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Analysis of Physicochemical Properties, Plant Nutrients, and Pesticide Residues in Soil Obtained from Pwani University Farm in Kilifi County, Kenya

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Abstract: Soil health is central to sustainable agricultural productivity, yet intensive farming practices can introduce physicochemical imbalances and pesticide contamination that threaten environmental quality and food safety. This study evaluated the soil's physicochemical properties, plant nutrient levels, and pesticide residues across thirteen agricultural sites to assess the soil's quality and contamination status. Soil samples were analyzed for pH, electrical conductivity, total dissolved solids, moisture content, organic matter, organic carbon, and plant nutrients using standard protocols. Pesticide residues were quantified using LC-MS/MS. Statistical analyses were conducted using Microsoft Excel and R software, applying one-way ANOVA to test for significant differences among sites and Principal Component Analysis to identify dominant factors influencing soil variability. Soil pH ranged from 6.87 to 7.96, while EC ranged from 254.91-1737.50µS/cm. Moisture content was not statistically significant ($p > 0.05$). Significant spatial variation ($p < 0.05$) was observed for most other parameters, with macronutrient concentrations ranging widely (N: 16.20–1608.62 mg/kg; P: 7.92–28.08 mg/kg; K: 141.84–370.20 mg/kg). PCA revealed that the first four components explained 70.9% of the total variance. Multiple pesticide residues were detected, with diazinon (0.03–486.82 ppb) and chlorfenvinphos occurring at notably high concentrations (4.13–624.86 ppb). Chlorpyrifos (0.104–5.94 ppb) was present at moderate levels. The findings emphasize the need for site-specific management strategies, adoption of integrated pest management, and stronger regulatory frameworks to minimize pesticide risks while optimizing nutrient use. These results provide a scientific basis for sustainable soil management and long-term agricultural productivity.

Keywords: Physicochemical properties, plant nutrients, pesticide residues, principal component analysis.

INTRODUCTION

Soil health sustains agricultural productivity and ecological stability through vital ecosystem services such as nutrient cycling, water regulation, and supporting biodiversity [1] [2]. Physicochemical properties are core factors influencing functionality, overseeing soil structure, water retention, nutrient availability, microbial activity, and pesticide degradation [3] [4]. Maintaining balanced physicochemical conditions in healthy soils is therefore crucial for preserving fertility, resilience, and ongoing productivity. Plant

nutrients, which could broadly be categorised as macronutrients (e.g., N, P, K, Ca, Mg, S) and micronutrients (e.g., Fe, Mn, B, Zn, Cu, Mo), are most important in crop development [5] [6]. Their availability as well as utilisation is strongly correlated to the pH of soil as well as other physicochemical properties [7]. Imbalance or deficiency could limit yield, whereas excess application will compromise soil health as well as cause soil and water pollution [8] [9]. Meanwhile, the widespread use of pesticides on crops to control pests and diseases raises concerns, since they can persist in soils and have the potential to disrupt microbial activity, alter soil properties, and contaminate water systems [10] [11]. These effects are even more significant in sensitive environments like the Kenyan coastal region, which features sandy soils, high rainfall, and salt intrusion [12] [13].

At Pwani University Farm, pesticides have been used routinely for crop protection and livestock management, particularly in cattle dip washes for tick control. Combined with fertiliser applications, these have the potential to affect soil composition and water quality, but their cumulative effects are not well understood. Although numerous studies on soil fertility and pesticide residues have been conducted in many farming systems, minimal attention has been given to their combined impact under coastal conditions. University demonstration farms, such as Pwani University Farm in Kilifi County, are important sites for training, food production, and applied research. However, the interconnections among physicochemical properties, nutrient dynamics, and pesticide residues in this setting have not been studied systematically.

