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Article

Sustainability Indicators for the Environmental Impact Assessment of Plant Protection Products Use in Moroccan Vineyards

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Abstract: The Sebou River Basin is vital for Moroccan agriculture, particularly in terms of producing industrial crops, fruits, vegetables, and olive oil. It is especially significant in viticulture, accounting for 80% and 60% of the national production area for wine and table grapes, respectively. However, the prevalence of diseases and pests requires extensive pesticide application in vineyards. This study aims to assess the impact of pesticides used in vineyards on the environment, human health and their associated sustainability. Agro-environmental indicators were evaluated across 30 vineyards covering 1197 hectares. Results show an average treatment frequency of 24.05 applications per growing cycle, the highest among grape-producing countries, with 77.94% being fungicides. The Quantity of Active Substances Indicator (QASI) reveals a high pesticide application rate of 44.60 Kg a.i./ha. Over 50% of chemicals are classified as "hazardous" based on the Environmental Impact Quotient (EIQ). A Pesticide Environmental Risk Indicator model (PERI) identifies three active ingredients with a high Environmental Risk Score (>5). Life Cycle Assessment (LCA) reveals that copper sulfate has significant environmental impacts compared to Mancozeb and sulfur. These findings highlight the extensive use of pesticides in vineyards, posing challenges to long-term sustainable agriculture due to associated environmental and health risks.

Keywords: grapevine; agro-environmental indicator; LCA; ecological risk; vineyard

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1. Introduction

Grapevine (*Vitis vinifera* L.) global production covers 7.2 million hectares, yielding over 79 million tons in 2022, marking it as a paramount fruit crop [1]. Grapes are versatilely enjoyed, whether consumed fresh or transformed into various products like wine, jam, juice, raisins, vinegar, and more [2]. In Mediterranean basin countries, including Morocco, the cultivation of grapevine holds significant socio-economic importance. In 2021, Morocco achieved a national grape production of 420,113 T, cultivated across 39,336 ha, boasting an average yield of 10.6 T/ha [3]. However, the phytosanitary challenges facing grapevine cultivation pose a significant obstacle to the advancement of the Moroccan vine sector [4]. Grapevines are highly susceptible to various diseases caused by bacteria, fungi and oomycetes, including powdery mildew (*Erysiphe necator*), downy mildew (*Plasmopara viticola*), gray mold (*Botrytis cinerea*), black rot (*Guignardia bidwellii*), Pierce's disease (*Xylella fastidiosa*), and crown gall (*Allorhizobium vitis*) [5–7], and pests such as the European grapevine moth (*Lobesia botrana*), mealybugs (*Planococcus ficus*), and grape leafhopper (*Empoasca vitis*) [8,9].

Furthermore, grapevines are susceptible to various abiotic stresses, with climate change emerging as a significant global and regional challenge affecting grapevine production [10]. The increased temperature, reduced precipitation, and water availability are already triggering significant negative impacts on the sector [11]. The Mediterranean region, experiencing a 20% faster warming rate than the global average, faces substantial consequences, particularly for economically important crops like grapevines [12,13]. The changes in climatic factors significantly influence the physiological state and phenological stages of grapevines, and the interaction between crops and pathogens, thereby exacerbating the incidence and severity of diseases and influencing disease management strategies [11].

While pesticides can enhance crop yields, with a global average application rate reaching 2.26 kg/ha in 2021 [14], their excessive use leads to serious concerns due to their potential toxicity, bioaccumulation, and environmental persistence [15]. Given the prevalence of diseases and the absence of genetically resistant grapevine varieties that yield high-quality fruit, winegrowers have resorted to extensive pesticide application to ensure consistent production of high-quality grapes [2]. These chemicals can contaminate air, water, soil, and the ecosystem, threatening the health of living organisms [16]. This concern assumes heightened significance within Mediterranean vineyards, characterized by their substantial reliance on pesticides as an integral component of their crop management system [17].

The influence of pesticides on overall bacterial biomass and enzyme activity within the living components of soil has been documented previously [18]. Several studies have shown the impact of pesticides on vineyard soil contamination, highlighting the accumulation of substances such as copper, commonly utilized to protect grapevine against fungal and oomycete diseases [19–21].

Groundwater and surface water contamination by agrochemicals used in vineyards is a pressing issue, often surpassing the limits for the Environmental Quality Standard (EQS) for groundwater, which is set at 1 μg/L for an active substance [22,23]. Several studies have reported pesticide contamination of groundwater in the Saïss Basin region. Radouane et al. [24] found that 30% of sampled sites were classified as unsuitable for human consumption, while Aakame et al. [25] detected the presence of pesticides in all water samples. Additionally, Berni et al. [26] highlighted a high ecological risk associated with the Saïss aquifer due to the presence of pesticides.

Life Cycle Assessment (LCA) is a comprehensive method used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through materials processing, manufacture, distribution, use, repair, and maintenance, to disposal or recycling. In the context of plant protection products (PPPs), LCA helps in understanding the environmental consequences of producing and using pesticides in agricultural practices. It assesses various impact categories such as ecotoxicity, eutrophication, and global warming potential [27]. Moreover, in the research study by Bragaglio et al. [28], it has been demonstrated that LCA can be an effective tool for evaluating precision agriculture strategies in livestock systems. By comparing a conventional dairy farm to one utilizing precision agriculture, the study reveals that the latter can offer enhanced environmental sustainability, thereby supporting the potential of advanced agricultural technologies to improve overall sustainability in animal farming.

In Morocco, winegrowers are currently facing a knowledge gap regarding the management and phytosanitary practices employed, hindering a comprehensive assessment of their environmental impact, despite the preservation of natural resources and sustainability of agricultural development being foundational aspects of the national agricultural strategy within the framework of the Generation Green vision 2020–2030. Consequently, it is crucial to undertake studies that scrutinize the environmental fate of these practices and evaluate the sustainability of pesticide use. To achieve this, various agro-environmental indicators have been devised to support the evaluation of risks to the environment and human health.

These indicators could assist farmers and stakeholders in evaluating the environmental effects of different pesticides, facilitating comparative analyses, and devising efficient control strategies with reduced environmental impacts.

The aim of this research is to assess the impacts of pesticide use within vineyards situated in the Sebou Basin in Morocco. This effort involves a detailed examination of agro-environmental indicators and Life Cycle Assessment (LCA) with the overarching goal of advocating for judicious applications of plant protection products and promoting the adoption of sustainable phytosanitary methodologies in the region.

Our study focuses on the assessment of risk indicators, including the Treatment Frequency Index (TFI) and the Quantity of Active Substances Indicator (QASI), which is used to evaluate the intensity of pesticide application [29,30]. Additionally, we employed the Environmental Impact Quotient (EIQ) as an indicator to evaluate potential ecological and health hazards associated with agricultural pesticides [31,32]. To evaluate potential risks associated with pesticide application, we used the Pesticide Environmental Risk Indicator (PERI), a composite amalgam of multiple indicators aimed at establishing a comprehensive framework to understand pesticide impacts. From this perspective, agro-environmental indicators can serve as a monitoring mechanism to reduce the use of pesticides in the Sebou Basin. Finally, LCA was used to evaluate the impacts due to the production of the most commonly used plant protection products in the Sebou Basin.

