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Research Article

Impact of pesticide on the physical and chemical agricultural soil in a semi-arid region of Algeria (M'Sila)

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Abstract

This study aims to monitor the impacts of pesticides on the physical and chemical quality of agricultural soil in Algeria's semi-arid region. The region primarily cultivates market garden crops such as potatoes and wheat. Sandy soil types and a semi-arid climate characterize it. Twenty-seven samples were collected from various soil horizons at different depths and locations within the study area. Among these, 9 samples were designated as controls, 9 were treated with a potent herbicide called haloxyfop-methyl ester, and the remaining 9 were treated with a fungicide containing two active ingredients: fenamidone and a methyl ester. The measured parameters (pH, conductivity, TDS, CO, MO, limestone, Mg+, Ca+, NO2, P2O5, K2O) exhibited variability, with the treated samples generally showing higher values than the control samples. This difference can be attributed to various factors, such as treatment conditions, characteristics of the study area, types of pesticides used, and the application of mineral and organic fertilizers, as well as chemical pesticides. Intensive agriculture often employs this approach, aiming to produce large quantities of food on a relatively small land area. The heavy metals analysis (iron, copper, manganese, aluminum, and chromium) of agricultural soil showed concentration values within international norms. Despite this, these metals remain toxic chemicals with bioaccumulative persistence in the environment. The uncontrolled use of pesticides impacts both the short-term and long-term soil quality. While they effectively kill weeds and fungi, they also penetrate and accumulate in the soil and pollute groundwater. It is crucial to use herbicides sparingly and choose those with minimal environmental impact.

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1. Introduction

Over time, due to the rapid growth of the population, the demand for food has increased (Bertrand et al., 2018). Agriculture is the key sector ensuring food security (Change, 2016). Agriculture in the semi-arid regions of Algeria is marked by considerable challenges due to harsh climatic conditions, such as low and irregular rainfall, high evaporation rates, and soils often poor in organic matter and nutrients (Benouadah et al., 2019). These regions, which largely cover Algerian territory, require specific strategies to ensure viable agricultural production (Adair et al., 2022). Farmers in these areas adopt various techniques to adapt to arid conditions, such as drip irrigation, using drought-resistant crops, and applying fertilizers and amendments to improve soil quality. However, the increased use of pesticides and chemical fertilizers raises questions about the long-term sustainability of these practices, particularly soil degradation and water resource pollution (Rafik et al., 2015).

Efforts to improve agricultural techniques, preserve natural resources, and promote sustainable practices are essential to ensure the resilience of agriculture in these vulnerable areas (Lakhdari & Ayad, 2020). From antiquity to the present day, the use of plant protection products (PPPs) in agriculture dates back to antiquity, with the use of sulfur seemingly dating back to ancient Greece (1000 BC) (Aubertot et al., 2005).

The state and farmers attempt to improve and develop agricultural practices by solving problems related to farming pests that cause damage to crops (Alain et al., 2014). The use of pesticides in agriculture represents a major and complex issue worldwide. These substances have been designed and deployed to improve crop productivity and sanitary quality. However, their use is increasingly controversial. Pesticides are toxic chemical compositions used to reduce and eliminate pests such as bacteria, weeds, fungi, insects, mollusks, and rodents (Feng et al., 2020). The presence of heavy metals in the soil can come from several sources, including the use of pesticides and chemical fertilizers. In table salt: cadmium, copper, and lead are generally toxic to humans and animals, even at low doses. Heavy metals can be found in the natural environment, in soils, water, and air. They can be produced by human activities, including mining, industry, and agriculture. They can have harmful effects on the environment and pollute soils, water, and air. They can disrupt ecosystems and harm animal health (Alengebawy et al., 2021). The FAO estimates that these diseases and pests reduce global harvests by 40% each year (Alain et al., 2014). The use of pesticides, therefore has been considered a way to secure agricultural production, by reducing the risk of significant yield loss or poor preservation. Only 20% of pesticides are used efficiently, the rest are used anarchically and uncontrollably. That can leading to risks to human health and the environment (Ali et al., 2024). Pesticides can infiltrate the soil and contaminate groundwater, thus threatening the quality of drinking water and affecting aquatic ecosystems (Viau et al., 2020). Loss of biodiversity: The use of pesticides kills pests as well as pollinators, earthworms, and other organisms beneficial to soil health and crop pollination.

Degradation of soil quality: Pesticides disrupt the microbial activity of the soil, that is essential for the decomposition of organic matter and soil fertility (Crouzet et al., 2015). Human health problems such as Acute poisoning. Direct exposure to pesticides can cause acute poisoning, with severe symptoms that can lead to death (WHO, 2016). Chronic diseases: Chronic exposure to pesticides, even at low doses, is associated with an increased risk of certain cancers, neurodegenerative diseases, and developmental disorders (Grandjean et al., 2012). Food contamination: Pesticide residues can persist on fruits and vegetables, thus exposing consumers to potential health risks (WHO, 2016).