This study, therefore, investigates the physicochemical properties, plant nutrients, and pesticide residues in soil, water, and dip wash samples from Pwani University Farm. By examining these closely interconnected parameters, it aims to acquire knowledge on managing soil quality in coastal agroecosystems and provide evidence to support sustainable agricultural practices in such ecosystems.

MATERIALS AND METHODS

Sampling Site

Thirteen sites were randomly selected across Pwani University Farm to capture site heterogeneity in terms of land use, management and potential exposure to agrochemicals. They included crop fields, vegetable plots, livestock sections, as well as demonstration plots. Table 1 is a summary of site characteristics, while Figure 1 illustrates their spatial distribution.

Table 1: Description of the 13 Sampling Sites at Pwani University Farm

Site	Latitude (S)	Longitude (E)	Code	Land use	Description
Site 1	3°37'3"	39°50'35"	S001A	Poultry Farm	Disposal Area: (Kerol and Norocleanse)
			S001B		Disposal Hole
Site 2	3°37'15"	39°50'13"	S002A	Rabbit farm	Soil adjacent to the rabbit house
			S002B	Fishpond	Soil inside the fishpond
Site 3	3°36'59"	39°50'33"	S003	Pig house	Area adjacent to the pig house
Site 4	3°36'62"	39°50'33"	S004A	Cattle resting	Cattle resting point 1
			S004B		Cattle resting point 2
Site 5	3°36'60"	39°50'33"	S005A	Milking shed	Disposal point from the milking shed

			S005B		Run off from the milking shed
			S005C		Disposal hole
Site 6	3°36'61"	39°50'33"	S006	Cattle treatment	Cattle treatment area
Site 7	3°37'11"	39°50'21"	S007A	Calf pen	Area adjacent to unused watering trough
			S007B		Area adjacent to calf feeding shed
Site 8	3°37'11"	39°50'30"	S008	Goats and sheep pen	Water trough soil
Site 9	3°36'52"	39°50'39"	S009A	Vegetable farm	Cowpea farm for 10 days
			S009B		Amaranth 14 days
			S009C		Amaranth harvesting time
			S009D		Amaranth abandoned
			S009E		Disposal pit
			S009F		Amaranth was sprayed 2 weeks ago
			S009G		Mixing area
			S009H		Okra farm
Site 10	3°36'49"	39°50'38"	S010A	Cattle Dip Area	Cattle dip outlet for cattle
			S010B		Cattle dip inlet for cattle
			S010C		Overflow side A (left)
			S010D		Overflow side B (right)
			S010E		Dip outlet
Site 11	3°36'49"	39°50'37"	S011A	Demonstration plot	Amaranth farm postharvest
			S011B		Sorghum farm sprayed with blue copper and emmeron
			S011C		Sorghum farm sprayed with blue copper and emmeron
Site 12	3°37'1"	39°50'39"	S012A	Nursery	Brinjols plot
			S012B		Tomato plot
			S012C		Amaranth plot
			S012D		Okra plot
Site 13	3°37'10"	39°50'50"	S013A	Biogas farm	Inside a shade net with tomatoes
			S013B		Outside shade net with brinjals

Table 1: Sampling sites at Pwani University showing the thirteen (13) locations selected for soil sample collection.