2. Materials and Methods

2.1. Study Area

The Sebou River Basin (SRB) (Figure 1), located between latitudes 33° N and 35° N and longitudes 4° W and 7° W, is an important area for Morocco's economy [33]. Encompassing an area of 40,000 square kilometers and inhabited by a population of 6.2 million, who are mainly engaged in agriculture, the SRB includes 17 provinces, 74 urban centers, and 288 rural communities. The region boasts 1.8 million hectares of agricultural land, with 357,000 hectares irrigated, and 92% of its water resources are devoted to agriculture. It is also home to over 1.8 million hectares of forests [34]. The SRB plays a pivotal role as a center for the cultivation of industrial crops, olive oil, fruit, and vegetable crops.

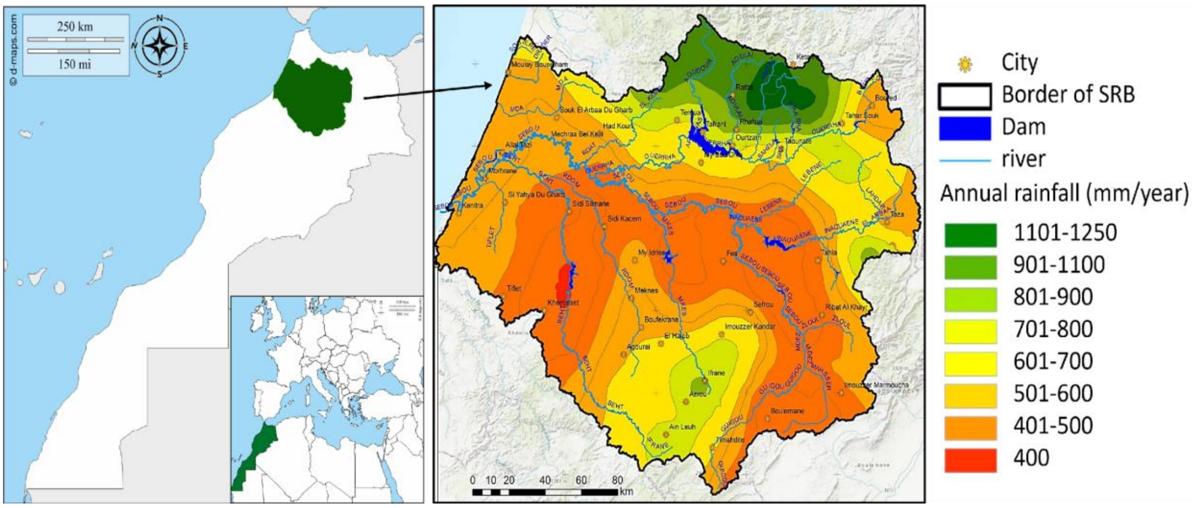

Figure 1. Geographical position of the investigated area (Sebou Basin, Morocco) [35,36].

2.2. Survey Execution

In the Sebou Basin, thirty vineyard owners were randomly selected to collect data on vineyard management practices. The data collection was conducted from March to June 2022 and included 25 rural communities. A data collection form was used to gather information on the grape-farming practices and phytosanitary measures used by producers in the Sebou Basin. Throughout the survey, we reached out to either the vineyard owner or the manager. The form covered the following: (1) basic information about the respondent, such as gender, age, and educational level (optional); and (2) production practices (yield obtained in the past three years, equipment used, significant pests and diseases, management practices, and use of chemical products). The data on grape production were based on the activities of the 2021 agricultural season. Consent was obtained from the respondents before recording their information and the data were processed by the general data protection regulations.

2.3. Agro-Environmental Indicators

2.3.1. Pesticide Intensity Index

The intensity of pesticide utilization in Sebou Basin vineyards was unveiled through the evaluation of agro-environmental indicators (Table 1). The first indicator is the number of treatments (NT), i.e., the total number of treatments administered throughout a growing season each time the vineyard received a treatment [29]. A treatment involves the application of a single product in a single pass, with dual-product applications during the same pass counted as two treatments. The Quantity of Active Substances Indicator (QASI) is a direct measure of the amount of active ingredients used per hectare [37]. The impact of pesticides was also assessed using the Treatment Frequency Index (TFI) [38]. The TFI is calculated for all pesticide applications on each vineyard (referred to as total TFI) and for individual pesticide categories ($TFI_{Fungicides}$, $TFI_{Insecticides}$, $TF_{Herbicides}$). Elevated TFI levels indicate frequent use and use at doses higher than those officially approved [39].

2.3.2. Environmental Impact Quotient (EIQ)

To assess trends in grapevine pesticide usage and their impacts on the environment, farmworkers, and consumers, we used the EIQ model as a risk indicator. This model efficiently synthesizes toxicological data on grapevine pesticides into a practical tool for addressing environmental concerns in agriculture [40]. Kovach et al. [40] further elaborated on the components that constitute this risk indicator, grouping them into a unified equation divided into three distinct sections (Table 1): "farmworker risk" (consisting of C, DT, and P), "consumer risk" (consisting of C, S, P, SY, and L), and "ecology" (consisting of F, R, D, S, P, Z, and B). The EIQ values were obtained from the EIQ Calculator website of New York State Integrated Pest Management to ensure the elimination of any potential inaccuracies [41]. For each pesticide, the dose, percentage of active ingredient in the product, and frequency of application were evaluated to determine the field use rating [42].

2.3.3. Pesticide Environmental Risk Indicator Model (PERI)

The development of the PERI model originated from the ISO 14001 certification process [43]. Its primary objective is to carry out a comprehensive analysis of the environmental risk related to pesticide use and to evaluate the associated risks [44]. By integrating groundwater, surface water, and air variables, the PERI model generates an Environmental Risk Score (ERS) based on toxicity and environmental fate [43].

Detailed information about the PERI model is available through the American Farmland Trust Centre for Agriculture in the Environment [45]. The model employs a ranking methodology to assess the properties and toxicity levels of pesticides using a scale ranging from 1 to 5 [46]. According to the American Farmland Trust [45], a more accurate evaluation of risk was attained by calculating the final environmental risk (F-ERS) indicator (Table 1). To facilitate the interpretation and comparison of final ERS indicator values and assess the risk linked to commonly used pesticides in the SRB, normalization of these values was required. This process entailed taking the active substance with the highest final ERS value as the reference for normalization. The normalized risk values were then derived by comparing them with the selected reference value.

Table 1. Agro-environmental indicators and Pesticide Environmental Risk Indicator model (PERI).