The use of pesticides in Algeria is a common practice in agriculture with significant consequences for the environment and human health. According to the Food and Agriculture Organization of the United Nations (FAO), Algeria is a large consumer of pesticides. Several studies have been conducted in Algeria to evaluate the impact of pesticides on soil quality. Soil quality is defined by its ability to function (Vasu et al., 2020). Furthermore, the notions of fertility, productivity, resource sustainability, and environmental quality, which are the main bases of current soil quality definitions, are also considered. The indicators that allow us to evaluate soil quality are its different properties (Shiva, 2020). The intimate relationships that soil creates with terrestrial ecosystems are important in regulating ecological processes. Therefore, it is logical to consider soil quality an essential component of a healthy ecosystem (Hage-Ahmed et al., 2019).

In our work, we tried to highlight the impact of the use of pesticides on the fertility of agricultural soils in the semi-arid zones of Algeria and evaluate its impacts on the physicochemical quality of soils in the region of Maader Boussaâda, M'sila as an example of agricultural yield. By analyzing the variations of the soil's physico-chemical parameters before and after the application of pesticides, we seek to understand the direct and indirect effects of these products on the health and fertility of the soils.

The results will provide valuable information for the sustainable management of soils and the reduction of risks associated with the use of pesticides in this semi-arid region. Despite the difficulties present in the region, such as permeable sandy soils and poor essential nutrients and minerals for plants, there are challenges to overcome to achieve abundant production. This involves using many modern methods aimed to improve soil quality and the harvested product.

The study was conducted on agricultural soil located in the semi-arid region (Maader Boussaâda - M'sila), an important agricultural area where the use of pesticides is a common practice. An important parameter to allow farmers to assess the levels of physico-chemical fertilization of the soils and adapt complementary fertilization programs according to the needs of the soils and crops (Chevallier, 2020). Before sampling, pesticide treatment, and implementing the experimental protocol, we formulated the following hypotheses: Farmers use pesticides intensively in the region of Maader Boussaâda. What is the impact on the soil's physico-chemical properties? What is the impact of pesticides on soil fertility and agricultural productivity?

2. Materials and methods

2.1 Study Area

Boussaâda region is situated 234 km southeast of Algiers and 13 km southwest of Chott El Hodna, at a latitude of 35°13'N, a longitude of 4°10'E, and an altitude of 611 m. The commune of Boussaâda covers an area of 249.34 km^2 and has a population of 123,236 inhabitants. The region of Boussaâda is characterized by the presence of reliefs, which are part of the northern end of the Saharan Atlas. They consist of an alternation of clay marls and limestone levels dating from the Cenomanian. The depressions are areas of concentration of runoff waters and deposition of solid particles, corresponding to two types according to their saline character (sebkha, chott) or freshwater (Daya), while the R'mel (400 m to 550 m) is composed of dunes, recent alluvial deposits, and isolated rocky hills. It is a fold composed of limestone, marl, and sandstone from the Jurassic and Cretaceous.

Maader Boussaâda, is a part of the commune of Boussaâda, it covers an area of 2,984 hectares, representing 80% of the total agricultural land in this region. This last known as a significant agricultural area rich in vegetable crops. Our study focused on a large agricultural field practiced in this area.

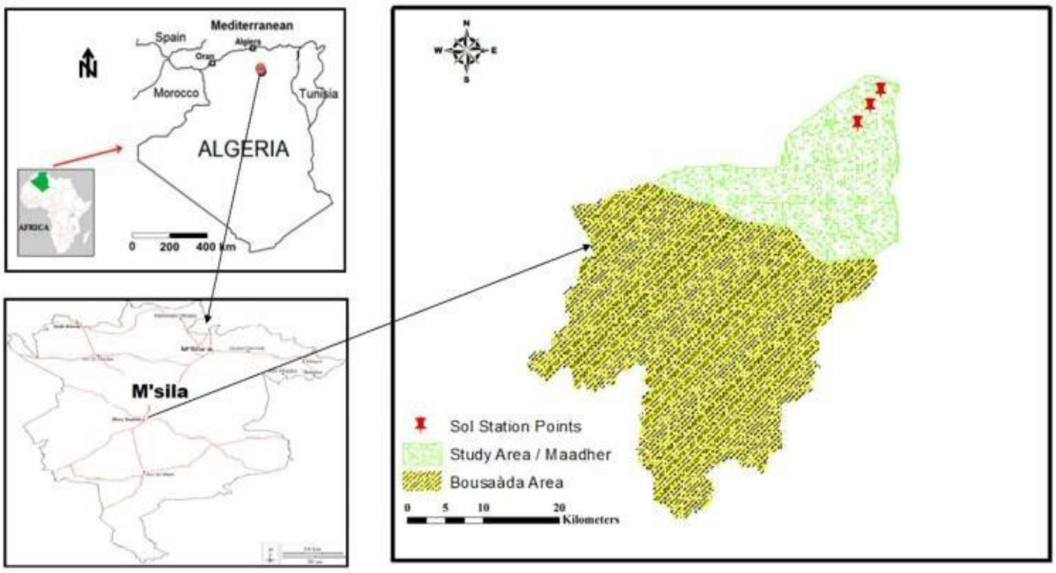


Figure 1. Map showing the study area of Maader Boussaâda, M'sila, Algeria (Bakhti)

