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Article

Pesticide residue in cucumber-exposed plants, and its associated effects on soil nematode population

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Abstract: This study investigates pesticide residues in cucumber plants and their impact on soil nematode populations while evaluating the effect of pesticides on cucumber growth and yield. Gas Chromatography Tandem Mass Spectrometry (GC-MS/MS) was used to quantify pesticide residues, comparing the results to the Maximum Residue Limits (MRLs) defined by the Codex Alimentarius. Significant differences in residue levels were found between various pesticides and application rates. Diazinon residues ranged from 0.86 to 2.28 mg/kg, exceeding the MRL of 0.1 mg/kg, indicating soil contamination. Endosulfan had the lowest residues, from 0.44 to 1.75 mg/kg, which were within acceptable limits. Conversely, Malathion and Methoxychlor residues notably surpassed their MRLs, raising potential safety concerns. Further analysis using a linear regression model revealed a negative correlation between pesticide application and soil nematode populations. There was a proportional decrease in nematode populations with increasing pesticide application rate, with Malathion having the most significant impact, followed by Endosulfan, Methoxychlor, and Diazinon. The impact of pesticide application on cucumber plant growth and yield was assessed using one-way ANOVA, which uncovered significant differences across treatment groups. While pesticides are effective for pest control, their application must be carefully managed to avoid phytotoxicity and ensure optimal plant and environmental health, thereby enhancing maximum productivity.

Keywords: pesticide; cucumber; Maximum Residue Limits (MRLs); nematode

1. Introduction

In Nigeria, cucumber cultivation is primarily undertaken in both the northern and southern regions of the country. The vegetable offers numerous health advantages, including promoting hydration due to its high water content [1]. Additionally, they are a source of vitamin K, essential for blood coagulation and maintaining bone health [2]. Pests, as organisms, are known for their propensity to infest crops, thereby facilitating the dissemination of diseases and exerting deleterious effects such as reduced crop productivity and plant mortality. Pesticides benefit crops; however, they also impose a serious negative impact on the environment [3]. According to [4], Nigerian farmers use a range of pesticides such as herbicides, fungicides, and insecticides to safeguard their crops. Although these chemicals are essential for pest and disease management, their widespread application poses risks to environmental and human health. Many studies have documented the extensive use of pesticides on fruits, particularly in developing countries [5–7]. Pesticide residues have the propensity to be absorbed and progressively accumulate as they traverse from soil to plants and subsequently to humans. The specific characteristics of the pesticide and its interactions with the body across different levels dictate whether it will be excreted without causing significant

harm or if it will accumulate, potentially leading to enduring subclinical and clinical ramifications [8]. Pesticide toxicity is linked to a variety of human health issues, including headaches, nausea, rashes, neurotoxicity, cancer, and endocrine dysfunction, which can arise from both direct and indirect exposure to pesticides [9]. Pesticide residues have also led to environmental problems, including soil contamination [10], threats to non-target species, bioaccumulation, and biomagnification within the food chain [5,11,12]. Nematodes, which are microscopic worms inhabiting the soil, are vital contributors to soil vitality and the cycling of nutrients. Nonetheless, the non-selective and widespread application of pesticides can negatively impact these organisms, leading to potential detriments in soil quality and plant vitality. Although aimed at safeguarding crops, some pesticides may exhibit phytotoxic characteristics, which can hinder seed germination, stunt plant growth, and reduce overall crop yields [13]. This research endeavors to explore the specific impacts of different pesticide formulations on the populations of soil-dwelling nematodes and to determine the resulting implications for plant growth and yield in agricultural settings. Through detailed examination of these interactions, this study aims to inform the creation of pest management practices that are not only effective but also sustainable, promoting soil ecosystem health while ensuring high levels of agricultural production.

2. Materials and method

2.1. Description of study area

The study area was 35 m long and 9 m wide. It is situated within the Teaching and Research Farm at the University of Port Harcourt in Choba, Rivers State, Nigeria, as shown in **Figure 1**. The four points represent the four corners of the farm range. Point 1 lies between longitude 6°55′24.21948″ E and latitude 4°54′31.68972″ N, Point 2 is at longitude 6°55′24.67632″ E and latitude 4°54′31.5687″ N, Point 3 is at longitude 6°55′25.19832″ E and latitude 4°54′32.28804″ N, and lastly Point 4 which is at longitude 6°55′24.942″ E and latitude 4°54′32.50764″ N.