Indicator	Formula	References
Number of Treatments (NT)	Total number of treatments that occur during a growing season	[29]
Quantity of Active Substances Indicator (QASI)	QASI = Use of pesticides × Concentration of active ingredient	[37]
Treatment Frequency Indicator (TFI)	$\text{TFI} = \sum x = \frac{ARt}{HRt} \times \frac{TAt}{PAt}$	[47]
Environmental Impact Quotient (EIQ)	EIQ = {C(DT × 5) + (DT × P)] + [(C × (S + P)2 × SY] + (L)] + [(F × R) + (D × (S + P)/2 × 3) + (Z × P × 3) + (B × P × 5)]}/3	[40]
Environmental Impact Quotient Field Use Rate (EIQ-FUR)	EIQ-FUR = EIQ × % active ingredient × Rate	[42]
Environmental Risk Score (ERS)	ERS = (GUS × Kh) + (B + W + D + A + S)/5 × Kow/10	
Final ERS (F-ERS)	Final Indicator of ER = ERS × (Actual Application Rate/Standard Application Rate)	[45]

ARt: applied dose, HRt: recommended dose, TAt: treated area, PAt: total area of the field, DT: dermal toxicity; D: bird toxicity; C: chronic toxicity; S: soil half-life, SY: systemicity; Z: bee toxicity; F: fish toxicity; B: beneficial arthropod toxicity; L: leaching potential; R: surface loss potential; P: plant surface half-life; GUS: groundwater ubiquity score, Kh: Henry's constant, B, W and D: lethal concentration values (LC50) for bees, earthworms and Daphnia, respectively, A: effective concentration (EC50) for algae, S: scores of soil microorganisms, Kow: the partition coefficient.

2.4. Life Cycle Assessment

Life Cycle Assessment was used to estimate the environmental impact due to the production of three commonly applied plant protection products: the fungicides Mancozeb, copper sulfate, and sulfur. The life cycle inventories for the three products were obtained from Agribalyse (https://doc.agribalyse.fr/documentation-en/; accessed on 12 February 2024) and the OpenLCA modeling suite was used for the LCA (https://www.openlca.org/openlca/; accessed on 12 February 2024). The ReCiPe 2016 Midpoint (H) method was employed [48] for the impact assessment, quantifying 18 impact indicators.

2.5. Statistical Analysis

The survey data were analyzed using SPSS v.24 and Microsoft Excel v.2013. Descriptive analysis, involving calculations of frequencies, means, and standard errors, was carried out using SPSS software. In addition to the number of treatments, factors potentially associated with vine productivity were examined using a log-linear regression model to understand their impact on vineyard yields.

3. Results

3.1. Vineyard Characteristics and Management Practices

This study covered a total land area of 1197.55 ha, with an average vineyard size of 39.9 ha. The land area exhibited significant variability, indicated by a standard deviation of 5.44, mainly attributed to variations in land area between vineyards designated for wine production and those intended for table grape cultivation. In this context, 46% of participants oversaw vineyards smaller than 5 ha, while 30% managed vineyards spanning 5 to 15 ha. Additionally, 20% owned extensive vineyards over 30 ha, and 3% fell within the range of 15 to 30 ha. The average yield per hectare stood at 25.11 T, with 43% of grape growers achieving yields exceeding 30 T/ha. In contrast, 26% obtained yields below 20 T/ha, and 20% fell within the 20 to 30 T/ha range. Figure S1 (Supplementary Materials) gives an overview of the vineyards selected and the characteristics of the vine growers involved in data collection.

The results of the survey regarding soil cultivation (Table S1; Supplementary Materials) showed that all winegrowers worked their soils with an average of 8 passes per crop year (s: 3.44; s2: 11.88; Std. Error: 0.833). These passes involve the use of a variety of tools such as chisel ploughs or ploughs and are mainly intended for tillage or weed control. Regarding cover crops, it is worth mentioning that only 10% of grape growers employ this practice, typically by preserving permanent vegetation on every second row.

Concerning organic amendments like manure and compost, 63.3% of winegrowers use manure and 20% compost. These applications are conducted a few weeks before the vines enter dormancy. Regarding the handling of pruning residues, most winegrowers (63.3%) crush and incorporate them into the soil, while 20% opt for burning. An additional 13% remove the residues from their vineyards, and 3% compost them.

3.2. Treatments against the Main Diseases and Pests

The field surveys conducted among winegrowers in the Sebou Basin provided an overview of the phytosanitary status of vines in the study area. Oomycete and fungal diseases such as downy mildew (*P. viticola*), powdery mildew (*E. necator*), and grey mold (*B. cinerea*) were identified as the main diseases affecting the vines. The most significant pests were mites (*Tetranychus urticae*), leafhoppers (*Empoasca vitis*), and the grape berry moth (*Lobesia botrana*). Based on the responses from surveyed winegrowers, the predominant diseases, namely downy mildew and powdery mildew, require the highest number of treatments, accounting for 39% and 32% of the total treatments, respectively. In terms of vineyard-invading pests in the surveyed region, mites, and leafhoppers emerged as the most important, representing 6.49% and 6.07% of the average treatments (Figure 2).

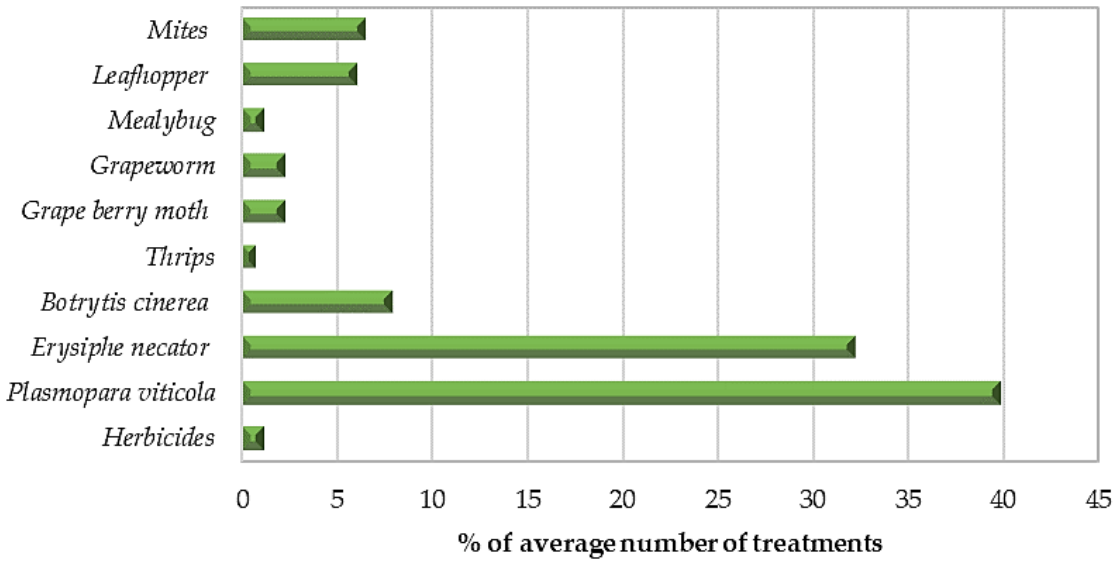

Figure 2. Percentage of the average number of treatments for each disease or pest in vineyards of the Sebou Basin.

3.3. Inventory and Characterization of Pesticide Use

Within the surveyed area, vineyard protection involved the application of 141 commercial products, incorporating 58 active ingredients covering 31 chemical families (Table S2; Supplementary Materials). Among these products, 69.5% were fungicides, 20.08% were insecticides, and 1.42% were herbicides. According to the World Health Organization's classification [49], 2% of chemical families involved, were classified as hazardous, 28% as moderately hazardous, 28% as slightly hazardous, and 29% presented a minimal risk of acute harm under normal use conditions (Figure S2; Supplementary Materials).

