0.160	0.001	0.001	4.915	5.000	2.340	0.000	0.000
Cyantraniliprole	0.020	1.200	3.730	1.681	1.710	0.241	15.477	0.000
Cypermethrine	0.000	0.013	54.350	6.822	6.940	30.758	1.767	0.000
Deltamethrine	0.001	0.000	37.900	5.997	6.100	1.024	37.012	0.000
Diazinon	0.001	0.004	27.100	3.736	3.800	0.609	44.499	0.000
Dieldrine	0.250	13.300	20.010	5.308	5.400	1.245	16.072	0.000
Endosulfan-sulfate	150.000	0.074	1500.000	3.559	3.620	0.526	2851.711	0.150
Ethoprophos	0.200	0.320	2.240	2.939	2.990	0.070	32.000	0.000
Fenazaquine	0.004	91.000	54.000	5.613	5.710	9.995	5.403	0.000
Fenthion	0.001	15.400	1.830	0.521	0.530	0.018	101.667	0.000
Flubendiamid	0.060	0.060	4.00	4.129	4.200	2.197	2.139	0.000
Imidacloprid	67.200	7.300	4.180	0.561	0.570	0.302	13.841	0.067
Indoxacarb	0.170	0.750	46.300	4.571	4.650	4.483	10.328	0.000
Malathion	0.000	0.000	1.320	2.320	2.360	1.800	0.733	0.000

EC_{50}: Median Effective Concentration (concentration causing 50% effect). LC_{50}: Median Lethal Concentration (concentration causing 50% mortality). Kd: Soil–water distribution coefficient. koc: Organic carbon partition coefficient. kow: Octanol–water partition coefficient. Foc: Fraction of organic carbon in soil. Pnec: Predicted No Effect Concentration.

The term "Pesticide" is frequently used as a synonym for "Plant protection product". Nevertheless, this terminology encompasses a broader concept, integrating other products, such as biocides, whose use is not intended on plants. These products are used for the control of pathogens and disease vectors, such as insects, rats or mice, and do not fall under the European Food Safety Authority (EFSA). The concentration levels of each insecticide detected during the 2018 monitoring campaign, along with their primary toxicological and environmental thresholds, are detailed in Table 7. These data serve as the basis for calculating risk quotients and enable the identification of substances with the highest potential for environmental degradation.

Plant protection products are therefore a category of pesticides and are mainly used to protect crops and prevent their destruction due to disease or infestation. They include herbicides, fungicides, insecticides, acaricides, growth regulators and repellents. They contain at least one active substance. An active substance may consist of a chemical, a microorganism or even a virus, which gives it the capacity to perform its function. A significant proportion of the risk assessments carried out by the European Food Safety Authority (EFSA) in the sector of plant protection products relate to these active substances [22]; they serve as the basis for the risk analysis conducted here, using the insecticide concentration data recorded during the 2018 sampling campaign [22].

D. Relationship between Contaminants and Agricultural Practices

Contamination of agricultural soils is mainly the result of agricultural practices such as crop protection, fertilization with residual fertilizers or the use of plastic films and pipes. Sustainable agricultural practices, like agroecology, aim to reduce the use of plant protection products, preserve nutrients and ensure the preservation of resources for future generations. These approaches aim to ensure that productivity is maintained while ensuring the protection of public health and the environment.

The term "Pesticide" is frequently used as a synonym for "Plant protection product". Nevertheless, this terminology encompasses a broader concept, integrating other products, such as biocides, whose use is not intended on plants. These products are used for the control of pathogens and disease vectors, such as insects, rats or mice, and do not fall under the European Food Safety Authority (EFSA).

Plant protection products are therefore a category of pesticides and are mainly used to protect crops and prevent their destruction due to disease or infestation. They include herbicides, fungicides, insecticides, acaricides, growth regulators and repellents. They contain at least one active substance. An active substance can be made up of a chemical compound, a microorganism or even a virus and gives the product its functionality. A considerable proportion of the risk assessments carried out by the European Food Safety Authority (EFSA) in the sector of plant protection products relate to these active substances.