2.2 Methodology

The methodology adopted in this study involved sampling from an agricultural area of 17 km^2 over four months. The study area is subdivided into three plots located respectively at the zone's beginning, middle, and end. Three soil sampling campaigns were conducted on each plot at different depths (0-20 cm, 0-40 cm, 0-60 cm) to study the impact of pesticides on the physico-chemical characteristics of the soil, including soil depth.

Table 1. The methodology for sampling and analysis in the study area of Maadher, Boussaâda, M'Sila

Sample	Weight (g)	Studied Area	Phytosanitary Treatment	Number of Samples	Physico-Chemical Analyses	Analytical methods	Products used
First Stage Samples	500(1g)	Vegetable crops irrigated by pivot water	Herbicide against weeds	09	pH, Electrical Conductivity, Salinity, TDS, Organic Matter, Organic Carbon, Total Limestone, Calcium, Magnesium, No2, P2O5, K2O	HIN: 9829, Walkley & Black (1934) Method, Bernard's Calcimeter Method, EDTA Titration	Gallant Super (Herbicide)
Second Stage Samples	500(1g)	Vegetable crops irrigated by pivot water	Against fungi	09	pH, Electrical Conductivity, Salinity, TDS, Organic Matter, Organic Carbon, Total Limestone, Calcium, Magnesium, No2, P2O5, K2O	HIN: 9829, Walkley & Black (1934) Method, Bernard's Calcimeter Method, EDTA Titration	Consento (Fungicide)
Control Samples	500(1g)	Vegetable crops irrigated by pivot water	No Treatment	09	pH, Electrical Conductivity, Salinity, TDS, Organic Matter, Organic Carbon, Total Limestone, Calcium, Magnesium, No2, P2O5, K2O	HIN: 9829, Walkley & Black (1934) Method, Bernard's Calcimeter method, EDTA Titration	Not Applicable
Additional Analyses			No2, P2O5, K2O, AL2O3, Fe2O3, Cr2O3, Mn2O3, Cu			Lafarge Laboratory in M'sila, XRF Analysis	

Consent is a systemic and penetrating fungicide against potato and tomato blight. Its active ingredients are propamocarb and fenamidone.