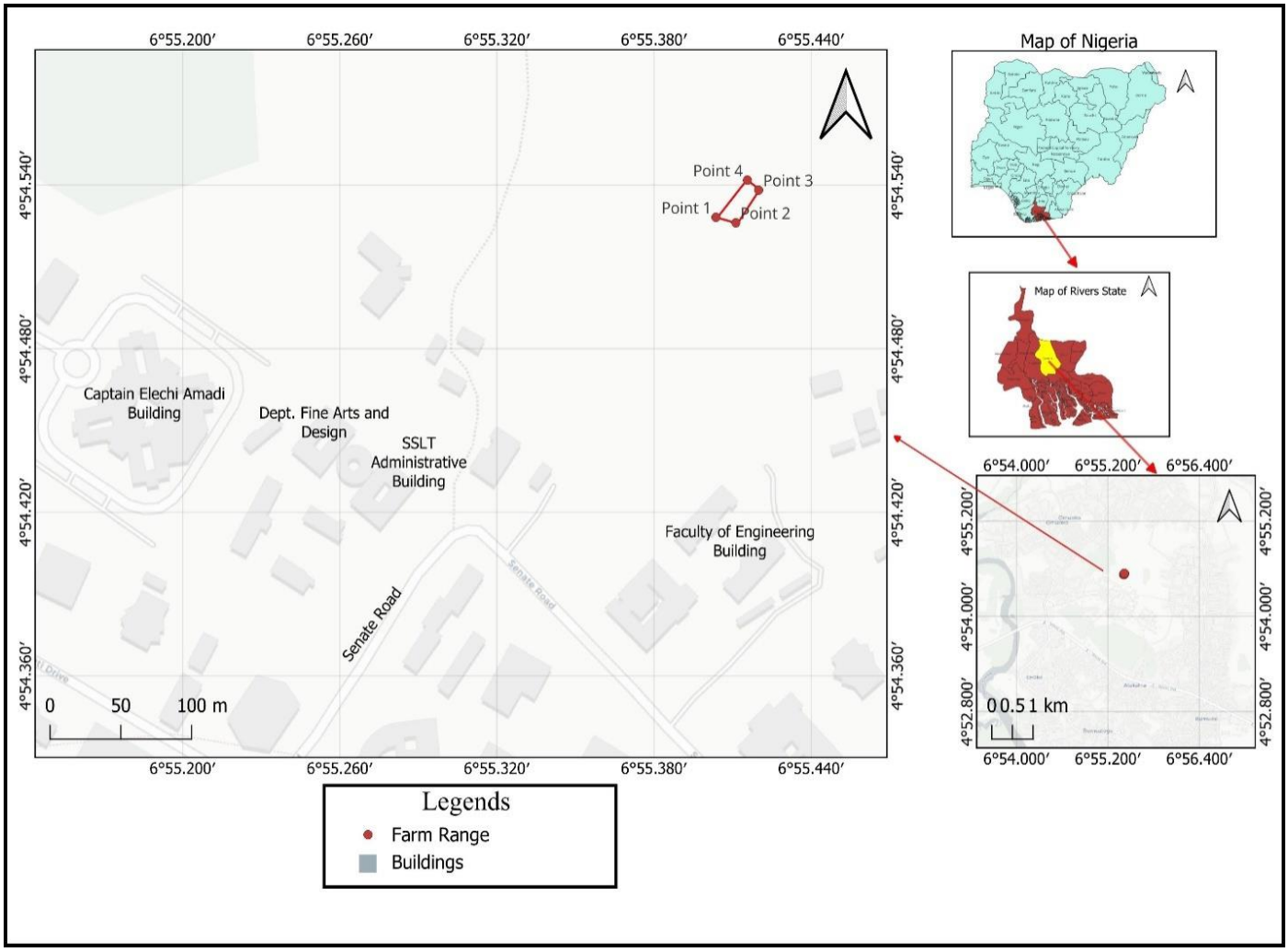

Figure 1. Map of the study area showing the study site at the University of Port Harcourt, Nigeria.

Soil type

The seeds were planted in a sandy loam soil (30% sand and 70% loam) (Ref), which has a balanced texture, good drainage, and nutrient retention. This makes it suitable for crops like cucumbers. The soil was prepared by removing bushes and shrubs and tilling.

Diazinon, Endosulfan, Malathion, and Methoxychlor were selected as the pesticide treatments for this study. These pesticides were selected for this study because of their wide use in agricultural practices, most especially in the control of pests that affect cucumber plants. Besides, these compounds are most times highlighted in pesticide residue monitoring programs due to their toxicity, bioaccumulation concerns, and regulatory significance.

The exact concentrations of the pesticides in the commercial products were not recorded during the study. However, the products were obtained from a certified Agro-Allied shop. The study was concerned with the residue limits in cucumber plants after application, not the initial formulation. In further works, the exact concentration of the active ingredient will be documented to ensure better replicability and scientific accuracy for such studies.

These pesticides, along with the cucumber seeds, were obtained from an Agro-Allied shop located in Eliozu, Rivers State, Nigeria. The specific cucumber seeds used for planting were the Monalisa F1 hybrid variety. Additionally, a 15-liter knapsack sprayer was procured for the application of the pesticides.

Pesticide application:

The pesticides were sprayed directly on the plants, targeting leaves, stems, and fruits to simulate the normal agricultural application methods in the control of pests. This was done to ensure even coverage and to reach areas where pests could take cover, such as the undersides of leaves and other crevices in the plant structure. The method avoided excessive runoff to the soil and focused on the parts of the plant most susceptible to pest activity.

The four pesticides were not sprayed consecutively on the same plants. Rather, each was sprayed on a different set of plants so that their effect could be segregated. This avoided cross-contamination and made the conduction of residue analysis quite simpler, attributing the result to the correct pesticide.

The exact concentrations of the pesticides in the commercial products were not recorded during the study. However, different volumes of the pesticides ranging from 40 mL, 20 mL, and 30 mL were what was taken note of, and this was based on the observations of common practices among local farmers. This approach aimed to replicate real-world agricultural practices to better assess pesticide residue under practical conditions. The exact ratios of pesticide to water were consistent with what farmers typically use but were not based on specific manufacturer recommendations. Moving forward, precise documentation of pesticide concentration and dilution ratios will be prioritized to enhance the scientific rigor of similar studies.

Cucumber planting

Control samples were obtained from planting and growing cucumber plants under the same conditions as the treated plants but without pesticide treatment. This was to allow the control plants to go through the same environmental conditions, like soil type, watering, and sunlight, but they were not influenced by pesticide treatments. This was done to provide a baseline for comparison, allowing us to determine the natural pesticide residue levels, if any, and to then isolate those effects created by the pesticides applied in the treated samples.

2.2. Experimental design

Pre-planting activities were conducted on the designated piece of land, involving site clearing, stump removal, and the creation of raised beds for planting. A total of 48 raised beds were established, each measuring 1.2 m by 1.2 m. These beds were divided into three replicates, with each replicate containing 16 beds. A spacing of 2 m was maintained between each replicate, while a distance of 1 meter separated each bed. The experimental design is shown in **Figure 2**.

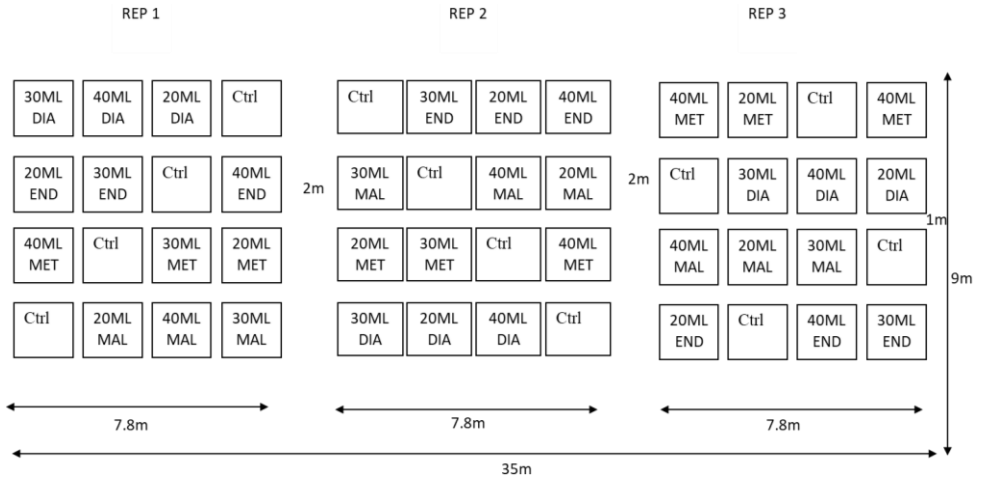

Figure 2. Experimental design of the study. "DIA" refers to diazinon, "END" refers to Endosulfan, "MET" refers to methoxychlor, and "MAL" refers to malathion.