1) Measuring the effectiveness of pesticide management and regulatory policies

Management of the effectiveness of pesticide management and regulation policies is based on a set of criteria and phases. These criteria include the assessment of health and environmental risks, the identification and quantification of hazards, as well as the estimation of exposures. The pesticide risk assessment and management procedure has been significantly formalized over the last decades, particularly as a result of European integration. The evaluation of active substances is carried out by the European Food Safety Authority, while commercial preparations are subject to an assessment by member states. These assessments are mutualised and harmonized in accordance with guidelines issued by the European Food Safety Authority (EFSA) or other transnational organizations, such as the Organization for Economic Co-operation and Development (OECD) [23].

2) The detection of pesticides in water

To evaluate the product's effectiveness, an experimental plot was created to exhibit uniform density and a diversity of weed species specific to vegetable crops. The floristic composition must align with the particular action spectrum of the product being examined. The trials should be conducted in various regions of West Africa, characterized by different agroclimatic conditions, preferably over several years or distinct growing seasons. The cultivation conditions must be homogeneous for all trial plots and comply with the recommended local practices.

Analyze the sample, the comparison product, and the untreated control. Align the experimental setup with the trial's objectives. For efficacy evaluation, use adjacent control plots with treated and untreated areas. For mono-specific weed infestation and efficacy evaluation, use randomized Fisher blocks. Plot size depends on the vegetable crop and treatment equipment.

Arrange the plot non-uniformly for perennial weed analysis, depending on infestation zones. Practical herbicide evaluations commonly measure the biological efficacy of pesticides. Include the product at a specific dose, the reference product, and the local control group. Distribute plots using a randomized block design. Carry out at least 10 repetitions for each object.

The size of the plots depends on the type of vegetable crop and the tools used for planting. Depending on the method of cultivation chosen, such as bed cultivation or open field cultivation, these techniques may differ. In this case, the dimensions are usually 100 square meters or more. When treatments can interact with one another, it is essential to take steps to ensure the plots are well-separated. The outcomes of the trials should be shown in a clear and organized way. Statistical analyses of the results must be clearly outlined [14].

3) Presentation of the pesticides used in the study area

Fig. 24 presents the evolutionary trend of residual concentrations detected for the four primary categories of phytosanitary products during the study period. The analytical results indicate relative stability in the levels of herbicides, acaricides, and insecticides, with values fluctuating near the 0.01 μg/L threshold. However, a significant divergence is observed for fungicides, which peak at a concentration of 0.033 μg/L. This finding confirms the predominant chemical pressure exerted by this class of compounds, correlating directly with the high sales volumes (76.5 tons) reported previously. Ultimately, these data underscore the heightened vulnerability of local water resources to the intensive antifungal treatments applied within the region.

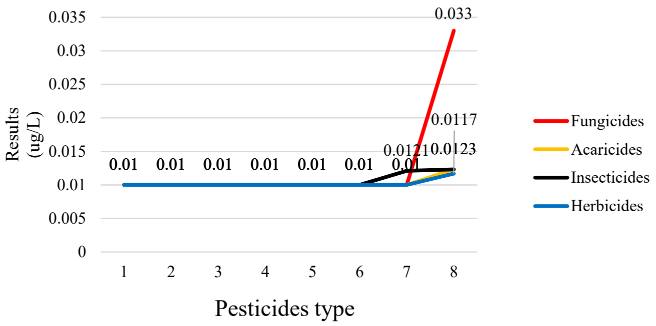

Fig. 24. Analysis and evolution of pesticide concentration levels in the full area of Feija.

The selection of these sample sizes adheres to a deliberate, context-specific methodological framework that aims to encompass the variety of agricultural practices and exposure pathways while accounting for logistical and analytical limitations (Table 8). Despite the seemingly limited number of wells, they were selected for their spatial representativeness, predominant agricultural use, and probable pesticide exposure, thereby facilitating the identification of significant trends in groundwater quality. However, we recognize that the sample size and the very brief monitoring duration restrict the direct extrapolation of the findings to other areas of Morocco. Consequently, the results should be regarded as context-dependent, mostly relevant to regions with analogous agri-environmental and hydrogeological characteristics. Table 8 presents the use of pesticides in the study area of Feija.