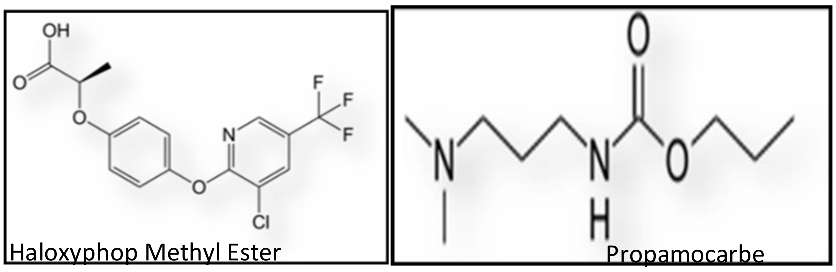


Figure 2. Chemical Structure of the Pesticides Used in Our Study

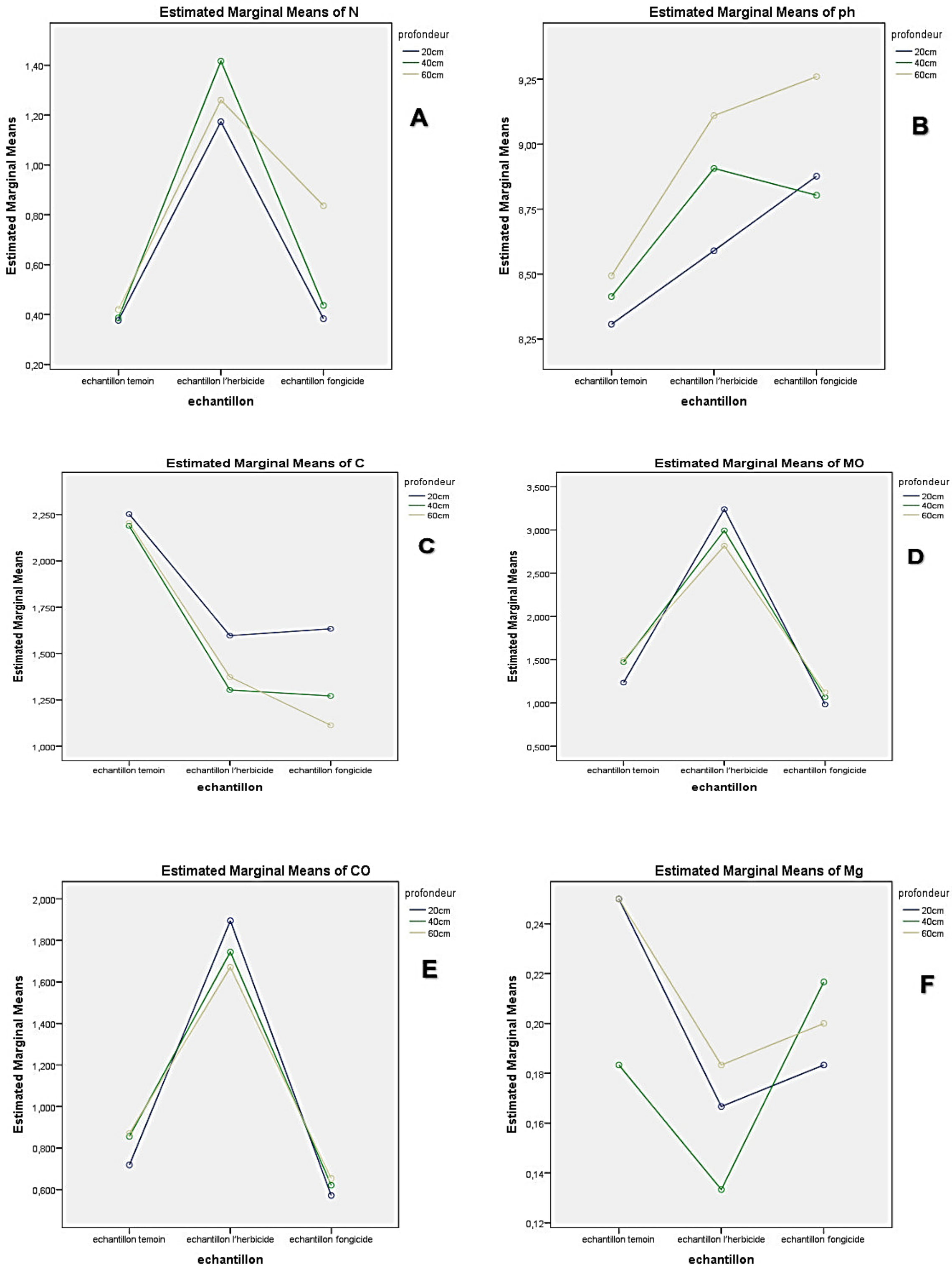
The treatment method, the crop's growth stage, the type of pest that threatens it, and the development phase were considered. After plowing, turning the soil, and watering, and once the weeds had grown to a considerable height, we mixed 1.5 liters of herbicide in a 500-liter tank, ensured thorough mixing, and then sprayed the solution back and forth across the field. Subsequently, we planted the potato tubers, fertilized the soil with compost and animal residues, and carried out irrigation using a pivot system. Once the potato plants reached a height of 25 cm, we applied a second treatment with fungicide.

	Crop	Dose	P.H.I.
Potato	Mildew, Alternaria	1.5 to 2 L/ha	14 days

2.3 Statistical analysis

To determine the significant effect of the results obtained from the physicochemical parameters of the agricultural soil, the control samples, the herbicide-treated samples, and the fungicide-treated samples with different depths, the data were analyzed using analysis of variance (ANOVA). ANOVA is a statistical method for comparing the means of three or more groups. It is used to determine whether differences between groups are statistically significant. In this study, ANOVA was performed with a significance level of $p = 0.05$. The factors studied were sample type (control, herbicide, and fungicide), soil depth (0-20 cm, 0-40 cm, 0-60 cm), and the interaction between these two factors. The ANOVA results showed that the following physicochemical parameters were statistically significant ($p < 0.05$): PH, organic matter, organic carbon, limestone, calcium, magnesium, nitrogen, and phosphorus. This means the effects of pesticides and soil depth on these parameters are interdependent. The curves show the mean values of the various parameters as a function of sample type (control, herbicide, fungicide) and depth (20, 40, 60 cm). All parameters are higher in the 40 cm depth range, and results are higher for herbicide-treated samples except for calcium and magnesium and the c/n ratio. In line with previous studies on the impact of pesticides on soil physicochemical properties, our research findings on the subject were relatively consistent, based on the studies referred (Tahar et al., 2017; Meliani et al., 2024).