For the purpose of the study, cucumber seeds of the variety Monalisa F1 were planted at a spacing of 60 cm, establishing 9 seed holes per bed. NPK fertilizer was applied a week before planting to boost nutrient availability. Seeds began to germinate within 4 to 8 days. Three weeks after germination, the crops suffered pest attacks from spotted cucumber beetles, flea beetles, and cabbage loopers. To combat this, pesticides such as Diazinon, Endosulfan, Malathion, and Methoxychlor were used, applied in varying concentrations (20 mL, 30 mL, 40 mL) according to a Randomized Complete Block Design (RCBD). Pesticide treatments were replicated three times, with applications made early in the morning weekly. Weed control was manually conducted to avoid affecting crop growth. The plants started bearing fruit a few weeks later and were harvested. Post-harvest, the fruits underwent pesticide residue analysis via Gas Chromatography Tandem Mass Spectrometry, comparing the results with Maximum Residue Limits standards set by the Codex Alimentarius.

2.3. Sample preparation for GC/MS analysis

To prepare the sample, a 20-gram portion was initially homogenized thoroughly to ensure uniformity. The 20 g portion of cucumber used for analysis included the skin. This approach was chosen to reflect real-world consumer exposure, as cucumbers are often consumed with the skin intact. Including the skin also ensures that surface-applied pesticide residues are adequately captured during analysis. The samples were measured with a weighing balance (G & G Deutschland, Germany) to an accuracy of 0.0001 g (0.1 mg).

From this homogenized sample, a 10-gram segment was carefully selected and enriched with labeled compounds. Subsequently, the sample was combined with anhydrous sodium sulfate to facilitate drying, and the mixture was allowed to dry for a minimum of 30 min. Following the drying process, the sample underwent an extended extraction period, typically lasting between 18 to 24 h, utilizing methylene chloride (Sigma-Aldrich, USA) in a Soxhlet extractor (Borosil Glass Works Ltd., India). Once the extraction was completed, the resulting extract was evaporated to complete dryness by an evaporator (Heidolph Instruments GmbH & Co. KG, Germany). The compounds analyzed include Malathion-d10 at a concentration of 100

ng/mL (Ehrenstorfer GmbH, Germany), Endosulfan at a concentration of 100 ng/mL (AccuStandard Inc., USA), Methoxychlor-d10 at 100 ng/mL (Sigma-Aldrich, USA), and Diazinon-d10 at 100 ng/mL (LGC Standards, UK).

The standard method used for pesticide extraction followed a modified Soxhlet extraction technique, which aligns with procedures outlined in the U.S. Environmental Protection Agency (EPA) Method 3540C for solid matrices and elements of the Codex Alimentarius guidelines for pesticide residue analysis in food.

Soxhlet Extraction Procedure for Pesticide Residue Analysis (Based on EPA Method 3540C and Codex Guidelines)

1) Sample Preparation:

20 grams of homogenized cucumber (with skin) were weighed and placed into a cellulose extraction thimble.

The sample was pre-dried slightly with anhydrous sodium sulfate to remove moisture and aid solvent penetration.

2) Apparatus Setup:

A 250 mL Soxhlet extractor connected to a 500 mL round-bottom flask and a reflux condenser was assembled.

3) Solvent Selection and Extraction:

200–250 mL of methylene chloride (analytical grade, ≥ 99.8% purity) was used as the extraction solvent.

The Soxhlet unit was heated gently to allow continuous reflux.

The extraction was allowed to proceed for 6 h, ensuring a minimum of 10 full siphon cycles per hour.

4) Concentration of Extract:

After extraction, the solvent extract was concentrated using a rotary evaporator under reduced pressure at 40 ℃ until the volume was reduced to about 5–10 mL.

Final concentration was carried out under a gentle stream of nitrogen to 1–2 mL, if required.

5) Cleanup (if applicable):

The concentrated extract was subjected to cleanup (e.g., silica gel column) to remove interfering matrix compounds, depending on the complexity of the sample.

6) Analysis:

The cleaned extract was transferred to a GC vial and analyzed using GC/MS under validated conditions.

Finally, the lipid content within the dried extract was accurately quantified. The lipid content was determined using the gravimetric method following Soxhlet extraction. After the Soxhlet extraction using methylene chloride as the solvent, the extract was concentrated using a rotary evaporator, and the lipid residue was allowed to dry in a pre-weighed dish. The increase in weight was used to calculate the lipid content of the cucumber samples, expressed as a percentage of the original sample weight.

Determining the lipid content was important because many pesticides, especially organochlorines (e.g., Endosulfan) and organophosphates (e.g., malathion, diazinon)—are lipophilic and tend to accumulate in fatty tissues. Measuring lipid content helped to better interpret pesticide residue levels and supported the understanding of pesticide affinity for the sample matrix.

2.4. Procedure for pesticide analysis

For the analysis of pesticides, the sample extracts underwent a cleaning process using a combination of methylene chloride and n-hexane in a 1:1 ratio. Subsequently,

The injection volume used for GC/MS analysis was 1.0 μL, which is appropriate for the narrow-bore capillary column, of these cleaned extracts was introduced into a gas chromatograph equipped with a capillary column made of fused silica, available in either narrow or wide bore configurations. The chromatograph also featured detection systems such as an electron capture detector (GC/MS) or an electrolytic conductivity detector (GC/MS). The method involved electron impact ionization and selected ion monitoring (SIM) mode for enhanced sensitivity and selectivity.

For GC-MS (Germany) analysis, an Agilent 6890 gas chromatograph paired with a 5973 MS detector was utilized. This setup incorporated a 30-meter-long capillary column with an internal diameter of r 0.25 mm, coated with SE-54DB-5) with a film thickness of 1 μm. The capillary column used for the GC-MS analysis was a DB-5MS column, 30 m × 0.25 mm ID × 0.25 μm film thickness. This configuration provided sufficient resolution, sensitivity, and peak shape for the pesticide residues analyzed.

The temperature protocol involved initially setting the oven to 200 ℃ for 1 min, followed by a gradual increase to 230 ℃ at a rate of 1.5 ℃ per minute, and then maintaining this temperature for 10 min. Pesticide identification and characterization were conducted in SCAN mode, scanning an m/z range from 35 to 450. Nitrogen served as the carrier gas at a flow rate of 1 mL per minute, and manual injection of a 1 μL sample was required.

For quantifying pesticide composition, an Agilent 6890 gas chromatograph was employed, fitted with a similar 30-meter-long capillary column with an internal diameter of 0.25 mm or 0.32 mm. This column had the same SE-54 chemical bonding and 1 μm film thickness as previously mentioned. Temperature settings followed a similar pattern, starting at 200 ℃ for 1 min, increasing to 230 ℃ at a rate of 1.5 ℃ per minute, and then holding for 10 min. Injector and detector temperatures were set at 250 ℃ and 280 ℃, respectively. Nitrogen was utilized as the carrier gas at a flow rate of 1 mL per minute, with a split ratio of 50:1, and the injected sample volume was 1 μL.