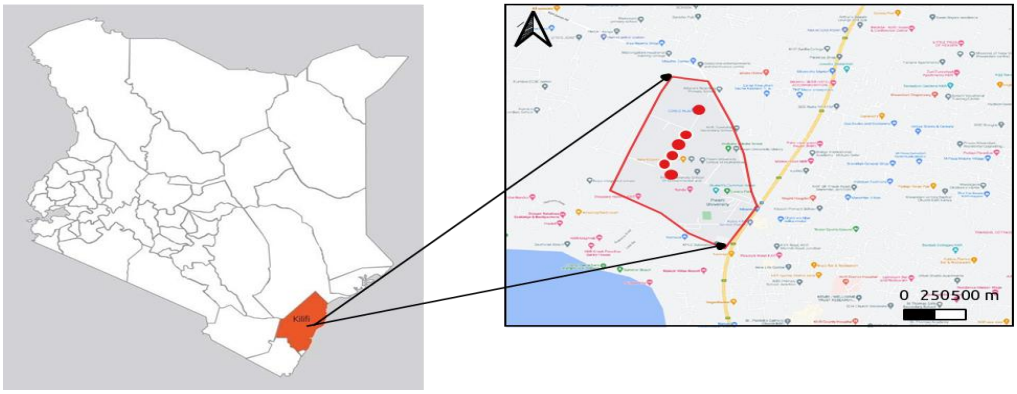

Figure 1: An illustration of Kenya (left), indicating the specific 13 sampling sites (right) in Kilifi County, Kenya (Source: QGIS Software).

Sample Collection

A soil auger was used to collect 37 soil samples from a depth of 0 to 15 cm. Approximately 500g of soil from each site was mixed to create a homogeneous sample before labelling, sealing, packing in sterile paper bags, and placing them in a cooler box. The cooler boxes

containing all the soil samples were transported to the Government Chemists' Department laboratories in Mombasa, Kenya, and stored in a refrigerator at -20ºC until analysis.

Sample Preparation

Physicochemical Properties of Soil

The standard methods were employed to determine various physicochemical parameters of the soil samples. Characterisation was performed on air-dried samples, ground into a fine powder with a mortar and pestle and passed through a 2mm sieve [14]. The processed soil samples were then used to measure pH and electrical conductivity (EC). For pH and EC analysis, the soil samples were suspended in water at a ratio of 1:2.5 (w/v). The pH and EC were measured using a laboratory pH meter (sensION MM374) [15]. Moisture content was determined through the oven method [16]. Soil organic carbon (SOC) levels were assessed via spectrophotometry and expressed as a percentage of organic carbon (%OC) [14], and organic matter (%OM) was estimated by the loss on ignition method [15].

Plant Nutrients in Soil

Soil samples were air-dried, gently crushed to break clods, and passed through a 2 mm sieve. Subsamples were finely ground (<0.5 mm) in an agate mortar for elemental determination. All analyses were expressed on an oven-dry weight basis after moisture correction (105 °C, 24 h). Total N was determined using the alkaline permanganate method, in which soil organic N is oxidised by alkaline $KMnO_4$ and the released ammonia quantified by distillation and titration [17]. Total elemental digestion of P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, B, and Mo. For multi-element analysis, a wet digestion method using aqua regia was utilised. Concisely, 0.5 g ground soil was measured into a 100 mL digestion beaker, to which were added 9 mL concentrated HCl (37%) and 3 mL concentrated HNO_3 (65%) (3:1 v/v). The solution was left to pre-digest overnight at room temperature, before being heated on a hot plate at about 95 °C under reflux for 2 hours until full dissolution was achieved, using standard procedures for the digestion of whole soils (ISO 11466, 1995; USEPA, 1996). The solution was then cooled and filtered through Whatman No. 42 filter paper and diluted to 50 mL with deionised water.

Extraction of Pesticide Residues in Soil for LC-MS/MS Analysis

Soil samples were prepared based on the procedure outlined by [18] with a few minor alterations. Using a mortar and pestle, a sample of each portion was obtained and blended thoroughly. Each homogenate weighed ten (10) grams, which was put into a 50 mL PTFE tube. Approximately 10 mL of acetonitrile (containing one percent acetic acid) was added, followed by 6 mL of water. Then, 6 g of anhydrous $MgSO_4$, 1.5 g of anhydrous NaAC, and 1 g of NaCl were added. Each sample was then vortexed for 1 minute, followed by a 5-minute centrifugation at 5000 rpm. For the dispersive-SPE clean-up operation, 3 mL of the supernatant was transferred to a 12-ml PTFE tube that contained 50 mL of PSA and 150 mg of anhydrous $MgSO_4$. After 30 seconds of vortexing the tube, centrifugation at 5000 rpm for 5 minutes was performed. 1mL of the supernatant was transferred to a vial for LC-MS analysis.