Table 8. Concentrations of active molecules detected in the wells studied and their corresponding results

Wells	Pesticides	Results (µg/L)
P1	No detected	No detected
P2	Fungicide	0.034 ± 0.012
P2	Acaricide	0.033 ± 0.014
P3	No detected	No detected
P4	Insecticides	0.0121 ± 0.006
P4	Acaricides	0.023 ± 0.012
P5	Insecticides	0.0121 ± 0.006
P5	Acaricides	0.0117 ± 0.006
P6	No detected	No detected
P7	No detected	No detected
P8	No detected	No detected

There is a significant increase particularly, for fungicides, reaching higher values (up to 0.033 µg/L). This increase indicates stronger agricultural pressure and more intensive use of fungicides. On the other hand, an average increase is mainly observed for herbicides, which reflects an average use of herbicides. Some pesticides remain poorly detected, revealing spatial variability and resulting in differentiated agricultural practices or distinct environmental behaviors. Overall, the results indicate a spatial heterogeneity of pesticide contamination, with generally low levels but higher concentrations for certain pesticides.

4) Level of pesticide detection in water

Fig. 25 presents the concentrations of active molecules in the wells studied and their corresponding trade names. At well P2, a fungicide (metalaxyl-M) was detected at a concentration of 0.034 µg/L, an acaricide (bifenazate) at 0.033 µg/L, and finally an insecticide (cypermethrin 25%) at 0.024 µg/L. These values are the highest, indicating that well P2 is highly exposed to pesticide infiltration from nearby cropland. At well P4, the presence of an acaricide (abamectin) was observed at a concentration of 0.023 µg/L, along with an insecticide (imidacloprid) at a concentration of 0.0121 µg/L. Other pesticides were detected at very low concentrations in well P5. The water from well P5 is characterized by the presence of a herbicide (glyphosate–isopropylamine salt) at a low concentration of approximately 0.0117 µg/L, along with 2 insecticides whose respective concentrations are 0.0121 µg/L and 0.0123 µg/L.

Groundwater analysis in the Feija plain reveals a marked polymetallic contamination (Table 9), characterized by a massive predominance of Iron (Fe), with concentrations ranging from 299.6 to 415.9 µg/L, significantly exceeding organoleptic comfort thresholds. This high presence of iron, accompanied by stable levels of Manganese (Mn) (approximately 90 µg/L), reflects a natural lithological signature linked to the dissolution of minerals from the bedrock in the Zagora region. However, the most concerning aspect lies in the systematic detection of highly toxic heavy metals such as Lead (Pb) (up to 14.5 µg/L), Chromium (Cr) (22.7 µg/L), and Cadmium (Cd) (up to 4.3 µg/L). The presence of these elements, particularly in well P6, which appears as the most polluted site, suggests an anthropogenic origin linked to intensive agricultural activity in the plain. The excessive use of phosphate fertilizers and pesticides for watermelon cultivation is the probable source of this Cadmium and Lead flux through infiltration into the aquifer. From a health perspective, exceeding WHO drinking water standards for lead and cadmium poses a real risk of bioaccumulation for local populations, potentially leading to long-term renal and neurological disorders. This situation highlights the urgent need to implement precise cartographic monitoring to identify pollution hotspots and protect this vital resource in a context of severe water stress [23].