Standard solutions used for calibration

The following pesticide standards were used: Malathion, Endosulfan (α- and β-isomers), Methoxychlor, and Diazinon. These standards were sourced from Dr. Ehrenstorfer GmbH (Germany) and Sigma-Aldrich (USA), each with a certified purity of ≥ 98%. Stock solutions were prepared at a concentration of 1000 μg/mL. The calibration curves for each pesticide were constructed using a series of standard solutions prepared at concentrations of 5, 10, 25, 50, 100, 250, and 500 ng/mL. These concentrations were selected to encompass the expected range of pesticide residues in the cucumber samples. Each standard solution was analyzed under the same GC/MS conditions as the samples, and a linear calibration curve was generated for each compound. The resulting calibration curves demonstrated excellent linearity, with correlation coefficients (R^2) exceeding 0.99 for all target analytes. The detection limits for Malathion, Endosulfan, Methoxychlor, and Diazinon are 2.0 ng/mL, 1.5 ng/mL, 2.5 ng/mL, and 1.0 ng/mL, espectively. The limits of detection were determined using

the signal-to-noise (S/N) ratio method in accordance with internationally accepted guidelines. The LOD was defined as the lowest concentration that produced a signal-to-noise ratio of 3:1.

The following Quality Assurance and Quality Control (QA/QC) measures were implemented throughout the study to ensure the reliability and validity of the analytical results.

1) Method Validation:

The analytical method was validated in terms of linearity, accuracy, precision, sensitivity, and specificity. Calibration curves for each pesticide showed excellent linearity ($R^2 > 0.99$) across the tested concentration range (5–500 ng/mL).

2) Recovery Studies:

Recovery tests were performed by spiking blank cucumber samples at three concentration levels (e.g., 25, 100, and 250 ng/mL). Recoveries ranged from 75% to 110%, with relative standard deviations (RSDs) below 15%, in accordance with Codex and SANTE/11312/2021 guidelines.

3) Blanks and Duplicates:

Procedural blanks were included in each batch of analyses to monitor potential contamination. Duplicate samples were analyzed periodically to assess analytical precision and reproducibility.

4) Use of Internal Standards:

Isotopically labeled internal standards were added to all samples prior to extraction to correct for variability in recovery and instrumental response.

5) Instrument Performance:

The GC-MS system was tuned and checked daily. System suitability tests (e.g., peak shape, retention time stability, and signal-to-noise ratios) were performed prior to sample injection.

6) Limit of Detection/Quantification:

LOD and LOQ were determined using the signal-to-noise (S/N) method, and all detected residues in real samples were above the LOQ.

2.5. Sample collection

2.5.1. Nematode collection

Nematode collection was conducted using a random sampling approach. Soil samples were collected indiscriminately from each of the designated soil beds using a soil auger. These samples were extracted from different depths, specifically from 0 to 5 cm. A total of 48 soil beds were sampled to assess the impact of varying pesticide concentrations on nematode populations, with results subsequently compared to those from control plots. Following collection, the soil samples were carefully placed in polyethylene bags, each clearly labeled for easy identification.

2.5.2. Nematode extraction

The Baermann technique was employed to isolate nematodes from soil samples. Initially, any stones and debris were removed by sieving the soil through a specially adapted sieve. Subsequently, a volume of 200 mL of the sieved soil was accurately measured in a beaker. This soil was then enclosed in a Paloma tissue and placed on top of a plastic plate, which featured a plastic sieve submerged in water. This setup

was left to settle for 48 h. After the extraction process, the nematode-water mixture from the plate was transferred into a sterile bottle labeled for identification. The contents were allowed to settle, and the liquid in the bottle was then reduced to a volume of 10 mL. This concentrated mixture of nematodes and water extracted from the soil was further stabilized by adding an equal amount of 10% formaldehyde. This preservation step was undertaken in preparation for the subsequent identification and quantification of the nematodes.

2.5.3. Nematode identification

The nematode identification process occurred in the parasitology laboratory within the Department of Animal and Environmental Biology. Initially, the sample in the bottle was allowed to settle, enabling the solids to settle at the bottom. The clear liquid, known as the supernatant, was then carefully removed until approximately one-fourth of the original volume remained, utilizing a Pasteur pipette for precise extraction. For microscopic examination, a 2 mL sample of this concentrated suspension was transferred onto a clean microscope slide. To improve visibility, a drop of iodine was added, and the slide was covered with a slip for examination under the microscope. Nematode identification and counting were carried out using the microscope's X4 and X10 objectives.

2.5.4. Crop growth and yield

Throughout the growing period, data on plant growth metrics such as leaf area, leaf height, leaf count, and stem thickness were collected weekly post-pesticide application. Sampling on specific plants for data collection and measurements was done using a random sampling method in each plant bed. Measurements for the leaf height were conducted using a metric ruler, while data on stem thickness was carried out using calipers. At harvest, data were also gathered on fruit yield metrics, including weight, width, and fruit count per pesticide concentration, to evaluate the impact of the pesticides on yield. These data were gotten through measurement using a weighing balance, metric ruler, and manual counting of the fruit yields.

2.6. Statistical analysis

Results of pesticide residue from the laboratory were analyzed statistically using one-way ANOVA to compare means across different groups to find significant variations within treatments and concentration levels. Regression analysis employing the linear regression model was used to model the relationship between nematode population and the different concentrations of pesticides. This approach aimed to quantify the impact of different pesticide concentrations on nematode population dynamics. The data gathered on the crop growth and yield were evaluated using a one-way ANOVA to compare means across different groups. This analysis was performed in IBM SPSS statistics software version 25.

3. Result

3.1. Concentration of pesticide residue

The study findings on pesticide residue levels in cucumbers ($n = 48$): each sample underwent the same homogenization, Soxhlet extraction, and GC-MS analysis. They also vary according to different concentrations of four pesticides, as follows:

Diazinon: Residues ranged from 0.86 mg/kg at 20 mL to 2.28 mg/kg at 40 mL, with the control group showing 0.48 mg/kg. Remarkably, even the control group's residue level exceeded the Maximum Residue Limit (MRL) of 0.1 mg/kg, suggesting potential cross-contamination from the soil.

The Maximum Residue Limits (MRLs) used for interpreting the pesticide residue levels in this study were based on the Codex Alimentarius international food standards established by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO).