Plant Nutrients Analysis by ICP-OES

All determinations were conducted with an Agilent 5110 ICP-OES (Santa Clara, California) with SPS 3 autosampler. The sample was introduced through a SeaSpray nebulizer, double-pass glass cyclonic spray chamber, and standard 1.8mm ID injector torch. Analysis was conducted in axial plasma viewing mode. Operating conditions of the instruments are given below in the following table.

Table 2: Agilent 5110 ICP-OES method and instrument operating parameters

Parameter	Setting
RF power (kW)	1.25
Aux flow (L/min)	1.10
Plasma flow (L/min)	13
Nebulizer flow (L/min)	0.7
Make up flow (L/min)	0.00
Pump speed (rpm)	12
Read time (s)	4
Replicates	3
Uptake delay (s)	30 (fast pump)
Stabilization time (s)	15
Rinse time (s)	25 (fast pump)
Viewing	Axial
Viewing height (mm)	8
Dilution factor	10
Autosampler rinse solution	1% HNO_3

Table 2: ICP-OES analytical method and instrument operating parameters used for elemental analysis

Chromatographic Conditions for Pesticide Residue Analysis

LC-MS/MS analyses were performed using a 1290 Infinity II LC system connected to a 6490 Triple Quad MS instrument, with data acquisition and processing handled by Agilent Mass Hunter Software. LC and MS conditions are listed below.

HPLC Parameters

The chromatographical separation was conducted with an Agilent ZORBAX Eclipse Plus C18 Rapid Resolution HD analytical column (2.1 × 100 mm, 1.8 µm), and a ZORBAX Eclipse Plus C18 guard column (2.1 × 5 mm, 1.8 µm) to protect the analytical column. The temperature of the chromatographic column was kept at 40 °C using an Agilent G1316C thermostatted column compartment. The mobile phases were (A) 10 mM ammonium formate solution in water: methanol (98:2, v/v) with 0.1% formic acid, and (B) 10 mM ammonium formate solution in methanol: water (99:1, v/v) with 0.1% formic acid. The injection volume was 2 µL by an Agilent G4226A autosampler.

Chromatographic separation was performed using an Agilent G4220A binary pump system with the following gradient at a flow rate of 0.5 mL/min. The initial conditions were 100% A (0.00–0.20 min) at 0.10 mL/min, followed by a stepwise increase to 0.50 mL/min at 0.21 min. The gradient was programmed accordingly: 50:50 (A:B) at 0.50 min, 45:55 at 2.50 min, 25:75 at 5.50 min, 15:85 at 7.50 min, 0:100 at 8.30 min (held until 12.00 min), and return to 100% A at 12.10 min and held until 14.90 min for re-eq. The overall run time was 15.0 min.

MS/MS Parameters

Mass spectrometric detection was achieved using an Agilent triple quadrupole mass spectrometer equipped with an Agilent Jet Stream (AJS) electrospray source in positive mode.

Data were collected using triggered multiple reaction monitoring (MRM) mode with three replications of acquisitions per transition and a 650 ms cycle time. The run time was 15.00 min with the divert valve being timed to route the flow to waste during 0.00–1.00 min, switched to mass spectrometer during 1.00–10.00 min, and switched to waste during 10.00 min. The first and second quadrupoles were operating at unit resolution (0.7 Da FWHM). Source parameters were optimised as follows: gas temperature, 180 °C; gas flow, 20 L/min; nebulizer pressure, 40 psi; sheath gas temperature, 225 °C; sheath gas flow, 11 L/min; capillary voltage, 4,500 V; and nozzle voltage, 0 V. The iFunnel RF high and low settings were 150 and 60, respectively [19].