Table 9. The average concentration and standard deviation of certain heavy metals in the water from the 8 wells on the Feija Plain (Zagora) in 2024. (All values are in µg/L)

Wells	Pb	Cd	Cr	Cu	Zn	Fe	Mn	Ni
P1	12.6 ± 0.7	3.3 ± 0.6	22.7 ± 0.82	42.8 ± 0.32	89.3 ± 1.76	299.6 ± 0.33	93.4 ± 1.66	20.9 ± 0.99
P2	14.3 ± 0.8	3.7 ± 0.5	18.2 ± 0.77	44.7 ± 0.3	88.0 ± 1.77	312.2 ± 1.2	83.6 ± 0.3	24.6 ± 1.0
P3	13.2 ± 0.6	3.6 ± 0.55	21.8 ± 0.81	42.7 ± 0.54	98.3 ± 1.6	323.8 ± 1.1	88.7 ± 1.4	23.3 ± 1.9
P4	12.1 ± 0.4	4.3 ± 0.2	17.0 ± 0.22	40.9 ± 0.3	78.0 ± 1.7	343.4 ± 0.5	91.6 ± 1.1	21.6 ± 1.6
P5	13.3 ± 0.7	4.2 ± 0.5	20.7 ± 0.7	46.8 ± 0.2	104.4 ± 1.6	300.2 ± 0.2	92.4 ± 1.6	22.5 ± 0.55
P6	14.5 ± 1.2	3.8 ± 0.7	22.5 ± 0.6	50.7 ± 0.77	106.8 ± 1.6	415.9 ± 0.5	88.9 ± 0.66	23.9 ± 1.6
P7	14.2 ± 0.77	3.2 ± 0.76	18.9 ± 0.66	41.5 ± 0.4	99.6 ± 1.77	353.2 ± 0.65	91.5 ± 1.2	23.7 ± 1.5
P8	12.9 ± 1.2	3.9 ± 0.9	21.8 ± 0.8	44.0 ± 0.3	101.7 ± 1.1	345.8 ± 0.33	94.6 ± 0.64	24.8 ± 1.3

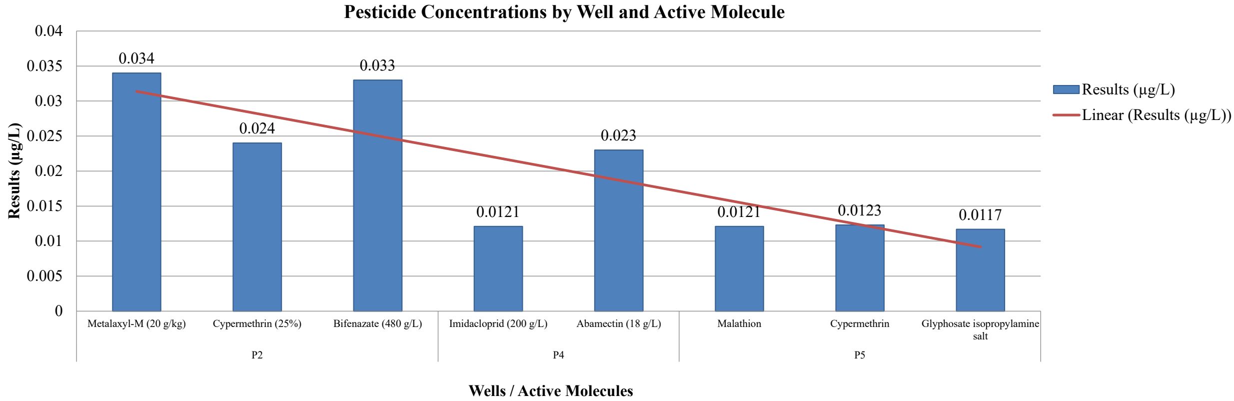

Fig. 25. Concentration of pesticides detected in the different wells in the study area.

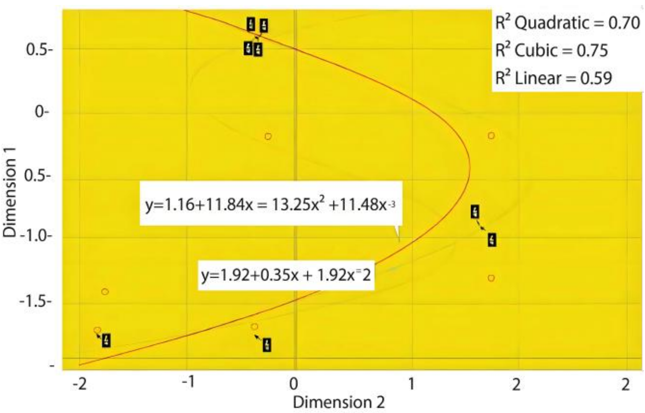

Fig. 26. The factorial map of the variation of concentrations at the level of the eight studied wells in the Feija plain.