Endosulfan: Residues were lowest among the pesticides, starting at 0.44 mg/kg for 20 mL and increasing to 1.75 mg/kg for 40 mL, while the control sample had 0.24 mg/kg, below the MRL of 1 mg/kg. This implies that Endosulfan application, within the studied concentration range, may not exceed legal residue limits.

Malathion: Significantly present, with residue levels ranging from 0.62 mg/kg at the lowest concentration to 2.74 mg/kg at the highest, compared to 0.38 mg/kg in the control. All treated samples surpassed the MRL of 0.2 mg/kg, raising concerns about its safety at these levels.

Methoxychlor: Levels remained consistently close to the MRL, escalating from 0.63 mg/kg at 20 mL to 2.26 mg/kg at 40 mL, against a control level of 0.42 mg/kg. With the MRL set at 0.01 mg/kg, Methoxychlor residues exceeded acceptable limits across all concentrations.

The findings revealed significant differences in residue levels between concentration levels and between pesticides, as shown in **Tables 1** below.

Table 1. Mean comparison of pesticide residue in cucumber ($n = 48$) with varying concentrations.

Pesticide	20 mL (mg/kg)	30 mL (mg/kg)	40 mL (mg/kg)	Control (mg/kg)
Diazinon	0.86 ± 0.01^{c}	1.65 ± 0.01^{b}	2.25 ± 0.01^{a}	0.48 ± 0.01^{d}
Endosulphan	0.44 ± 0.01^{c}	1.64 ± 0.01^{b}	2.75 ± 0.01^{a}	0.24 ± 0.01^{d}
Malathion	0.62 ± 0.01^{c}	1.77 ± 0.01^{b}	2.74 ± 0.01^{a}	0.38 ± 0.01^{d}
Methoxychlor	0.63 ± 0.01^{c}	1.53 ± 0.01^{b}	2.26 ± 0.01^{a}	0.42 ± 0.01^{d}

* Mean values with different letters in the same row indicate a statistically significant difference at $p < 0.05$.; a, b, c, d- mean different letters indicate significant differences

3.2. Impact of pesticide on nematode population

The analysis of the impact of various pesticide concentrations on soil nematode populations was conducted using a linear regression model as shown in **Figure 3**. The nematode species found at the study site was *Meloidogyne incognita*. The aim was to quantify the relationship between the concentration of each pesticide and the nematode population in the soil. The study findings revealed a significant relationship between pesticide concentration and nematode population in the soil. The regression equations for Diazinon ($y = -2.1459x + 131.36$), Endosulfan ($y = -2.4773x + 158.56$), Malathion ($y = -2.6049x + 167.34$), and Methoxychlor ($y = -2.4952x + 173.47$) demonstrate negative slopes, indicating a decrease in nematode population with increasing pesticide concentration. The slopes suggest that for each unit increase in pesticide

concentration, there is a proportional decrease in the nematode population, with Malathion showing the steepest decline, followed closely by Endosulfan, Methoxychlor, and Diazinon. The coefficient of determination (R^2) for each pesticide's model was found to be significantly high (Diazinon: 0.9603, Endosulfan: 0.9621, Malathion: 0.9634, and Methoxychlor: 0.9726), indicating that the linear models explain a substantial portion of the variance in the nematode populations. These high R^2 values suggest a strong linear relationship between pesticide concentration and the decline in nematode populations across the range of concentrations studied. Upon examining the slopes and their absolute values, we infer a close range of effectiveness among the pesticides, with Malathion marginally exhibiting the greatest impact per unit concentration on reducing nematode populations. Nevertheless, the slopes are relatively similar, indicating comparable effectiveness in the range of concentrations used in this study. The proximity of the observed data points to the regression lines across all pesticides suggests that the linear regression model is a good fit for the data. This indicates that the model is reliable for predicting the nematode population at different pesticide concentrations within the range tested. The study presents clear evidence that the application of Diazinon, Endosulfan, Malathion, and Methoxychlor negatively affects soil nematode populations in a concentration-dependent manner.

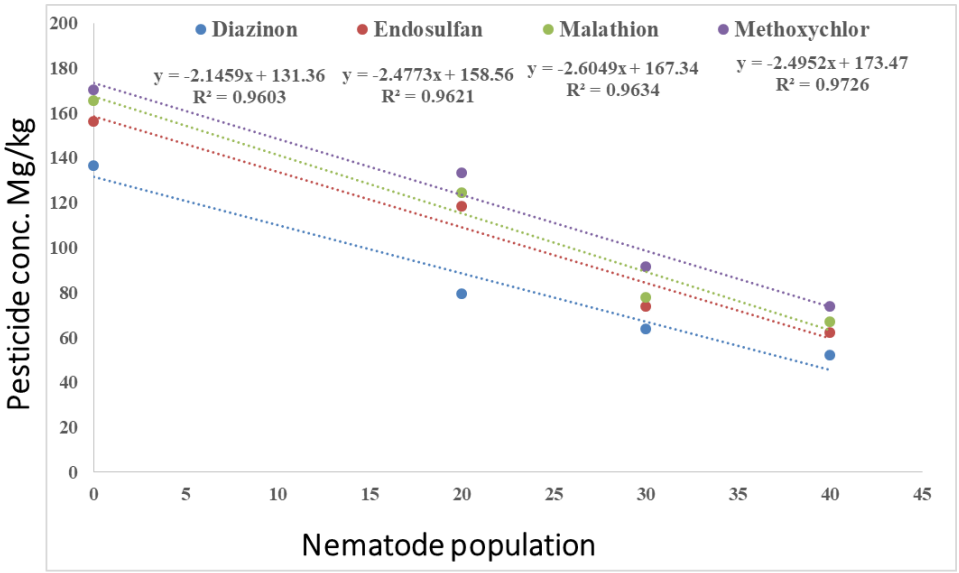

Figure 3. Impact of pesticide on nematode population in the soil.