3. Results and discussion



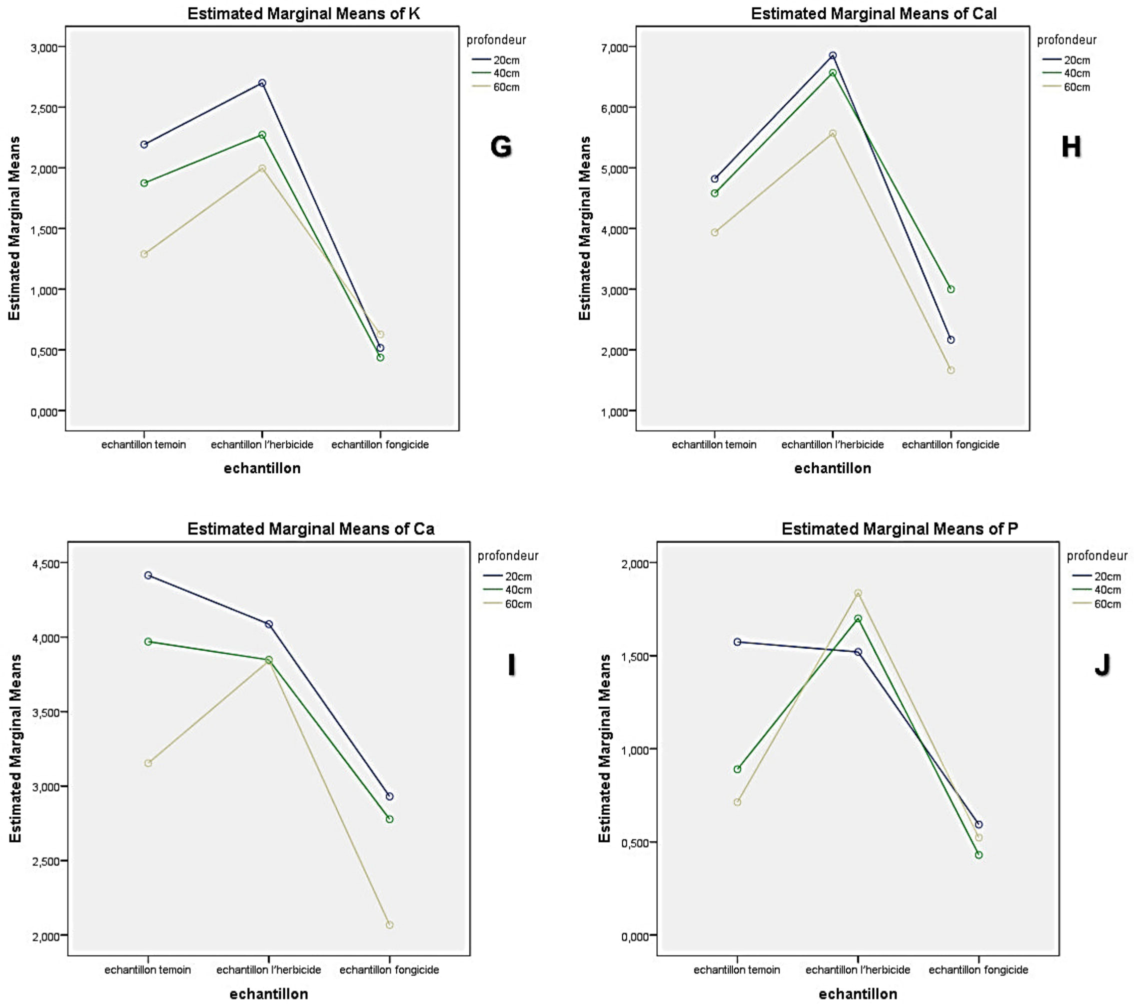


Figure 3. Influence of treatments with the two pesticides (herbicides and fungicides) on the different physical and chemical parameters.

Table 2. Untreated soil samples (controls)

Parameters		pH	Salinity	TDS (mg/L)	CE µs/cm	MO %	CO	Cal%	Ca+. (Mg/L)	Mg+++ (Mg/L)	N%	P%	K%	C/N
Visit	Depth													
P1	20cm	8.16	0.01	228	345	1.60	0.931	3.5	5.362	0.30	0.26	2.25	3.404	3.580
	40cm	8.38	0.01	192.9	287	0.421	0.245	2.41	3.274	0.25	0.28	1.22	3.389	0.875
	60cm	8.45	0.03	176.3	263	0.498	0.29	2.87	3.231	0.25	0.28	1.40	1.603	1.035
P2	20cm	8.51	0.01	134.5	200	0.760	0.442	4.59	3.650	0.15	0.55	2.33	2.543	0.803
	40cm	8.45	0.02	150.9	228	1.806	1.05	5.02	4.012	0.15	0.54	1.06	1.581	1.944
	60cm	8.45	0.01	163	243	1.432	0.833	3.83	3.11	0.3	0.63	0.35	1.5543	1.322
P3	20cm	8.25	0.02	269	407	1.348	0.784	6.37	4.231	0.3	0.32	0.141	0.631	2.375
	40cm	8.41	0.03	460	693	2.191	1.274	6.32	4.622	0.15	0.34	0.39	0.655	3.747
	60cm	8.58	0.03	129	193	1.562	1.49	5.11	3.120	0.20	0.35	0.39	0.712	4.257
MEAN		8.40	0.02	211.5	317.5	1.402	0.815	4.44	3.845	0.25	0.33	1.059	1.785	2.215
MAX		8.58	0.03	460	693	2.562	1.49	6.37	5.362	0.5	0.63	2.33	3.404	4.257
MIN		8.25	0.01	129	193	0.421	0.245	2.41	3.120	0.15	0.11	0.35	0.631	0.803