An evaluation of the environmental, ecological, and human health risks associated with pesticides in the Sebou Basin was carried out using the pesticide properties and toxicology database [50]. The analysis encompassed environmental fate, including water solubility, soil degradation, and degradation of aquatic environment. Among the active substances used, 38.6% raised a high alert, 52.63% a medium alert, and 3.51% a low alert with regard to environmental risks. Regarding ecotoxicity, based on the measurement of harmful effects on plants and animals, 59.65% of the active ingredients used were on high alert, 35.06% on medium alert, and 1.7% on low alert. Examining human health effects via indicators like the threshold for toxicological concern (Cramer class), skin penetration studies, or genotoxicity, 47.37% of active substances were classified as high alert, 45.61% as medium alert, and 5.26% as low alert (Figure S3; Supplementary Materials). The ecological information suggests that the pesticides used in vineyards could potentially present a high risk to humans, flora, and fauna, with a moderate risk to the environment.

3.4. Agro-Environmental Indicators and Pesticide Intensity Index

3.4.1. Number of Treatments

Disease and pest infestations affect both the quantity and quality of grape production. As a result, grape growers rely heavily on phytosanitary treatments to meet these challenges. In the Sebou Basin, an average of 24.53 treatments are applied during a single growing season, with a range of 5 to 48 treatments per season. Fungicides lead the average number of treatments, with 19.4 treatments per crop year, representing 79.1% of the total treatments (Figure 3). Insecticide and acaricide treatments account for an average of 4.8 treatments per year, representing 20% of the total treatments, while herbicide treatments represent an average of 0.2 treatments per year, corresponding to 1.2% of the total number of treatments (Figure 3). In addition, farmers exhibit a preference for employing machinery-dependent methods to control weeds, such as the use of trailed machines like plows called cover crops or rotary cultivators. This preference translates into a significantly lower average use of herbicide treatments in this agricultural context.

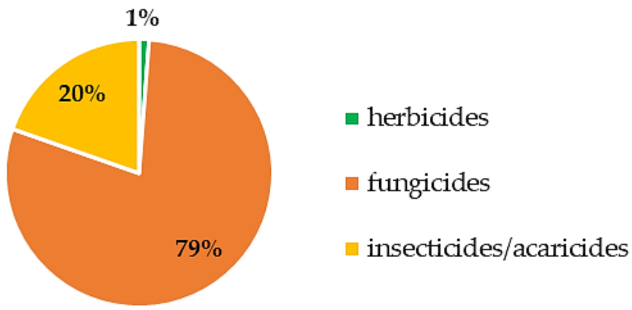

Figure 3. Percentage of treatments according to category of chemical products.

Maximizing yield stands is a primary objective for any farmer. The Sebou region survey disclosed an annual yield range of 3 to 42 T/ha, underscoring the variability in productivity across vineyards. Typically, farmers resort to pesticide applications to manage pests and diseases, striving for increased yields. To explore the potential correlation between the number of treatments and the observed yield variation among vineyards, a regression analysis was carried out. The model (R^2 = 0.705, $p > 0.05$), based on the number of treatments (B = 1.029, $p > 0.05$), offered insights into this variability (Table S3; Supplementary Materials). The outcomes of the analysis unveiled that the quantity of pesticides applied by each winegrower appears to heavily impact the yield, which is reasonable to expect.

3.4.2. Quantity of Active Substances Indicator (QASI)

According to our findings, winegrowers in the region use a significant quantity of pesticides throughout the crop production cycle, with an average quantity of active ingredients of 44.60 kg/ha (Table 2). Fungicides constitute the predominant category of chemical products used, with 41.13 kg/ha, representing 92.21% of the total amount applied. Contact products such as mancozeb, copper, and sulfur remain the main active substances, representing 13.36%, 16.72%, and 55.44%, respectively, of the total fungicidal active ingredients. These are primarily used against powdery mildew and downy mildew. Insecticides/acaricides constitute the second most widely used category, with an average of 3.07 kg/ha of active ingredient, accounting for 6.89% of the total applied. Herbicides, on the other hand, are the least used, with an average of 0.4 kg/ha of active ingredients, representing 0.9% of the total QASI.

Table 2. Total quantity and percentage per chemical category (% QASI).

Category of Pesticides	QASI (kg/ha)	Frequency	Standard Deviation
Acaricides/insecticides	3.07	6.89%	3.61
Herbicides	0.40	0.9%	0.93
Fungicides	41.13	92.21%	24.84
Total	44.60	100%	24.88

3.4.3. Treatment Frequency Indicator (TFI)

The Treatment Frequency Indicator (TFI) reflects the intensity of pesticide use in agriculture and the dependence of farmers on these products. The TFI considers products used at low rates when assessing the impact of pesticides on the environment. On average, the TFI for all surveyed farmers stands at 24.05, indicating a substantial use of phytosanitary products while respecting reference doses. Fungicides predominate the calculated TFI, comprising the largest portion, with a score of 19.12 accounting for 77.94%, followed by insecticides/acaricides with a score of 4.6 TFI and herbicide treatments with 0.28 TFI, rating 18.75% and 1.14%, respectively (Figure 4). It is worth noting that the average treatment frequency rate is lower than the total number of treatments, a phenomenon that can be explained by farmers' preference for frequent use of contact phytosanitary products in conditions conducive to disease development. This preference involves reducing doses and shorter intervals between treatments. The low $TFI_{Herbicides}$ use confirms our previous conclusions regarding the number of treatments. TFI calculation has many advantages, making it a compelling tool for informed action and decision making. Despite the importance of this indicator in our study, research into the use of other agro-environmental indicators is essential for a comprehensive assessment of different aspects of the environmental impact of pesticides.

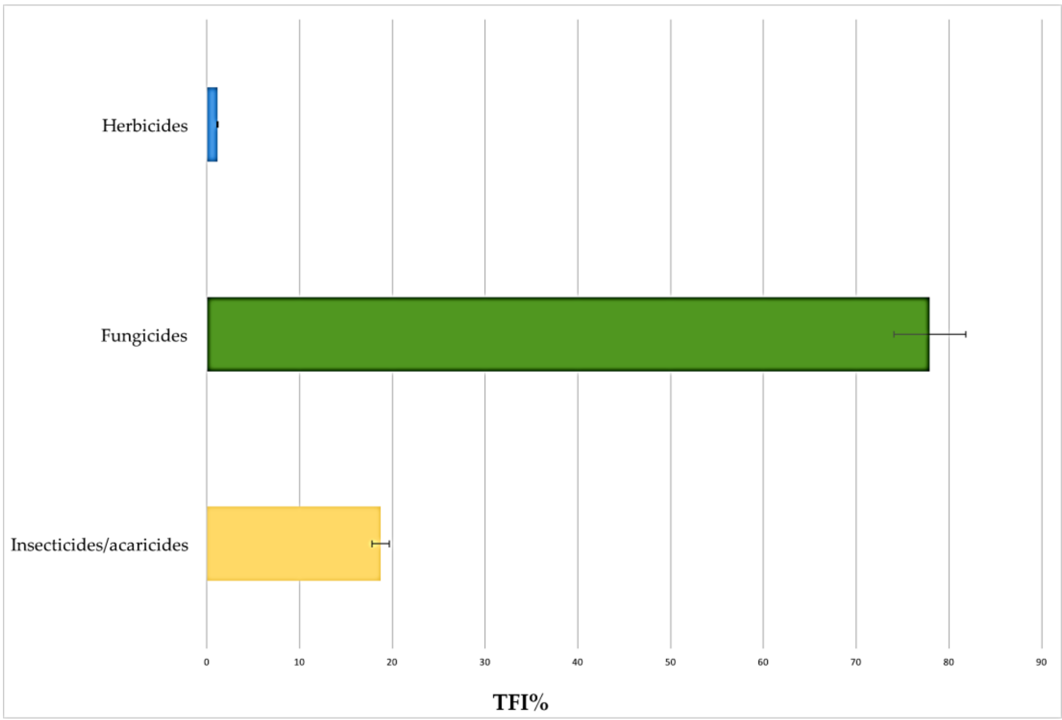

Figure 4. Treatment Frequency Indicator (%TFI) according to chemical categories.