The water from this well exhibits low pesticide concentrations but indicates multiple sources of contamination. A spatial variability is therefore observed: P2 is the most contaminated well, followed by P5, which presents lower concentrations but a more diversified range of pesticides, and finally P4, which also shows low concentrations.

The multivariate graph (Fig. 26) reveals a separation of wells according to the type and dose of pesticides present in their water. The most polluted wells (P2 and P5) are located in isolated areas, reflecting a specific chemical signature, whereas P4 appears more central, indicating lower concentrations.

The trend line (visible polynomial equations) highlights a non-linear relationship between pesticide variables and the spatial distribution of samples. The coefficients of determination (R2 = 0.76 and R2 = 0.66) indicate that the model explains the variance well and that the selected dimensions are representative. The 8 pesticides identified in this study remain below Moroccan, European, and World Health Organization standards.

5) The average concentration of some heavy metals in the water of the eight wells in the Feija Plain (Zagora)

Tables 10 and 11 present the representative concentrations calculated from 2 databases corresponding to the years 2024 and 2025. All values are expressed in micrograms per litre (µg/L). The results indicate that the concentrations of 3 heavy metals—lead, cadmium, and iron, are slightly higher than Moroccan standards, while the remaining detected elements show concentrations below national and international standards.

These tables present the average concentrations and their standard deviations for several heavy metals in the water from eight wells in the Feija Plain. The results make it possible to assess the chemical quality of groundwater, identify heavy metals likely to exceed regulatory standards, and evaluate the spatial variability of contamination between wells.

Table 10 presents the average concentration and standard deviation of certain heavy metals in the water from the eight wells of the Feija Plain (Zagora) in 2024.

The results show moderate contamination of groundwater by certain heavy metals, particularly lead, cadmium, and iron, whose concentrations exceed Moroccan standards. The other heavy metals present concentrations that remain below international and Moroccan standards.

This table presents the results of physicochemical analyses carried out on the water from 8 wells. It allows assessment of the chemical quality of groundwater, identification of the dominant heavy metals, comparison of contamination levels between wells, and evaluation of the spatial variability of concentrations.

Table 10 presents the average concentration and standard deviation of certain heavy metals in the water from the eight wells of the Feija Plain (Zagora) in 2025.

Table 10. The average concentration and standard deviation of certain heavy metals in the water from the 8 wells of the Feija Plain (Zagora) in 2025. (All values are in µg/L)

Wells	Pb	Cd	Cr	Cu	Zn	Fe	Mn	Ni
P1	13.2 ± 0.3	3.8 ± 1.1	23.1 ± 0.7	45.5 ± 0.6	112.3 ± 0.8	389.1 ± 0.7	95.6 ± 1.12	20.5 ± 1.0
P2	15.4 ± 0.9	4.2 ± 0.6	20.7 ± 0.67	47.2 ± 0.3	98.7 ± 0.62	412.0 ± 1.7	88.9 ± 0.3	25.1 ± 1.2
P3	14.1 ± 0.7	3.9 ± 0.5	22.4 ± 0.8	44.3 ± 0.2	106.5 ± 1.7	378.4 ± 1.6	92.2 ± 0.8	23.8 ± 1.4
P4	12.8 ± 1.6	4.5 ± 0.8	18.9 ± 0.9	41.7 ± 0.5	102.8 ± 0.44	365.7 ± 1.2	90.1 ± 0.6	21.9 ± 1.5
P5	13.9 ± 0.7	4.1 ± 0.51	20.3 ± 0.3	48.8 ± 0.6	110.6 ± 0.1	390.2 ± 1.1	93.3 ± 1.6	22.7 ± 0.7
P6	16.0 ± 0.6	4.4 ± 0.1	24.0 ± 0.6	50.2 ± 0.3	115.2 ± 1.2	400.3 ± 1.77	89.4 ± 1.6	26.5 ± 1.6
P7	14.8 ± 1.6	3.7 ± 1.7	19.6 ± 0.8	42.9 ± 0.5	103.9 ± 0.8	385.6 ± 0.4	91.0 ± 0.3	24.1 ± 0.2
P8	13.4 ± 1.2	4.3 ± 0.1	21.5 ± 0.4	46.1 ± 0.66	108.1 ± 0.55	392.8 ± 0.66	94.2 ± 0.4	23.3 ± 0.66