Table 3. Herbicide-treated soil samples.

Parameters Visit	Depth	pH	Salinity	TDS (mg/L)	CE µs/cm	MO %	CO	Cal%	Ca+. (Mg/L)	Mg+++ (Mg/L)	N%	P%	K%	C/N
P1	20cm	8.43	0.04	486	723	3.87	2.27	5.94	3.58	0.20	1.18	2.84	3.71	1.92
	40cm	8.52	0.02	373	559	3.78	2.20	5.45	3.69	0.15	1.23	1.9	3.39	1.78
	60cm	9.11	0.04	308	307	2.61	1.52	5.75	3.86	0.2	1.01	1.41	2.14	1.50
P2	20cm	8.56	0.01	220	314	3.64	2.12	8.53	4.32	0.15	1.33	2.12	2.23	1.59
	40cm	9.1	0.01	329	343	2.66	1.55	8.67	4.52	0.10	1.15	2.0	2.20	1.34
	60cm	9.1	0.02	320	426	3.61	2.10	6.09	4.64	0.15	1.21	2.78	2.23	1.73
P3	20cm	8.78	0.1	177.8	305.2	2.21	1.294	6.09	4.36	0.15	1.01	2.44	2.16	1.28
	40cm	9.1	0.1	160	298.1	2.54	1.482	5.59	3.33	0.15	1.87	1.20	1.23	0.79
	60cm	9.12	0.1	186	200	2.23	1.392	4.87	3.02	0.20	1.56	1.32	1.62	0.89
MEAN		8.65	0.03	284.4	386.1	3.01	1.768	6.3	0.15	0.1	1.33	2.01	0.560	1.424
MAX		9.12	0.04	486	723	1.517	0.882	8.67	0.6	0.2	1.87	2.12	3.71	1.111
MIN		8.43	0.01	65.5	98.1	0.505	0.39	4.87	0.1	0.1	0.63	0.32	0.62	0.52

Table 4. Soil samples treated with fungicide

Parameters Visit	Depth	pH	Salinity	TDS (mg/L)	CE µs/cm	MO %	CO	Cal%	Ca+. (Mg/L)	Mg+++ (Mg/L)	N%	P%	K%	C/N
P1	20cm	8.63	0.02	324	492	0.421	0.245	2	3.137	0.2	0.22	0.64	0.541	1.113
	40cm	8.59	0.03	356	528	1.432	0.833	3.5	3.754	0.3	0.31	0.5	0.532	2.687
	60cm	8.71	0.01	212	315	1.264	0.735	2	3.071	0.25	0.33	0.24	0.443	2.22
P2	20cm	8.90	0.01	78.4	113.4	1.095	0.637	1.5	2.652	0.15	0.63	0.62	0.87	1.011
	40cm	8.96	0.01	103.4	158	0.674	0.392	2	2.365	0.2	0.8	0.66	0.66	0.49
	60cm	9.97	0.02	107.1	160	1.264	0.735	1.5	2.01	0.20	1.08	1.01	0.54	0.680
P3	20cm	9.10	0.01	96.5	104	1.432	0.833	3	3.001	0.20	0.3	0.52	0.14	2.776
	40cm	8.86	0.03	91.3	135.9	1.095	0.637	3.5	2.214	0.15	1.00	0.13	0.12	0.637
	60cm	9.10	0.03	127.2	189.4	0.842	0.49	1.5	1.123	0.15	1.1	0.32	0.9	0.44
MEAN		8.83	0.01	163.2	243.96	0.91	0.615	3.57	2.591	0.19	0.604	0.515	0.527	1.339
MAX		8.97	0.03	356	528	1.432	0.833	3.5	3.754	0.3	1.08	1.01	0.87	2.687
MIN		8.59	0.01	69.5	104.5	0.421	0.245	1.5	1.123	0.15	0.22	0.13	0.12	0.637