Method Validation

The analytical approach was validated according to SANTE/12682/2019 and ICH Q2(R^2) regulations for the measurement of pesticide residues. The critical parameters examined were linearity (calibration equation and R^2), accuracy (% recovery), precision (%RSD at three levels), and sensitivity (LOD and LOQ).

Multiple reaction monitoring (MRM) transitions were optimised for selectivity and identification of the pesticides. Linearity was determined by the calibration curve of calibration solutions, whereas precision and accuracy were set by replicate analysis of spiked samples. LOD and LOQ were calculated based on the blank response standard deviation and calibration curve slope by 3σ and 10σ criteria.

Data Analysis

Physicochemical properties, plant nutrients, and pesticide residues data were entered into an Excel spreadsheet and analysed using R version 4.5.0 software. Multivariate relationships among variables were assessed using Principal Component Analysis (PCA). Comparisons of multiple means were conducted using one-way Analysis of Variance (ANOVA) followed by Tukey's HSD post hoc test, and $p < 0.05$ was considered statistically significant. All results are presented as mean ± standard error of the mean (SEM) except pesticide results, which were presented as mean ± standard deviation (SD).

RESULTS

Method Validation Results

Method validation results are summarised in Table 3 below.

Table 3: Summary of validation parameters for LC-MS/MS determination of pesticide residues in soil in Pwani University Farm.

	Ret time	Linearity		Quantifier	Qualifier		Accuracy	Precision (%RSD, n=6)		Sensitivity (ng/ml)	
Pesticide	(min)	Equation	R^2	ion (m/z)	Ion (m/z)	(%)	5ng/ml	25ng/ml	75ng/ml	LOD	LOQ
Atrazine	14.213	y=4802x + 7820	0.9977	216.1	174.1	105.31	16.69	11.23	3.09	0.005	0.02
Buprofezin	18.771	y=1780x + 2225	0.9979	306.2	116.2	99.0	18.46	12.8	3.65	0.002	0.007
Carbendazim	8.417	y=364x + 10	0.9872	192.1	160.1	85.95	15.83	11.72	5.39	0.002	0.006
Chlorpyrifos	19.146	y=574x + 23416	0.9892	349.9	97.0	82.69	17.41	14.65	5.32	0.002	0.05
Chlofenvinphos	6.423	y=60x + 647	0.9906	359.0	155.0	96.39	17.94	11.23	4.65	0.008	0.02
Diazinon	17.504	y=6567x + 572	0.9995	305.1	169.1	100.99	12.68	7.81	2.61	0.003	0.008

Table 3: Retention time, linearity, quantifier and qualifier ions, accuracy, precision (%RSD, n = 6), limit of detection (LOD), and limit of quantification (LOQ) are presented for each pesticide.

Physicochemical Properties Across Sites in Pwani University Farm

Soil samples were analyzed for their physicochemical properties; the results are represented in Table 4 below. Table 4 presents the physicochemical properties across sites

Table 4: Mean ± standard error (SE) of soil physicochemical properties across different sites.