3.3. Effect of varying concentrations of pesticide on plant growth

The tables below contain detailed results assessing the effects of different pesticide volumes on various growth parameters of cucumber plants over several time points. The data is presented with mean values and standard deviations for each parameter across different pesticide treatments and control groups. The analysis, using ANOVA to compare mean values marked by different subscript letters (a, b), shows significant differences at $p < 0.05$. These differences highlight the intricate effects of pesticide concentrations on plant height, leaf area, number of leaves, and stem girth. In examining the impact of various pesticide concentrations on plant development

across three time intervals—21, 28, and 35 days—as shown in **Tables 2–4**. The study revealed the following findings. Initially, at 21 days, Endosulfan emerged as the most effective with a mean value of 18.17 ± 6.00 cm at a 20 mL concentration level, and the mean value increased as the concentration level increased, with the 40 mL concentration level having a mean value of 23.17 ± 11.43 cm. This shows its ability to enhance plant height significantly, whereas Methoxychlor exhibited minimal growth promotion. Progressing to 28 days, elevated doses of Malathion and Endosulfan were beneficial, particularly Endosulfan at 40 mL, having a mean value of 46.33 ± 22.85 when compared to its control mean value of 19.17 ± 12.00 cm, which signifies a significant increase in plant height. However, Methoxychlor and Diazinon displayed a dose-responsive variation, with Diazinon at a 20 mL dose having a mean value of 49.00 ± 17.52 cm, outperforming its highest concentrations, which had a mean value of 18.67 ± 4.93 cm. By 35 days, both Malathion and Diazinon at a 30 mL dosage demonstrated substantial growth improvements, with Malathion at this concentration noted for its efficacy. Conversely, higher concentrations of Methoxychlor and Malathion hinted at potential plant toxicity. The results suggest that optimal growth results are attained with mid-range concentrations of Endosulfan and Malathion, highlighting the critical balance between pesticide effectiveness and plant health, while also noting the varied responses to Methoxychlor and Diazinon, which performed inconsistently across different stages and concentrations.

Table 2. Effect of varying concentrations of pesticide on plant growth (cm ± SE) after 21 days of planting.

Duration	Pesticide	Volume (mL)	Plant Height (cm)	Leaf Area (cm)	Number of Leaves	Stem Girth (cm)
21 Days	Malathion	0	16.33 ± 1.26^{a}	38.50 ± 4.98^{a}	7.00 ± 2.65^{a}	0.60 ± 0.17^{b}
		20	12.67 ± 8.94^{a}	36.38 ± 14.01^{a}	7.00 ± 3.00^{a}	0.80 ± 0.17^{ab}
		30	19.17 ± 8.25^{a}	38.75 ± 15.45^{a}	7.67 ± 3.51^{a}	1.17 ± 0.28^{a}
		40	9.33 ± 2.36^{a}	24.25 ± 3.68^{a}	6.33 ± 2.31^{a}	1.13 ± 0.12^{a}
	Endosulfan	0	9.60 ± 6.00^{a}	24.52 ± 11.89^{b}	5.00 ± 0.00^{a}	0.80 ± 0.35^{a}
		20	18.17 ± 6.00^{a}	46.67 ± 5.34^{ab}	5.67 ± 2.52^{a}	0.90 ± 0.17^{a}
		30	22.33 ± 8.08^{a}	50.80 ± 2.10^{ab}	7.00 ± 2.00^{a}	1.20 ± 0.17^{a}
		40	23.17 ± 11.43^{a}	43.62 ± 19.99^{a}	7.33 ± 5.86^{a}	0.90 ± 0.35^{a}
	Methoxychlor	0	9.83 ± 1.15^{a}	22.14 ± 2.52^{a}	4.33 ± 0.58^{a}	0.77 ± 0.12^{a}
		20	15.33 ± 14.18^{a}	30.50 ± 18.31^{a}	5.67 ± 2.08^{a}	0.80 ± 0.17^{a}
		30	16.00 ± 9.34^{a}	28.50 ± 15.26^{a}	5.67 ± 2.52^{a}	0.90 ± 0.35^{a}
		40	16.67 ± 6.82^{a}	38.84 ± 19.20^{a}	5.67 ± 1.53^{a}	0.90 ± 0.17^{a}
	Diazinon	0	24.83 ± 8.81^{a}	36.82 ± 10.86^{ab}	5.00 ± 1.00^{b}	0.90 ± 0.35^{a}
		20	24.50 ± 8.76^{a}	45.25 ± 14.88^{a}	7.00 ± 1.00^{a}	1.10 ± 0.17^{a}
		30	13.67 ± 5.51^{ab}	22.22 ± 4.84^{b}	4.67 ± 0.58^{b}	0.70 ± 0.00^{a}
		40	9.33 ± 2.47^{b}	22.67 ± 4.04^{b}	5.00 ± 1.00^{b}	0.90 ± 6.35^{a}

** Mean values in the same column with different letters indicate statistical significance at $p < 0.05$.; a, b-different letters indicate significant differences

Table 3 Effect of varying concentrations of pesticide on plant growth (± SE) after 28 days of planting.

Duration	Pesticide	Volume (mL)	Plant Height (cm)	Leaf Area (cm)	Number of Leaves	Stem Girth (cm)
28 Days	Malathion	0	32.67 ± 2.52^{a}	152.33 ± 18.52^{a}	14.33 ± 5.13^{a}	1.50 ± 0.00^{b}
		20	25.33 ± 17.90^{a}	143.67 ± 54.27^{a}	14.00 ± 6.55^{a}	1.83 ± 0.29^{ab}
		30	38.33 ± 16.50^{a}	155.00 ± 61.80^{a}	15.67 ± 6.51^{a}	2.33 ± 0.58^{a}
		40	18.67 ± 4.73^{a}	97.17 ± 18.07^{a}	12.67 ± 5.51^{a}	2.33 ± 0.29^{a}
	Endosulfan	0	19.17 ± 12.00^{a}	101.50 ± 44.08^{b}	10.33 ± 0.58^{a}	1.67 ± 0.58^{a}
		20	36.33 ± 12.01^{a}	186.67 ± 21.39^{ab}	10.83 ± 0.29^{b}	1.83 ± 0.29^{a}
		30	44.67 ± 16.17^{a}	208.60 ± 15.13^{a}	12.33 ± 0.29^{b}	2.33 ± 0.29^{a}
		40	46.33 ± 22.85^{a}	171.92 ± 79.28^{ab}	12.67 ± 0.29^{b}	1.83 ± 0.58^{a}
	Methoxychlor	0	19.67 ± 2.31^{a}	87.42 ± 14.21^{a}	4.33 ± 4.73^{a}	1.67 ± 0.29^{a}
		20	30.67 ± 28.36^{a}	128.50 ± 90.52^{a}	10.33 ± 5.77^{a}	1.67 ± 0.29^{a}
		30	32.00 ± 18.68^{a}	111.33 ± 57.27^{a}	11.67 ± 5.13^{a}	1.83 ± 0.58^{a}
		40	29.33 ± 13.65^{a}	153.67 ± 75.73^{a}	12.00 ± 3.61^{a}	1.83 ± 0.29^{a}
	Diazinon	0	44.00 ± 7.20^{a}	155.25 ± 55.67^{ab}	9.67 ± 1.53^{b}	1.83 ± 0.58^{ab}
		20	49.00 ± 17.52^{a}	183.67 ± 63.52^{a}	14.00 ± 1.73^{a}	2.17 ± 0.29^{a}
		30	27.00 ± 11.27^{ab}	93.75 ± 14.81^{b}	9.33 ± 1.15^{b}	1.50 ± 0.00^{b}
		40	18.67 ± 4.93^{b}	100.00 ± 0.00^{ab}	9.33 ± 1.53^{b}	1.50 ± 0.00^{b}

** Mean values in the same column with different letters indicate statistical significance at $p < 0.05$.; a, b-different letters indicate significant differences

Table 4. Effect of varying concentration of pesticide on plant growth (± SE) leaves after 35 days of planting.