Table 5. The toxic chemical elements in the soil of the study area

Sample name	SiO2 (%)	Al2O3 (%)	Fe2O3(%)	TIO2%	CR2O3	MN2O3	Copper%
P1tcons	78,34	2,064	0,811	1.46	0.50	0.16	0,04
P11tcons	91,001	2,562	0,783	1.36	0.30	0.13	0,02
P1tcons	83,542	1,58	0,697	1.22	0.30	0.13	0,032
P2th	83,256	2,486	1,859	1.297	0.20	0.32	0,020
P2th	68,115	2,131	2,36	1.33	0.17	0.40	0,010
P2th	86,312	2,265	2,662	1.115	0.26	0.72	0,014
P1control	89,208	1,155	0,711	0.93	0.42	0.10	0,015
P1control	93,296	1,033	0,793	0.57	0.64	0.13	0,061
P1control	84,808	1,782	0,752	0.60	0.65	0.14	0,01
P1temoin	98,96	1,729	0,732	0.48	0.10	0.16	0,017
P2control	85,509	1,697	0,722	0.48	0.17	0.16	0,014

Sample name	SiO2 (%)	Al2O3 (%)	Fe2O3(%)	TIO2%	CR2O3	MN2O3	Copper%
P3control	86,169	1,608	0,671	0.12	0.14	0.15	0,012
P3control	98,55	1,835	0,841	0.10	0.14	.016	0,023
The limits	Indicate soil texture	0-20ppm	20100 ppm	PBT	0.5-20ppm	20- 50ppm	2-40ppm

The data were analyzed using an analysis of variance (ANOVA). This statistic analysis was performed with three sampling factors (control, herbicides, fungicides) and the soil depth factor (0-20 cm, 0-40 cm, 0-60 cm) as treatment factors.

In line with previous studies on the impact of pesticides on soil physicochemical properties, our research findings were relatively consistent based on the studies referred to (Tahar et al., 2017; Meliani et al., 2024). Their work is about the effect of hymexazol and promethryne on the physicochemical and biological quality of agricultural soils, which focused on applying different concentrations of two types of fungicides to the physicochemical properties of soil and biomass. The study demonstrates how these substances contribute to increasing and stabilizing agricultural yields and enhancing the soil's physicochemical properties. The work focused on the effects of Sulfonylureas on soil chemical properties and crop yield in a semi-arid region of Algeria. The study examined two types of herbicides: the first, "SEKTOR," which decreased the values of the soil's physicochemical parameters, and the second, "ZOOM," which increased these values. The study demonstrates the ability of herbicides to alter the soil's chemical properties (Meliani et al., 2024). The effects of herbicide application on the agricultural soil properties of Algeria are significant. One begins with the pH parameter (Figure. 3.D), which is considered a very important indicator of soil dynamics. Soils treated with an herbicide or fungicide (Table 2, Table 3) have a basic pH with a tendency toward alkalinity, ranging from 8.97 to 9.12, due to the release of alkaline cations by the herbicides (Gallant Super) in the soil. The pH was varied between different samples (ANOVA ($F(1.17) = 7.17$, $p = 0.005$). However, releasing calcium and magnesium from the decomposition of organic matter is probably the most likely cause of the increase. Sandy soils have a low water retention capacity. Organic matter: all plant and animal debris that decomposes gradually in the soil under the effect of microorganisms (Mathieu et al., 2003) is important for soil fertility (Figure. 3.D). The study showed that the control soils were poor in organic matter, with an average of 1.40, (Table 1), a result that can be explained by the influence of the semi-arid climate and the type of sandy soil of the studied region. This last is characterized by low annual precipitation and high evaporation rate. The use of pesticides as soil improvers helped to improve soil conditions (Ouédraogo et al., 2019)

Soils treated with herbicides are significantly different from those not treated (ANOVA ($F(1.17) = 6.92$, $p = 0.003$). Treated soils have a higher organic matter content, with an average of 3.01 (Table 2). This increase is explained by the fact that (Super Gallant) kills weeds, which are sources of organic matter, and can also be attributed to the action of adjuvants. These last are products used with the active ingredients of a pesticide, intended to improve the effectiveness of chemical properties (Pereira et al., 2009). The NPK fertilizers and the product kind promote the decomposition of organic matter (OM). On the other hand, soils treated with fungicides (Consento) (Table 3) have a low organic matter content. That may be due to the absorption of organic matter by the plant (potato). Organic carbon makes up the majority of the mass of organic matter, (Figure 3.E) and the values of the control samples, samples treated with herbicides (Gallant Super) (Table 2) are higher than the control values (Table 1). Total carbon and nitrogen are essential elements to know the fertility of the soil used by microorganisms and constitute a source of energy playing a role in the solubility of pesticides (Tahar et al., 2017). The adsorption of pesticides by the carbon of organic matter increases their solubility and stability in soil profiles (Tahar et al., 2017). For this reason, it is higher in samples treated with herbicides, at 1.76%, because the higher organic matter can also be attributed to positive products that affect the soil by killing weeds, which are organic carbon sources (Crespo et al., 2015).