The results show persistent contamination of groundwater by certain heavy metals, particularly iron, lead, and cadmium, whose concentrations exceed Moroccan standards. However, other heavy metals present acceptable concentration levels. In 2025, the analysis of groundwater in the Feija Plain shows elevated concentrations of iron, lead, and cadmium in several wells, suggesting contamination related to agricultural activities and the chemical characteristics of the environment.

6) Comparison between the pesticides detected in groundwater in some regions in Morocco and California in the United States

Table 11 presents a comparison between pesticides detected in groundwater from selected regions of Morocco and California (USA) [13, 14].

Table 11. Comparison between pesticides detected in groundwater from selected regions of Morocco and California (USA)

Country/Region	Year	Matrix	Method	Substance	Concentration (µg/L)	Threshold exceeded
Morocco (Feija Plain)	2025	Groundwater	LC-MS/MS, GC-MS/MS	Malathion	0.0121 ± 0.006	Yes
Morocco (Gharb Plain)	2023	Groundwater	LC-MS/MS, GC-MS/MS	Malathion	0.005 ± 0.83	Yes
Morocco (Feija Plain)	2025	Groundwater	LC-MS/MS, GC-MS/MS	Imidacloprid	0.0121 ± 0.006	Yes
USA (California)	2021	Groundwater	GC-MS/MS, LC-MS/MS	Imidacloprid	0.022 ± 0.126	Yes

This table aims to compare the presence of pesticides detected in groundwater in Morocco and California. This table reveals that groundwater contamination by pesticides is a common problem in agricultural regions, both in developing countries and industrialized countries. An exceedance of the threshold was observed in Morocco and in California, highlighting the vulnerability of groundwater.

7) Pesticides application rates worldwide

Despite the pesticide reduction policies implemented in the European Union and other regions, Morocco uses a significantly lower number of pesticides than the international average. According to Food and Agriculture Organization of the United Nations (FAO) data compiled by Hort Info, Israel applies 12.61 kilograms of pesticides per hectare to its crops. In comparison, the Netherlands uses 7.90 kilograms per hectare, and Spain employs 3.59 kilograms per hectare for its crops. The levels of pesticide use in Chinese and Japanese crops are 13.07 kilograms per hectare and 11.76 kilograms per hectare, respectively. The consumption of pesticides per hectare of agricultural land amounts to 6.68 kilograms in Belgium, 6.14 kilograms in Italy, 5.95 kilograms in Brazil, 5.44 kilograms in Portugal, and 3.63 kilograms in France, slightly higher than that of Spain. In South Africa, another country facing issues related to citrus fruits exported to the European Union, the number of pesticides used is 2.16 kilograms per hectare of crop [24].

E. Discussions

The results obtained reveal the presence of various pesticide molecules in groundwater samples collected from the investigated wells. Concentrations vary from one well to another, with higher values recorded particularly in wells P2, P4, and P5, ranging from 0.033 to 0.034 mg/L. In contrast, other wells show significantly lower concentrations or levels below the detection limit (ND), as detailed in Table 12.