3.5. Environnemental Impact Quotient (EIQ)

To assess and compare the environmental impacts of different pesticides, we used the Environmental Impact Quotient (EIQ) indicator. This was applied to farmers, consumers, and the environment for the 58 active substances used in the Sebou Basin vineyards (Table S4; Supplementary Materials). The final EIQ score is calculated as the average of these three component scores. There are five levels of pesticide risk: unlikely to be hazardous (6.7 < EIQ < 25), slightly hazardous (25 < EIQ < 50), moderately hazardous (50 < EIQ < 75), very hazardous (75 < EIQ < 100), and extremely hazardous (100 < EIQ < 210) [51]. Based on this classification, most of the products used (94.8%) are deemed unlikely to present hazards to farmworkers. However, a small portion, approximately 1.72%, falls into the category of extremely hazardous, including copper sulfate and lime. In terms of consumer safety, 96.5% of the products are classified as unlikely to be hazardous, with the remaining products considered slightly hazardous. In terms of ecological impact, 6.8% of products surveyed are labeled as extremely hazardous, including insecticides like lambda-cyhalothrin and fungicides like copper sulfate. Additionally, 15.5% are classified as highly hazardous, including the insecticides spirotetramat and imidacloprid, the herbicide oxyfluorfen, and the fungicide copper oxychloride (Figure 5).

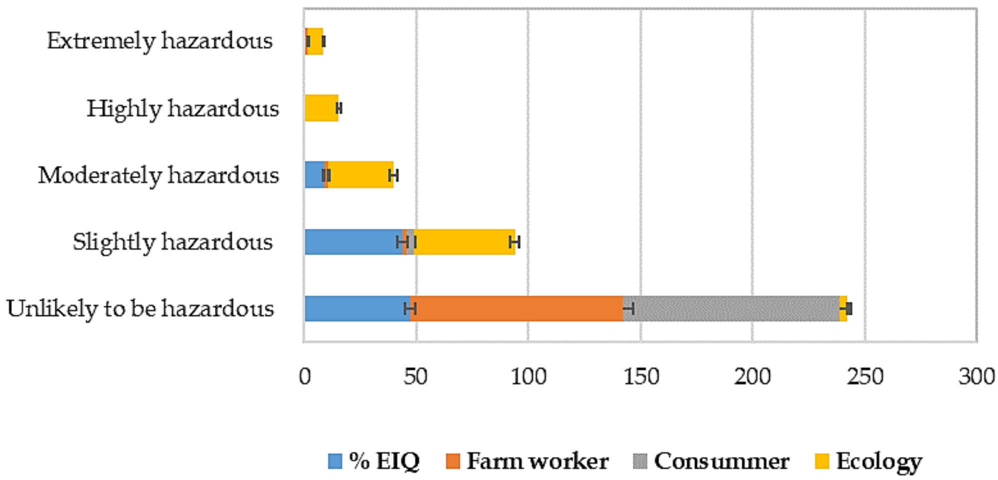

Figure 5. Outcome of EIQ classification and its three compartments based on risk levels.

As observed, the EIQ values range from 10.6 (famoxadone) to 69.83 (copper sulfate pentahydrate). Among these, 8.7% are classified as moderately hazardous, with the majority being copper-based products, while 47.3% and 43.8% are classified as unlikely to be hazardous and slightly hazardous, respectively (Table S4; Supplementary Materials).

According to the EIQ field use rating values, several examples of best agricultural practices can be evaluated and presented for the Sebou region (Table 3). These examples will help to demonstrate alternative ways of controlling certain target pests harming the local vineyards. Based on the EIQ field use rating values, best management practices can be evaluated and implemented. This sort of best management practice will guide the farmworkers and the decision-makers towards better pest management and ecosystem conservation. The EIQ-FUR equation provides a practical and quantifiable way of assessing and comparing the environmental impact of different pesticide-based pest control strategies. If an EIQ-FUR score exceeds 20, the practice is considered to have a high environmental impact, while a score between 10 and 20 indicates a moderate impact and a score below 10 indicates a low impact [52]. We selected the 25 most commonly used active ingredients to calculate the EIQ-FUR index. For herbicides, the EIQ-FUR index is 29 for oxyfluorfen and 16.7 for glyphosate-isopropylamine, both having the same target but a different classification, one having less environmental impact than the other. For fungicides used against *P. viticola*, the causal agent of downy mildew, the EIQ-FUR index ranges from 4.8 for azoxystrobin to 132.5 for copper sulfate. This suggests that azoxystrobin may be the best choice with the least environmental impact. According to the results, treatments against E. necator, the causal agent of powdery mildew, with penconazole appear to be the best choice with the least environmental impacts. On the other hand, for *B. cinerea*, thiophanate-methyl presents a high EIQ field use rating value of 29.8, whereas pyraclostrobin has a lower EIQ field use rating value of 1.52. In the Sebou region, two insecticide groups, namely deltamethrin and malathion, are commonly used to combat grapevine moths. Deltamethrin, with an EIQ-FUR value of 0.4, is considered to be the best choice with the least environmental impact. The EIQ-FUR index is a practical tool for the selection of the most appropriate treatment with the least environmental impact.

Table 3. EIQ-FUR values of pesticides used in the Sebou Basin vineyards. H: herbicide, F: fungicide, I: insecticides, Ac: acaricide.