Site	pH	EC (µS/cm)	TDS (mg/L)	MC (%)	OM (%)	OC (%)
Site 1	7.27 ± 0.01^{h}	381.17 ± 3.18^{f}	253.95 ± 3.74^{f}	1.23 ± 0.11^{a}	8.82 ± 0.08^{c}	1.14 ± 0.008^{e}
Site 2	7.11 ± 0.06^{j}	518.67 ± 8.30^{d}	348.61 ± 12.97^{d}	9.28 ± 8.42^{a}	54.66 ± 0.15^{a}	0.59 ± 0.002^{f}
Site 3	7.42 ± 0.01^{e}	314.00 ± 1.32^{g}	207.47 ± 7.87^{g}	1.49 ± 0.23^{a}	$4.59\pm0.14e^{f}$	0.32 ± 0.001^{h}
Site 4	7.53 ± 0.01^{d}	524.67 ± 4.92^{d}	349.11 ± 4.71^{d}	6.09 ± 5.15^{a}	$5.65\pm0.18d^{e}$	2.37 ± 0.001^{b}
Site 5	6.87 ± 0.01^{j}	1737.50 ± 12.69^{a}	1112.00 ± 8.12^{a}	2.3 ± 0.49^{a}	27.74 ± 1.49^{b}	2.08 ± 0.001^{c}
Site 6	7.71 ± 0.01^{c}	739.00 ± 5.97^{b}	475.83 ± 1.47^{b}	2.37 ± 0.25^{a}	9.23 ± 0.23^{c}	2.65 ± 0.002^{a}
Site 7	7.35 ± 0.02^{fg}	486.67 ± 4.30^{e}	315.69 ± 4.48^{e}	1.64 ± 0.25^{a}	3.31 ± 0.15^{fg}	1.58 ± 0.013^{d}
Site 8	7.89 ± 0.01^{b}	309.33 ± 1.30^{g}	201.62 ± 4.37^{g}	1.40 ± 0.16^{a}	2.73 ± 0.13^{gh}	1.42 ± 0.001^{d}
Site 9	7.36 ± 0.02^{efg}	303.63 ± 1.40^{g}	197.39 ± 6.02^{g}	1.60 ± 0.90^{a}	3.82 ± 0.07^{fg}	0.71 ± 0.205^{f}
Site 10	7.96 ± 0.02^{a}	648.33 ± 3.11^{c}	430.93 ± 10.51^{c}	3.03 ± 1.74^{a}	9.21 ± 0.58^{c}	2.69 ± 0.091^{a}
Site 11	7.09 ± 0.03^{j}	302.47 ± 1.48^{g}	200.34 ± 7.05^{g}	0.58 ± 0.03^{a}	2.71 ± 0.14^{gh}	0.38 ± 0.003^{gh}
Site 12	7.31 ± 0.02^{gh}	254.91 ± 2.47^{h}	167.31 ± 5.84^{h}	0.55 ± 0.03^{a}	1.56 ± 0.05^{h}	0.53 ± 0.001^{fg}
Site 13	7.40 ± 0.01^{ef}	310.22 ± 1.94^{g}	198.54 ± 1.24^{g}	2.22 ± 0.15^{a}	6.64 ± 0.10^{d}	1.10 ± 0.000^{e}
p-value	<0.001	<0.001	<0.001	0.687	<0.001	<0.001

Means with the same letter in a column are not statistically significantly different at p=0.05.

Table 4 shows the mean ± SE for the physicochemical properties of soils across 13 sites. ANOVA results indicate significant differences ($p < 0.05$) for pH, EC, TDS, OM, and OC, while MC did not vary significantly ($p = 0.687$). The soil pH ranged from 6.87 ± 0.01 at Site 5 to 7.96 ± 0.02 at Site 10. This suggests that soils across the sites are neutral to slightly alkaline. Site 5 had significantly lower pH compared to other sites, indicating possible localised acidification. EC ranged from 254.91 ± 2.47 µS/cm at Site 12 to 1737.50 ± 12.69 µS/cm at Site 5. Similarly, TDS ranged from 167.31 ± 5.84 mg/L at Site 12 to 1112.00 ± 8.12 mg/L at Site 5. MC varied between 0.55 ± 0.03% at Site 12 and 9.28 ± 8.42% at Site 2, but this variation was not statistically significant ($p = 0.687$). OM was highest at 54.66 ± 0.15% (Site 2) and lowest at 1.56 ± 0.05% (Site 12). OC ranged from 0.32 ± 0.001% (Site 3) to 2.69 ± 0.091% (Site 10).