Table 13 presents a summary of pesticide contamination indicators used in the study. This spatial diversity reflects generalized groundwater contamination mainly attributable to agricultural activities, but it is also influenced by the proximity of pollution sources such as treated fields, surface runoff, and soil infiltration processes. Wells located near intensively cultivated and frequently treated areas naturally exhibit the highest pesticide concentrations. According to international standards established by the World Health Organization (WHO) and the European Union (EU), some measured values exceed or approach the Maximum Residue Limits (MRLs) defined for drinking water (0.1 µg/L for an individual pesticide and 0.5 µg/L for total pesticides in the EU). This situation suggests a potential risk to human health, particularly in cases of long- term consumption of contaminated water.

Table 12. Detection limits of pesticides in groundwater samples

Pesticide	Detection Limit (µg/L)
Malathion	0.01
Imidacloprid	0.01
Cypermethrin	0.01
Metalaxyl-M	0.01
Glyphosate	0.02

Although some wells remain below regulatory thresholds, the frequent detection of multiple pesticide residues indicates chronic contamination that requires enhanced monitoring. Surveys conducted among farmers highlight a substantial use of plant protection products, often characterized by high application rates that may exceed technical recommendations. The intensive use of insecticides and herbicides is clearly correlated with the pesticide molecules detected in groundwater. These observations reveal a strong link between reported agricultural practices and the analytical results. Furthermore, some agricultural operators tend to underestimate environmental risks, which contributes to the continued intensive use of chemical inputs.

Table 13. Summary of pesticide contamination indicators used in the study

Indicator	Description	Unit
Mean concentration	Average pesticide level	µg/L
Maximum concentration	Highest observed value	µg/L
Detection frequency	Percentage of positive samples	%
Risk threshold	Regulatory reference value	µg/L

These findings are consistent with studies conducted in other regions of Morocco and internationally, which emphasize the vulnerability of aquifers to pesticide contamination. For example, research carried out in the Gharb and Souss-Massa regions reported similar elevated levels, particularly for organophosphorus insecticides.

Consequently, the present analysis confirms that current plant protection practices significantly contribute to groundwater pollution.

The detection of pesticides in drinking water raises a dual concern. From an environmental perspective, it reflects a deterioration in water resource quality, which is critical for both agricultural and food systems. From a public health perspective, chronic exposure—even at low concentrations—may lead to adverse effects such as endocrine disruption, neurotoxicity, and increased carcinogenic risk.

It is therefore essential to promote more rational pesticide management strategies. These include farmer training, which is a key component in agricultural development, the implementation of alternative practices such as Integrated Pest Management (IPM) and the use of biopesticides, as well as systematic monitoring of water quality. Such measures are crucial to ensure the sustainable development of the agricultural sector while protecting human health and the environment.

In the Feija Plain, the presence of pesticides in groundwater at concerning concentrations highlights the impact of inappropriate local agricultural practices. The contamination observed is largely associated with intensive pesticide use and inadequate management strategies. Corrective measures must therefore be implemented to safeguard public health and environmental quality, including the promotion of environmentally friendly pest control alternatives.

The results of this study demonstrate the detection, identification, and quantification of several pesticide compounds in groundwater. Although concentrations vary among wells, the overall pattern indicates diffuse pollution closely linked to local agricultural practices and the intensive use of synthetic plant protection products. This situation underscores the need for alternative management approaches and continuous environmental monitoring. Similar contamination patterns were reported by Qryefy *et al.* [26] in the Gharb Plain, where groundwater pollution was mainly associated with organophosphorus insecticides and pyrethroids.

In Morocco, analyses conducted in the Feija Plain generally reveal low pesticide concentrations; however, exceedances of regulatory thresholds were observed in approximately 50% of the samples. These findings suggest prolonged pesticide application combined with aquifer vulnerability related to local hydrological conditions. In California, despite stricter regulatory frameworks, imidacloprid has also been detected in groundwater at concentrations exceeding the threshold value of 0.126 µg/L. This elevated concentration reflects intensive agricultural activity and the extensive use of insecticides characterized by high soil mobility.