Active Ingredient	Type	EIQ	a.i. %	Recommended Dose (Lbs AI/Acre)	Target	EIQ-FUR
Glyphosate-isopropylamine	H	20.75	45	0.803	Dicotyledonous weeds and annual grasses	16.70
Oxyfluorfene	H	33.82	48	0.857	Dicotyledonous weeds and annual grasses	29
Azoxystrobin	F	26.92	25	0.178	*Plasmopara viticola/Erysiphe necator*	4.80
Copper hydroxide	F	33.20	50	2.23	*Plasmopara viticola*	74.04
Copper oxychloride/ Dimethomorph	F	12.76	46	1.026	*Plasmopara viticola*	10.75
Copper oxychloride	F	29.80	50	2.23	*Plasmopara viticola*	66.45
Copper sulfate	F	61.90	20	2.14	*Plasmopara viticola*	132.50
Sulfur	F	32.66	80	3.569	*Erysiphe necator*	116.60
Boscalid/Pyraclostrobin	F	10.12	38	0.271	*Botrytis cinerea*	1.52
Cyprodinil/Fludioxonil	F	16.01	62.5	0.344	*Botrytis cinerea*	2.83
Cymoxanil/Mancozeb	F	19.30	74	1.092	*Plasmopara viticola*	16.34
Thiophanate-methyl	F	23.82	45	1.205	*Erysiphe necator/Botrytis cinerea*	28.70
Thiophanate-methyl	F	23.82	70	1.249	*Erysiphe necator/Botrytis cinerea*	29.80
Mancozeb/Metalaxyl	F	17.51	72	1.606	*Erysiphe necator*	23.68
Mancozeb	F	25.72	80	2.498	*Erysiphe necator/Guignardia bidwellii*	64.30
Maneb	F	21.43	80	1.428	*Erysiphe necator/Guignardia bidwellii*	30.60
Paraffinic oil	F	20.17	99	17.669	Winter treatments	356.40
Deltamethrin	I	28.38	2.5	0.016	Vine moth	0.40
Malathion	I	23.83	50	0.558	Vine moth	13.30
Spirotetramat	I	35.29	10	0.134	Mealybug	4.70
Lambda-cyhalothrin	I	44.17	5	0.011	Leafhopper (Cicadellidae)	0.60
Tau-fluvalinate	I	23.17	24	0.054	Leafhopper (Cicadellidae)	1.20
Imidacloprid	I	36.71	20	0.089	Leafhopper (Cicadellidae)	3.30
Abamectin	Ac	34.68	20	0.008	Phytophagous mites	0.30
Dicofol	Ac	29.92	25	0.446	Phytophagous mites	13.30

3.6. PERI Models

All 19 active ingredients (AIs) primarily used in the vineyards of the Sebou Basin are presented in Table S5 (Supplementary Materials), along with their corresponding parameter scores required to calculate the pesticide's Environmental Risk Score (ERS) (GUS score, Kh score, Kow score, B score, W Score, D score, and A score) [43]. The assessment of soil microbial toxicity was excluded from the ERS score calculation due to a lack of references, focusing only on available values related to the toxicity for algae (A), bees (B), daphnia (D), and worms (W).

Application of the PERI model to assess the environmental risks linked to commonly used pesticides in the studied regions revealed ERS scores ranging from 1.3 to 5.75. Obtaining accurate log Kow values for sulfur remains difficult due to its unique physicochemical attributes, as sulfur is a natural element that does not degrade. Therefore, due to insufficient information, sulfur has not been considered in this assessment (Table S6; Supplementary Materials).

The fungicides hexaconazole and azoxystrobin present the highest environmental risk, with respective ERS scores of 5.75 and 5.375, while the copper oxide fungicide had the lowest value 1.3. Azoxystrobin and imidacloprid had higher GUS scores compared to other pesticides and could potentially contaminate groundwater. The Kh score was the same for all pesticides. Eight active ingredients had a Kow score of 5, while the others had a Kow score of 1.

Regarding toxicity to bees, four insecticides (malathion, lambda-cyhalothrin, Abamectin, and imidacloprid) and six fungicides (copper (I) oxide, maneb, cymoxanil, dimethomorph, penconazole, and azoxystrobin) were found to be the most toxic in our study.

Concerning the W score, most AIs exhibited moderate toxicity to earthworms. Eight AIs had a higher D score compared to other pesticides and could potentially pose a problem for daphnia species. For algae, six AIs obtained an A score of 5. Different degrees of toxicity were observed among the 19 AIs, emphasizing the presence of environmental risk in the Sebou Basin region.

To provide a more realistic risk characterization, the final ER indicator was determined. As indicated (Table S7; Supplementary Materials), the final ER indicator was calculated for each chemical product used. The values of the final ER indicator ranged from 0.68 to 7.64. The higher values could result from non-compliance with recommended doses on labels and/or from the toxicity and physicochemical properties of the active substances. Additionally, as shown in Table S7, the same active ingredient can be found in various commercial formulations, with different standard application rates [53].

To compare the risk scores of the selected pesticides, the environmental scores were normalized (Figure 6) by dividing each value by the maximum value of each risk indicator. In our study, all EIQ results were divided by 7.6475 as the maximum score for the EIQ application in this study, corresponding with hexaconazole.

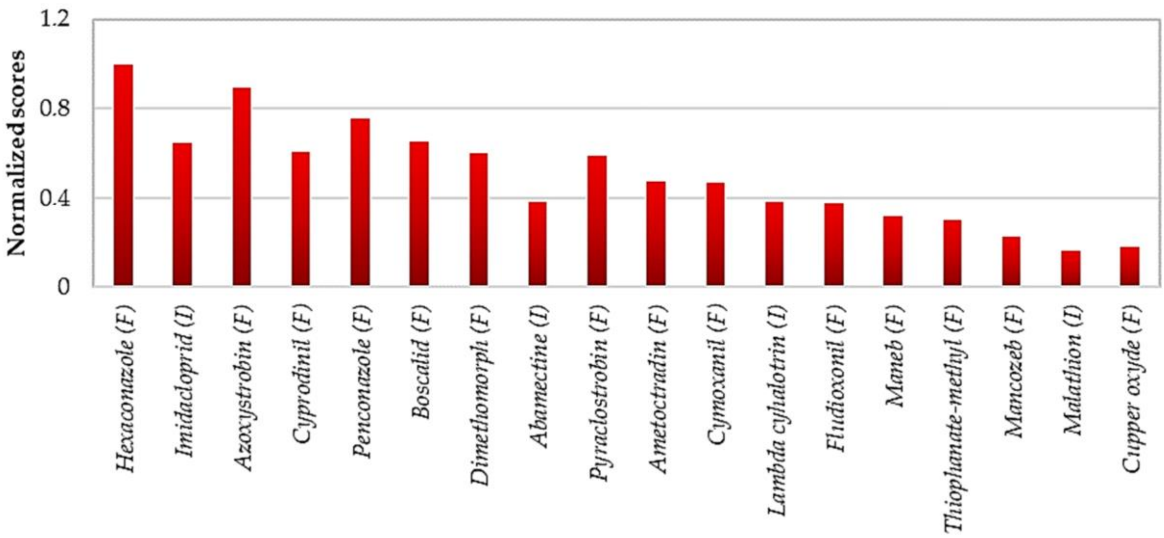

Figure 6. Normalized risk scores of PERI indicators for fungicides (F) and insecticides (I) used in the Sebou Basin vineyards.

3.7. Life Cycle Assessment

The results of the LCA to produce the three most used plant protection products, in terms of quantity and frequency of application, are presented in Table 4. Data represent the absolute values per indicator (green the lower, red the highest, yellow the moderate). The comparison of the three plant protection products by environmental impact parameter is shown in Figure S4 (Supplementary Materials).

Table 4. Results of the LCA due to the production of plant protection products. The color is related to the absolute value of each indicator (red: higher, yellow: moderate, green: lower).