Plant Nutrients Across Different Sites in Pwani University

Primary and Secondary Macronutrients

The concentrations of N, P, and K varied significantly across the study sites ($p<0.001$) (Table 3). Soil nitrogen levels differed markedly among sites, ranging from 16.2 ± 1.25 mg/kg at Site 10 to 1608.62 ± 30.72 mg/kg at Site 5. Phosphorus concentrations ranged between 7.92 ± 0.83 mg/kg at site 6 and 28.08 ± 1.10 mg/kg at site 8. Potassium concentrations were highest at site 10 (370.20 ± 2.75 mg/kg) and lowest at site 2 (141.84 ± 1.32 mg/kg). Ca levels varied widely across the sites, ranging from 1071.86 ± 3.03 mg/kg at Site 2 to 2066.77 ± 1.79 mg/kg at Site 5. Relatively higher Ca concentrations were consistently observed at Sites 5, 6, and 10, while Sites 2, 3, 11, and 12 recorded the lowest values. Mg concentrations also showed considerable variation, with the lowest content measured at Site 2 (143.22 ± 1.43 mg/kg) and the highest at Site 10 (390.50 ± 4.14 mg/kg).

Table 5: Macronutrients across different sites in Pwani University Farm

	Primary Macronutrients (mg/Kg)			Secondary Macronutrients (mg/Kg)		
Sites	N	P	K	Ca	Mg	S
Site 1	267.63±8.20^{c}	18.19±0.33^{cd}	326.31±3.71^{b}	1697.95±5.61^{e}	306.34±3.09^{c}	42.26±1.12^{g}
Site 2	211.98±9.53^{d}	12.99±0.23^{e}	141.84±1.32^{h}	1071.86±3.03^{h}	143.22±1.43^{h}	60.14±0.96^{bcd}
Site 3	214.2±8.01^{d}	25.33±0.65^{a}	246.72±1.20^{ef}	1456.84±13.21^{g}	198.98±5.55^{f}	40.00±1.02^{g}
Site 4	65.27±4.14^{f}	11.63±0.78^{e}	277.29±1.99^{d}	1523.47±6.55^{f}	227.89±0.65^{e}	32.10±0.93^{h}
Site 5	1608.62±30.72^{a}	21.24±1.00^{b}	332.1±2.40^{b}	2066.77±1.79^{a}	322.44±4.63^{c}	45.46±1.30^{fg}
Site 6	363.54±10.08^{b}	7.92±0.83^{f}	171.54±3.76^{g}	1964.47±2.71^{b}	360.45±7.73^{b}	31.91±2.94^{h}
Site 7	285.4±7.09^{c}	11.65±0.22^{e}	176.78±1.37^{g}	1781.07±5.52^{d}	232.13±0.38^{e}	62.16±0.47^{bc}
Site 8	63.11±2.05^{f}	28.08±1.10^{a}	365.14±12.91^{a}	1670.20±8.79^{e}	164.77±2.27^{g}	84.48±1.78^{a}
Site 9	197.36±4.54^{d}	16.63±0.18^{d}	258.91±2.85d^{e}	1536.39±8.55^{f}	265.12±0.10^{d}	50.87±0.33^{ef}
Site 10	16.2±1.25^{f}	25.45±0.15^{a}	370.2±2.75^{a}	1983.73±18.05^{b}	390.5±4.14^{a}	66.41±1.64^{b}
Site 11	33.59±0.35^{f}	20.9±0.14^{bc}	226.98±2.28^{f}	1469.38±6.01^{g}	272.81±0.66^{d}	54.26±0.55^{de}
Site 12	141.61±3.99^{e}	19.14±0.54^{bcd}	252.21±1.31^{e}	1436.19±4.59^{g}	345.42±0.60^{b}	57.97±1.08^{cd}
Site 13	212.1±4.52^{d}	17.66±0.14^{d}	300.29±1.56^{c}	1823.31±6.44^{c}	318.95±2.67^{c}	50.03±1.29^{ef}
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter in a column are not statistically significantly different at p=0.05.

Table 5: Mean ± standard error (SE) of primary and secondary macronutrients across different sites.