The empirical results highlight an agro-environmental dynamic characterized by a strong dependence on chemical inputs and a notable vulnerability of groundwater resources in the Fejja plain (Zagora). The analysis of agricultural practices indicates a predominant use of insecticides and acaricides, which reflects a phytosanitary pressure primarily focused on pest control. This situation results both from the bioclimatic constraints specific to semi-arid zones and from the lack of integrated pest management approaches. The vast majority of farmers reporting regular pesticide use confirms the structural nature of this chemical dependency.

At the same time, the level of knowledge among farmers about the different types of pesticides and fertilizers remains limited. The high proportion of operators who do not master the technical specifics of the products used constitutes a central explanatory factor for the observed environmental pressures. Insufficient training promotes practices such as overdosing, repeated and uncontrolled application, as well as the inappropriate use of mixtures, which increases the risks of transfer to soils and groundwater. This issue therefore goes beyond the purely agronomic dimension and falls within a broader perspective that includes agricultural governance, technical supervision, and the effectiveness of extension services.

The physicochemical analyzes confirmed the presence of pesticide residues in several wells studied. Although in the majority of cases, the individual concentrations measured remain below the recommended international thresholds, their repeated detection indicates a process of diffuse contamination. The statistical distribution of concentrations, marked by positive skewness and the presence of outliers, reveals the existence of localized vulnerability zones. This spatial heterogeneity results from the variable intensity of agricultural practices and specific hydrogeological properties that favor infiltration.

The simultaneous presence of heavy metals such as iron, zinc, copper, chromium, cadmium, lead, manganese, and nickel supports the hypothesis of cumulative anthropogenic pressure. Although some elements may originate from geogenic sources, others, such as cadmium and lead, are often linked to the use of phosphate fertilizers and certain phytosanitary formulations. The levels recorded in certain wells thus indicate an interaction between agricultural contributions and the natural dynamics of the soils. A comparison with studies conducted in other agricultural regions confirms that the local situation is part of a broader context of agricultural intensification, which leads to increased environmental constraints.

The descriptive statistical analysis highlights a significant variability in concentrations, indicating heterogeneous pollution. The coefficients of skewness and kurtosis indicate a distribution centered around low values, but marked by notable peaks. This configuration is typical of diffuse pollution related to agricultural activities, where repeated inputs gradually lead to localized accumulations.

From a global perspective, the results highlight an agroecological system under increasing pressure, where productivity gains related to the intensive use of chemical inputs generate measurable environmental externalities. Although the detected concentrations do not systematically exceed international standards, the persistence of residues and the risk of cumulative or synergistic effects justify the adoption of a preventive approach.

V. Conclusion

The intensive use of pesticides is one of the greatest threats to the quality of surface and groundwater resources. After irrigation of crops, these chemicals can either be absorbed by the cultivated plants or carried away by rainwater runoff, ultimately ending up in rivers, lakes, or groundwater, where they can cause widespread and lasting pollution. This could lead to the disruption of aquatic ecosystems, and this persistent pollution would compromise the quality of drinking water. Some pesticides are highly persistent, accumulating in living organisms and remaining in the environment for months or even years. These products would have an impact on the biodiversity of ecosystems. The residues of phytosanitary products would affect non-phytopathogenic organisms, such as fish, invertebrates, and microalgae, leading to severe biological imbalances in ecosystems. Plant-based buffer zones and drainage water treatment systems would be agricultural innovations that could help reduce the transfer of these substances.

GC-MS was used for the detection and quantification of pesticides present in the water samples from the studied wells. The analysis of heavy metals, on the other hand, revealed that the metal concentrations in the well water samples varied among them and were lower than the Moroccan and who standards, except for lead, cadmium, and iron. However, this research has a certain limit, the limited number of the wills and short monitoring period, this research opening at the future researches.

Conflict of Interest

The authors declare no conflict of interest.

Authors Contributions

Hamid Nadi: Data collection, analysis, and interpretation. Reviewing the literature and writing the paper. Hicham Ouhakki: Reviewing the literature. Naima Dohou: Reviewing the literature. Khalid Yamni: Conceptualization methodology, supervision, and final revision. Moulay Laarbi Ouahidi: Data collectionon. Nabila Auajjar: Reviewing the literature. All authors had approved the final version.

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