Parameter	Unit Per ha	Mancozeb	Copper	Sulfur
Fine particulate matter formation	kg PM2.5 eq	0.248	0.325	0.0130
Fossil resource scarcity	kg oil eq	12.736	4.860	14.8053
Freshwater ecotoxicity	kg 1,4-DCB	15.871	45.921	0.0544
Freshwater eutrophication	kg P eq	0.017	0.243	0.0005
Global warming	kg CO_2 eq	31.413	18.003	5.5255
Human carcinogenic toxicity	kg 1,4-DCB	1.433	10.087	0.0879
Human non-carcinogenic toxicity	kg 1,4-DCB	636.861	1617.053	1.5894
Ionizing radiation	kBq Co-60 eq	2.743	1.265	0.2201
Land use	m2a crop eq	0.727	1.269	0.0355
Marine ecotoxicity	kg 1,4-DCB	22.683	66.036	0.0821
Marine eutrophication	kg N eq	0.009	0.014	0.0001
Mineral resource scarcity	kg Cu eq	0.522	3.403	0.0074
Ozone formation, human health	kg NOx eq	0.079	0.138	0.0155
Ozone formation, terrestrial ecosystems	kg NOx eq	0.081	0.141	0.0172
Stratospheric ozone depletion	kg CFC11 eq	0.000013	0.000030	0.000005
Terrestrial acidification	kg SO_2 eq	0.774	0.943	0.0390
Terrestrial ecotoxicity	kg 1,4-DCB	390.655	6098.526	4.8357
Water consumption	m^3	0.680	0.382	0.0313

4. Discussion

This study explored in depth the sociodemographic characteristics, agricultural practices, and pesticide treatment approaches adopted by grape growers in the Sebou Basin region (Morocco). Male farmers are the most numerous in the surveyed region, with an average age of 42 years. In addition, this study emphasized a significant educational level among the surveyed grape growers, with 40% of these professionals having attained a higher education level. Regarding the size of the operated vineyard, this study unveiled a notable dominance of small-scale winegrowers managing vineyards covering less than five hectares. This category accounted for 46.6% of the surveyed area in the region.

Regarding soil management practices (Table S1; Supplementary Materials), although this was not the primary focus of this research, our study highlights that all surveyed farmers use soil tillage, with an average of 8 treatments (harrows, plows) per growing season. While soil tillage provides benefits in terms of aeration and drainage, it is important to note its negative impact on the vineyard soil moisture content [54]. Concerning organic amendments, our survey reveals that most farmers (63.3%) prefer the use of manure, while only 20% opt for compost. This practice highlights the importance of organic amendments in vineyards, not only for improving soil fertility and properties, but also for promoting sustainable plant production, as mentioned by Herrero-Hernández et al. [55]. The management of pruning residues is also an important aspect of agricultural practice, with 63% of farmers choosing to shred these residues and incorporate them into their own vineyards. Although this practice may contribute to carbon sequestration in soils, recent studies, such as that conducted by Schneider et al. [56], emphasize that the effects on vine vigor and grape quality parameters are not significant. However, it contributes to carbon storage in soils and may play a role in mitigating the effects of climate change on vineyards [56].

Through our survey, we were able to compile a comprehensive inventory of the pesticides used in the study area, listing a total of 58 active ingredients belonging to 31 chemical families, with the majority (69.5%) being fungicides (Table S2). According to the World Health Organization's (WHO) classification, 1.7% of the listed pesticides are considered hazardous, such as Abamectin and methomyl-based insecticides, while 28% are moderately hazardous, including substances such as copper hydroxide, deltamethrin, and tebuconazole. Furthermore, 28% are considered slightly hazardous, including spirotetramat, penconazole, and hexaconazole, while 29.2% present a minimal risk of acute harmful effects using standardized dosages, including maneb, thiophanate-methyl, and pyriproxyfen.

Using a second database, the PPDB, which assesses pesticides based on environmental fate, ecotoxicity, and human health, it is revealed that high percentages of listed substances show a high alert level, namely 38.6%, 59.65%, and 47.37%, respectively. Numerous studies have highlighted the environmental repercussions of pesticide use in vineyards. Negative impacts on soil biodiversity have been documented [57,58], along with reported adverse effects on both deep and surface waters [59]. In addition, pesticides can affect the physiological processes of grapevines, particularly by reducing photosynthesis [60]. The highest risk of pesticide exposure is faced by vineyard workers and people living close to vineyards [61], thereby elevating the vulnerability to diseases such as cancer [62].

The survey results raise major concerns due to the extent of pesticide use, revealing a high number of treatments, with an average of 24.53 applications performed from dormancy to harvest, encompassing both preventive and curative measures. The total number of treatments (NT) obtained in this survey exceeds levels recorded in Italian vineyards from 2015 to 2020, where the number of treatments ranged between 12 and 14 applications per season [63]. Similarly, during the 2016 campaign in France, vineyards received an average of 20.1 treatments nationwide [64]. The strong correlation between the frequency of applications and fungicide treatments (r = 0.98316), representing 81.6% of the total number of treatments, followed by insecticide treatments at 17.33%, highlights the reliance on fungicides in viticultural practices. Additionally, many pesticides currently employed by farmers lack approval for grape cultivation by the National Office of Food Safety (ONSSA) [53], the regulatory body for pesticides in Morocco. Examples include Abamectin and Iprodione. This situation could have major consequences for the environment.

The indicator of active substance quantity (QASI) used in the surveyed vineyards showed an average value of 44.60 Kg/ha over an area of 1197.55 ha. Fungicidal QASI dominates, constituting 92.21% of the total QASI, owing to the extensive and repeated application of contact products containing copper and sulfur to combat downy mildew and powdery mildew, respectively. In the absence of control measures, these diseases can lead to yield losses of up to 100% during years with high disease pressure [65]. However, the widespread use of elemental sulfur in vineyards may have ecosystem-wide effects, manifested by the accumulation of SO_4^{2-} and organic sulfur in the soil during the growing season [66]. Copper, on the other hand, has the potential to impact microbial activity, earthworm biomass, and the reproduction of springtails and enchytraeids [67,68]. Nonetheless, at the currently authorized dosage, its usage should not substantially alter the quality and biological functions of the soil [69].

The average total Treatment Frequency Index (TFI) value stands at 24.05, indicating the significant influence of the massive use of pesticides in the region. The mean TFI values registered significantly exceed values recorded in vineyards in France, with national averages of 12.9, 13.0, and 20.1 during the years 2006, 2010, and 2016, respectively [64,70]. These results indicate a higher intensity of pesticide use in the studied region compared to other wine-producing regions. Such a high treatment frequency can potentially have environmental repercussions and underscores the need to carefully evaluate crop management practices to minimize impact on ecosystems while preserving vineyard health. Furthermore, although the TFI considers the impact of pesticide active substances on a treated agricultural area, its main drawback is that it does not measure the potential toxicity of pesticides, which may have harmful effects on human health or the environment. Different pesticide treatments can generate similar TFIs because pesticide active substances have different approved doses [71]. It is therefore essential to assess not only the quantitative impact of pesticide use, but also to compare the environmental impact of different pesticides with the same target and design effective pest control practices while minimizing their impact on the environment.