In addition to all of these Clay-loam soils showed a strong persistence of herbicide residues. While sandy soils exhibited lower persistence, as indicated by Meliani et al. (2024). This last research focuses on the effects of herbicide application on the properties of agricultural soil in Algeria.

Overall, these elements: nitrogen, phosphorus, and potassium (Figure 3.A, Figure 3.J, and Figure 3.G) are determining factors for both the balance and quality of production and responsible for plant growth (Vasu et al., 2020). The simple mean values differed significantly between simples for nitrogen No_2 (ANOVA (F (1.17) =7.89, p = 0.002), phosphorus P_2O_5 (ANOVA (F (1.17) =2.34, p = 0.008), and potassium K_2O (ANOVA (F (1.17) =6.65, p = 0.004). They were higher for samples treated with the herbicide (Gallant Super) (Table 1). This increase may be due to several factors, such as the use of traditional and chemical fertilizers rich in nutrients, and the increase and intensive use of polluted water.

Also, a significant difference was found between calcium levels (ANOVA (F (1.17) = 3.12, p = 0.05). Contrary to magnesium, where no significant difference was found between simples (ANOVA (F (1.17) = 4.34, p = 0.03).

According to the obtained results, pesticides don't significantly impact the calcium level (Figure 3.I) and magnesium (Figure 3.F) in limestone soils. The results are homogeneous, meaning they are comparable between the control samples and those treated with pesticides. Limestone (Figure 3.H) is the type of soil with a high pH, above 8. It has a poor and dense structure, low infiltration capacity, and slow permeability. The limestone soil samples treated with herbicides have higher values than the control samples. The average value for the herbicide (Gallant Super), while the average value for the control samples is 4.55 (Table 1). The semi-arid climate, high temperatures, and drip irrigation may also contribute to the observed results. The semi-arid climate can affect water loss through evaporation, which can lead to an accumulation of pesticides in the soil. High temperatures can also accelerate the decomposition of pesticides, leading to lower levels of calcium and magnesium in the soil (Mathieu et al., 2003).

According to Council Directive 86/278/EEC on environmental protection, particularly soil, when using sewage sludge in agriculture. The results of heavy metals analysis in agricultural soils presented above (Table 4; Table 5) indicate that the levels of heavy metals in all samples are within the indicated limits. However, it is important to note that heavy metals are PBT substances that can accumulate in the environment and living organisms. It is therefore important to regularly monitor the quality of agricultural soils and implement measures to reduce the risk of contamination by heavy metals (Peshin et al., 2014).

Our research findings were mostly in concordance with the numerous other studies on the potential implications of pesticides on the physicochemical characteristics of soil (Tahar et al., 2017; Meliani et al., 2024). Furthermore, chemical residues impact human health through environmental and food contamination (Chiou, 2008).

Uncontrolled pesticide use has both immediate and long-term effects. They efficiently eradicate weeds and fungi, but they also contaminate groundwater and infiltrate and build up in the soil (Tahar et al., 2016).

Indeed, reducing the negative impacts of pesticides on soil and the environment requires regulations about pesticide usage and soil management.

4. Conclusion

Our results confirmed that the nature and characteristics of the soil, cultivation conditions, treatment methods, and the regulated use of pesticides influence the physical and chemical quality of agricultural soil. According to our main findings, all factors affecting soil fertility have increased, with improvements in organic matter content, organic carbon, NO2, P2O5, and K2O. The treatments with herbicides and fungicides significantly alter the soil characteristics as well as:

- Herbicides increase pH, salinity, TDS, and organic matter. Otherwise, improve nutrient levels such as nitrogen and potassium.
- Fungicides increase pH, stability in salinity, and decrease TDS and organic matter. Also, the variations in nutrient levels with a decrease in nitrogen and potassium.

This is due to several factors, including the rational and controlled use of pesticides, such as the application of both chemical and traditional fertilizers and additives by farmers, and the ability of herbicides to alter the soil's chemical properties. Therefore, we emphasize the research objective of monitoring the effects of plant protection products on soil properties in the Maader Boussaâda region. Ultimately, the farmer's goal is to improve soil conditions and achieve good crop yields, but it is crucial to monitor soil conditions after pesticide use and replace them with biological solutions. The use of pesticides should be minimized as much as possible to protect soil quality in the future, and by consequently preserve natural resources and human health.

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Authors' declaration and contribution

I, the undersigned, declare that the work presented in this study is original and has not been published elsewhere. I confirm that all authors have contributed significantly to the research and have approved the final version of the manuscript. I also declare that there are no conflicts of interest regarding the publication of this study, and all ethical guidelines have been followed throughout the research process. Furthermore, I acknowledge that proper citations and references have been provided for all sources used in this study.

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