Duration	Pesticide	Volume (mL)	Plant Height (cm)	Leaf Area (cm)	Number of Leaves	Stem Girth (cm)
35 Days	Malathion	0	88.33 ± 12.58^{a}	183.33 ± 40.02^{a}	7.00 ± 4.00^{ab}	1.93 ± 0.15^{ab}
		20	106.67 ± 36.17^{a}	210.00 ± 14.00^{a}	7.00 ± 3.00^{ab}	2.23 ± 0.23^{a}
		30	116.67 ± 20.82^{a}	225.00 ± 15.00^{a}	15.00 ± 5.00^{a}	2.33 ± 0.29^{a}
		40	63.67 ± 43.32^{a}	136.67 ± 91.66^{a}	6.33 ± 4.73^{b}	1.47 ± 0.55^{b}
	Endosulfan	0	85.33 ± 17.47^{a}	192.67 ± 56.58^{a}	25.33 ± 5.13^{a}	2.10 ± 0.20^{a}
		20	44.67 ± 31.34^{b}	89.33 ± 54.78^{a}	14.67 ± 7.57^{b}	1.33 ± 0.55^{b}
		30	103.33 ± 15.28^{a}	201.33 ± 60.18^{a}	19.00 ± 4.36^{b}	2.03 ± 0.11^{a}
		40	117.00 ± 14.73^{a}	212.33 ± 95.52^{a}	27.67 ± 2.52^{a}	2.27 ± 0.21^{a}
	Methoxychlor	0	55.00 ± 21.79^{ab}	143.00±75.01^{ab}	15.33 ± 5.51^{bc}	1.67 ± 0.49^{ab}
		20	123.33 ± 50.58^{a}	242.00 ± 57.42^{a}	32.67 ± 11.24^{a}	2.23 ± 0.31^{a}
		30	100.17 ± 47.46^{ab}	176.30 ± 56.20^{ab}	27.33 ± 6.43^{ab}	2.07 ± 0.25^{a}
		40	30.00 ± 17.32^{a}	60.67 ± 43.14^{b}	10.00 ± 5.00^{c}	1.10 ± 0.35^{b}
	Diazinon	0	86.67 ± 30.55^{a}	182.50 ± 24.79^{b}	22.67 ± 7.57^{a}	2.00 ± 0.10^{a}
		20	120.00 ± 45.83^{a}	222.67 ± 70.44^{a}	24.00 ± 5.29^{a}	2.10 ± 0.35^{a}
		30	120.00 ± 18.03^{a}	215.33 ± 16.74^{a}	32.33 ± 6.81^{b}	2.30 ± 0.00^{a}
		40	76.67 ± 15.28^{a}	180.83 ± 32.41^{a}	25.33 ± 15.31^{b}	2.03 ± 0.23^{a}

** Mean values in the same column with different letters indicate statistical significance at $p < 0.05$.; a, b-different letters indicate significant differences

3.4. Effect of varying concentration of pesticides on crop yield

Based on the provided statistical analysis as shown in **Table 5** below, the efficacy of different pesticides on crop yield, measured through the number of fruits, fruit weight, and fruit width, showed significant differences across the concentration levels, and this can be interpreted as follows: Diazinon shows the most remarkable performance in enhancing fruit weight, particularly at the 20 mL concentration with a mean value of 483.33 ± 28.87 cm, indicating its superior efficacy in promoting fruit growth compared to the other pesticides tested. Its impact on fruit width is also noteworthy, suggesting a balanced enhancement in fruit size. Endosulfan stands out for its ability to increase the number of fruits, especially at the 20 mL concentration, having a mean value of 10.00 ± 5.29 cm, which implies its effectiveness in fruit quantity production over quality enhancement. Methoxychlor and Malathion, while effective to a certain extent across all measured parameters, do not consistently outperform Diazinon and Endosulfan in their respective best categories. Methoxychlor displays a moderate improvement in fruit weight and width at certain concentrations but does not lead in any specific category. The least effective seems to be Malathion at the 40 mL concentration for fruit weight, where it shows no significant improvement over its control as they both had the same mean values of 266.67 ± 76.38 cm, indicating a decrease in effectiveness beyond a certain concentration. Diazinon excelled in fruit weight enhancement, making it the most effective pesticide for improving fruit size among the ones tested. Endosulfan was most effective in increasing the number of fruits, suggesting its use when aiming for quantity.

Table 5. Effect of the pesticides on crop yield (± SE).

Pesticide	Volumes (mL)	Number of fruits	Fruit weight (g)	Fruit Width (cm)
Malathion	0	6.00 ± 2.00^{a}	266.67 ± 76.38^{a}	16.33 ± 2.84^{a}
	20	4.97 ± 0.58^{a}	300.00 ± 100.00^{a}	14.66 ± 1.76^{a}
	30	8.00 ± 4.36^{a}	366.67 ± 104.08^{a}	15.43 ± 1.50^{a}
	40	5.33 ± 2.51^{a}	266.67 ± 76.38^{a}	16.63 ± 2.40^{a}
Endosulfan	0	5.67 ± 2.08^{a}	383.33 ± 104.08^{a}	18.00 ± 1.73^{a}
	20	10.00 ± 5.29^{a}	333.33 ± 104.08^{a}	17.40 ± 0.53^{a}
	30	9.00 ± 1.73^{a}	330.00 ± 86.60^{a}	17.37 ± 2.26^{a}
	40	9.3 ± 2.52^{a}	300.00 ± 5.00^{a}	15.90 ± 1.73^{a}
Diazinon	0	7.00 ± 5.00^{a}	$216.6728.87^{c}$	15.30 ± 3.48^{a}
	20	8.67 ± 2.89^{a}	483.33 ± 28.87^{a}	19.43 ± 0.819^{a}
	30	7.67 ± 2.52^{a}	333.33 ± 28.87^{b}	16.93 ± 0.67^{a}
	40	4.33 ± 1.15^{a}	283.33 ± 104.08^{bc}	15.37 ± 2.47^{a}
Methoxychlor	0	4.00 ± 1.00^{a}	266.67 ± 76.38^{ab}	16.00 ± 2.65^{b}
	20	6.67 ± 3.06^{a}	316.67 ± 57.74^{a}	16.27 ± 1.91^{a}
	30	6.33 ± 3.21^{ab}	350.00 ± 86.60^{b}	17.33 ± 1.01a
	40	3.67 ± 1.53^{b}	300.00 ± 50.00^{a}	14.73 ± 1.03^{a}