The Environmental Impact Quotient (EIQ) has been employed to assess the environmental impact of pesticide use in vineyards and to compare the environmental impact of different pest control strategies. The resulting EIQ value allows us to quantify the relative risk for farmworkers, consumers, and the environment [40]. The EIQ field use rating system can be useful to compare different agricultural strategies such as traditional, integrated, or organic pest management [42]. Based on on-field EIQ scores, several examples of good agricultural practices can be considered. These examples will help demonstrate and implement alternative means of controlling specific pests. This type of management practice will guide farmers and decision-makers towards sustainable ecofriendly solutions. This study highlighted significant disparities in scores for the same target. For the control of *P. viticola*, among the 6 most frequently used treatments, the copper sulfate-based treatment obtained a score 27 times higher than the azoxystrobin-based treatment. Similarly, among the 8 fungicides used to control *E. necator*, the sulfur-based treatment recorded a score 233.2 times higher than the penconazole-based treatment. In practice, it is recommended to use pesticides with the lowest EIQ-FUR score to minimize environmental impact. This growing awareness of the impact of pesticides on the environment will encourage farmers to prioritize less harmful pesticides, paving the way for more sustainable agricultural development.

To further analyze environmental risks, the Pesticide Environmental Risk Indicator (PERI) model was employed, generating ERS scores ranging from 1.3 to 5.75. These scores reflect the levels of risk associated with different pesticides, highlighting active substances that could have a more significant environmental impact. Three pesticides, namely hexaconazole, imidacloprid, and azoxystrobin, ranked ERS scores of 5 and above, indicating a high level of risk. These substances may have toxic or physicochemical characteristics that increase their potential impact on the environment. The risk analysis was refined by calculating the final risk indicator, with values ranging from 0.88 to 7.64. These values provide a more in-depth insight into the potential hazards associated with the specific use of pesticides in the region. It should be noted that higher values can result from the toxic nature of the active substance, its physico-chemical properties, and its presence in various commercial formulations with different standard application rates, as indicated in the Pesticide Index [53].

The application of LCA in evaluating PPPs aims to optimize agricultural practices by identifying products and application strategies with the least environmental burden while ensuring crop protection and productivity [27]. Our research focused on the production process of the three most widely used fungicides, Mancozeb, copper sulfate, and sulfur, and it is complementary to the environmental impact assessment implemented. Copper sulfate had the highest values in most of the LCA indicators. This approach could be expanded by including other production stages (e.g., grape cultivation, transportation of grapes to the winery and/or the market) in future research.

Assessing environmental risks is crucial to steer agricultural practices towards more sustainable approaches and reducing negative impacts on ecosystems. These results underscore the need to seek less risky and more environmentally friendly alternatives in agricultural pest management, thereby contributing to sustainable agriculture and ecosystem preservation.

A comparison of all standardized risk values revealed that hexaconazole, followed by azoxystrobin and penconazole, has the highest standardized risk values. Hexaconazole stands out due to its widespread use in agricultural operations and its concerning characteristics. Belonging to the triazole class of pesticides, hexaconazole is the second most produced and used fungicide globally. Its environmental impact is accentuated by its persistence, with a soil half-life ranging from 135 to 845 days. Furthermore, studies have shown that no significant degradation of hexaconazole occurs in water within three weeks [72]. In addition to its persistence, hexaconazole has been associated with human health concerns, as it has been observed to disrupt endocrine function and has bioaccumulation potential. Hexaconazole residues have been frequently detected in various matrices, including fruits, vegetables, human urine, and hair, highlighting potential public health concerns associated with its use [73,74]. These findings underscore the need for a thorough risk assessment associated with the use of hexaconazole, as well as the exploration of safer and more sustainable alternative solutions to minimize negative impacts on human health and the environment. On the other hand, insecticides can pose a significant threat to non-targeted species, such as bees, which are more susceptible to any insect-killing substances [75]. In addition, the combination of insecticides and fungicides can be more harmful and lethal to bees [76].

Pesticide monitoring has garnered increasing interest over the past few decades due to its potential toxic effects on horticultural crops and humans. Concurrently, sustainable management practices aimed at improving vineyard performance within an eco-friendlier agricultural system have been considered. Although these practices may have potentially positive effects on vine growth and productivity, it is noteworthy that this research area remains largely unexplored.

Precision agriculture emerges as a promising approach for sustainable viticulture. It involves the use of advanced technologies such as sensors, drones, and geographic information systems to optimize farming practices. This approach enables more precise management of agricultural inputs such as water, fertilizers, and pesticides, which can contribute to reducing environmental impacts while improving their efficiency.

Agricultural practices can also reduce the use of PPPs in vineyards by implementing various strategies. One successful strategy is the use of cover crops, which can help avoid groundwater pollution and reduce the demand for PPPs like copper and organic fungicides that are commonly used in viticulture [77]. Additionally, altering and testing variable dose treatments in vineyards can help in reducing pesticide use [78]. Organic farming practices can also play a key role in lowering the dependency on PPPs. Organic farming restricts the use of synthetic fertilizers and PPPs, advocating for the use of natural chemicals and techniques to grow food crops [79].

Furthermore, the development of tailored policies, adapted to the specificities of vineyard regions, should play a crucial role in shaping the future of this economic sector. These policies could encourage the adoption of sustainable practices, the exploration of alternative crop protection methods, and the reduction of potentially harmful pesticide use. Therefore, the ongoing exploration of these innovative approaches in the field of sustainable viticulture is essential to balance agricultural productivity with environmental preservation and the protection of human health.

5. Conclusions

The Sebou Basin area is highly important for food security and the economy in Morocco, as it is the main production area for grapes, as well as industrial crops, fruits, vegetables, and olives. Farmers pursue high yields and apply plant protection products on a regular basis. This work aimed to evaluate the use and impacts of pesticides in the Sebou Basin, using different indicators and models. Data were collected in collaboration with grape growers and used to estimate indicators and run models, such as the PERI model. LCA was also used to estimate the impacts of fungicide production. Overuse of plant protection products has been observed in vineyards, compared with other grape production areas, mainly in the EU. The plethora of commercial products and active ingredients used raises questions about the effects on human health and the environment, which are addressed in this study, but many others focused on specific topics (e.g., the toxicity of mixtures of PPPs) are expected to follow. This work supports the design and implementation of plant health programs focusing on food security and environmental–human health. However, our findings highlight the extensive use of pesticides, which can present significant challenges for long-term sustainable development due to the associated environmental and health hazards.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae10050473/s1. Figure S1: characteristics of winegrowers and vineyards in region surveyed; Figure S2: distribution of chemical families listed according to the WHO classification; Figure S3: risks associated with the active ingredients used in the study area according to the Pesticide Properties Database; Figure S4: comparison of the three most commonly used plant protection products; Table S1: frequency of practices related to carbon sequestration according to yield; Table S2: different pesticides used in grapevine cultivation in Sebou Basin area and some toxicological information; Table S3: regression analysis of grapevine yield on number of pesticide applications; Table S4: EIQ values of pesticides in Sebou Basin vineyards; Table S5: list of the nineteen most used AIs in vineyard located in Sebou Bassin with their biological activity, their physicochemical (soil half-life, Koc, GUS, Kow, Kh) and toxicological properties (LC50 for Bees, earthworm and Daphnia, and EC50 for Algae (PPDB, 2018; NCBI, 2018), and CLP Classification according the EU Pesticides database (EU database, 2019); Table S6: pesticide ERS calculated using the PERI model for eighteen AIs commonly used in Sebou vineyards and GUS, Kh, Kow, algae (A), bee (B), daphnia (D) and worm (W) values used in the calculations; Table S7: the AIs most commonly used in Sebou bassin, the chemical products, and the corresponding final indicator of ERS.

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