** Mean values in the same column with different letters indicate statistical significance at $p < 0.05$.; a, b-different letters indicate significant differences

4. Discussion

The global prevalence of pesticide residues in fruits and vegetables presents a significant concern because of its impact on human health and the environment. Our research highlighted elevated pesticide residue levels surpassing the Maximum Residue Limit (MRL) across all cucumber samples, further accentuating the severity of the matter. As shown by a detailed investigation carried out by [14] into the pesticide levels in fruit imported into the United Arab Emirates. The study revealed that most of the imported fruits surpassed the Maximum Residue Limit (MRL) for pesticides, and this underscores a pressing environmental health issue, aligning closely with the outcomes of our investigation. This trend suggests systemic shortcomings in pesticide management and regulation, raising significant concerns regarding pesticide oversight and application practices in agriculture.

The similarities observed between the results of the UAE study and our own study, which revealed significant differences in residue levels between concentration levels and between pesticides, highlight the pressing necessity for enhanced regulation and enforcement of pesticide usage, along with the implementation of more robust monitoring systems to uphold food safety standards. The proactive steps taken in the UAE, such as preventing the sale of fruits with excessive pesticide residues, serve as a model of regulatory rigor essential for ensuring consumer well-being. Such stringent measures ought to be embraced by the Nigerian government.

The presence of detectable residues in the control samples can be attributed to environmental contamination. In the Niger Delta region, soil contamination is prevalent due to the extensive use of pesticides in agriculture by farmers. Tudi et al. [15] reported that the soil absorbs, retains, and translocates these pesticides to crops in the surrounding environment, leading to their presence in agricultural produce. Additionally, these pesticides persist in the soil for extended periods, exacerbating the issue of contamination over time. The pesticides present in the soil are absorbed, retained, and transported to nearby crops, resulting in their contamination. This was illustrated in a study on maize by [16], in which six pesticides were applied to the soil, and maize seedlings were subsequently introduced into the contaminated soil. Upon harvesting and analysis, it was found that all six pesticides had translocated into the maize plants. These findings raise the possibility that the pesticides detected in our control cucumbers may have originated from residual pesticides present in the soil.

This study also presents compelling evidence that there is a significant relationship between pesticide concentration and nematode population in the soil, revealing that the application of Diazinon, Endosulfan, Malathion, and Methoxychlor negatively impacts soil nematode populations in a concentration-dependent manner. These findings highlight the importance of carefully managing pesticide application rates to mitigate their adverse effects on non-target soil organisms like nematodes, which are essential for soil health and ecosystem functioning. Furthermore, these findings align with previous studies conducted on the impact of pesticides on nematode populations. El-Marzoky et al. [17] revealed that using abamectin at 500 ppm notably reduced nematode reproduction and gall numbers. This finding parallels the results of our study, where pesticide levels were found to influence soil nematode counts. Fabiyi et al. [18] also revealed that pesticides, especially at higher

concentrations, significantly harm beneficial nematodes and bacteria, which are essential for soil fertility and plant growth. This overlap underscores the importance of careful pesticide management, suggesting that sustainable practices and lower pesticide doses could mitigate adverse effects on non-target organisms. Implementing such practices supports healthier ecosystems and more productive agriculture. Together, these insights advocate for an integrated approach to pest management, prioritizing environmental conservation alongside agricultural efficiency.

Research has indeed demonstrated that the application of certain pesticides can positively impact plant growth and yield. By effectively protecting plants from pests and diseases, these pesticides contribute to improved photosynthetic efficiency and nutrient uptake. This protection allows plants to allocate more energy and resources towards growth and development, ultimately leading to enhanced yields. Hand et al. [19] indicated a clear differential impact of herbicide type, application rate, and timing on both crops. The study demonstrates that higher rates of herbicide application, especially during early stages of vegetative growth, lead to more severe crop damage and yield reduction, underscoring the critical timing for herbicide exposure.

Integrating findings from the study by [19] on the impacts of auxinic herbicides on sensitive crops with our research on the differential effects of pesticides like Diazinon and Methoxychlor on plant development clarifies or makes clear the complicated and varied aspects of using chemical treatments, such as pesticides and herbicides, in farming practices. While auxinic herbicides such as 2, 4-D and dicamba caused significant damage to non-target crops, leading to reduced growth and yield. Diazinon emerged as a beneficial agent under certain conditions, enhancing plant height, leaf surface area, stem thickness, and foliage count, indicative of a positive influence on vegetative growth. This comparison underscores the critical need for precise, informed application of pesticides considering type, dosage, and timing to harness potential growth-promoting effects while minimizing adverse impacts.

The findings from our study align with the existing body of work, demonstrating a detailed response of cucumber plants to varying pesticide volumes. The significant differences with a P value less than 0.05 observed in the study, which highlight the intricate effects of pesticide concentrations on growth and yield parameters across different pesticide treatments, underscore the importance of optimizing pesticide application rates. Balancing pest control benefits with potential phytotoxicity risks is crucial for maximizing crop productivity while minimizing adverse effects on plant health and yield.

These findings significantly contribute to the development of Integrated Pest Management (IPM) strategies, emphasizing the nuanced approach required in the selection and use of chemical controls within agricultural systems to balance pest management with plant health and environmental sustainability.

5. Conclusion

This study clearly shows the complex relationship between the use of pesticides, the growth of cucumbers, the health of the soil, and the overall goal of keeping agriculture environmentally sustainable. The findings reveal that while pesticides like diazinon, malathion, and methoxychlor are effective at controlling pests, their residue

levels often exceed safety thresholds, with diazinon reaching up to 2.28 mg/kg (MRL: 0.1 mg/kg), malathion 2.74 mg/kg (MRL: 0.2 mg/kg), and methoxychlor 2.26 mg/kg (MRL: 0.01 mg/kg). Residues in the control group suggest potential soil contamination. Only Endosulfan remained within safe limits (maximum of 1.75 mg/kg, MRL: 1 mg/kg). This proves that although pesticides are good at getting rid of pests, the chemicals left behind can often be more than what is considered safe, leading to serious concerns for environmental health. Moreover, the use of pesticides affects the number of soil nematodes, which indicates wider effects on the ecosystem.

The research highlights the urgent need for careful planning in how pesticides are used, calling for methods that manage pests effectively while also looking after the environment and keeping farming practices sustainable. Achieving this balance is essential for future agricultural practices, as it ensures food security while preserving ecological integrity and minimizing potential risks to human health and the environment.

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