Micronutrient Concentrations in Soil Across the Study Sites

Table 6 shows that the micronutrient concentrations varied significantly among the sampling sites ($p < 0.001$). The highest Fe content was recorded at Site 1 (448.4 ± 4.03 mg/kg), while the lowest was observed at Site 7 (211.20 ± 0.96 mg/kg). Mn levels ranged from 3.51 ± 0.04 mg/kg at Site 13 to 24.56 ± 0.37 mg/kg at Site 3. Cu concentrations ranged from 2.89 ± 0.17 mg/kg (Site 8) to 8.43 ± 0.43 mg/kg (Site 10). Zn values varied between 2.12 ± 0.08 mg/kg at Site 10 and 7.48 ± 0.12 mg/kg at Site 9. B levels ranged from 0.44 ± 0.03 mg/kg at Site 2 to 0.84 ± 0.02 mg/kg at Site 1.

Table 6: Micronutrients in soil across the study sites in Pwani University Farm

Sites	Fe (mg/Kg)	Mn (mg/Kg)	Cu (mg/Kg)	Zn (mg/Kg)	B (mg/Kg)	Ni (mg/Kg)	Mo (mg/Kg)
Site 1	448.40 ± 4.03^{a}	8.88 ± 0.08^{h}	4.64 ± 0.20^{d}	4.52 ± 0.22^{bcd}	0.84 ± 0.02^{a}	0.70 ± 0.02^{a}	0.026 ± 0.002^{cde}
Site 2	371.26 ± 0.90^{c}	10.81 ± 0.09^{g}	4.05 ± 0.31^{de}	2.93 ± 0.08^{fg}	0.44 ± 0.03^{e}	0.50 ± 0.02^{ef}	0.019 ± 0.002^{e}
Site 3	262.32 ± 3.70^{gh}	24.56 ± 0.37^{a}	3.13 ± 0.02^{ef}	3.07 ± 0.05^{fg}	0.53 ± 0.02^{cde}	0.64 ± 0.02^{abc}	0.032 ± 0.002^{abcd}
Site 4	287.75 ± 2.73^{f}	17.18 ± 0.07^{d}	4.19 ± 0.12^{de}	3.96 ± 0.15^{cde}	0.82 ± 0.02^{ab}	0.63 ± 0.01^{abcde}	0.024 ± 0.001^{cde}
Site 5	382.01 ± 1.41^{bc}	20.49 ± 0.14^{b}	7.56 ± 0.12^{ab}	3.89 ± 0.14^{de}	0.46 ± 0.00^{de}	0.64 ± 0.02^{abcd}	0.034 ± 0.001^{abc}
Site 6	257.36 ± 4.87^{h}	9.46 ± 0.18^{h}	3.73 ± 0.12^{def}	2.60 ± 0.22^{gh}	0.68 ± 0.11^{abc}	0.68 ± 0.06^{ab}	0.040 ± 0.002^{a}
Site 7	211.20 ± 0.96^{j}	18.36 ± 0.08^{cd}	3.37 ± 0.25^{ef}	4.87 ± 0.04^{b}	0.53 ± 0.01^{cde}	0.51 ± 0.03^{def}	0.025 ± 0.004^{cde}
Site 8	385.76 ± 1.90^{b}	5.55 ± 0.13^{j}	2.89 ± 0.17^{f}	4.53 ± 0.09^{bc}	0.53 ± 0.06^{cde}	0.55 ± 0.01^{bcdef}	0.027 ± 0.002^{cde}
Site 9	309.23 ± 0.85^{e}	19.12 ± 0.10^{c}	5.90 ± 0.19^{c}	7.48 ± 0.12^{a}	0.64 ± 0.01^{bcd}	0.62 ± 0.01^{abcde}	0.026 ± 0.001^{cde}
Site 10	395.09 ± 4.04^{b}	13.45 ± 0.06^{f}	8.43 ± 0.43^{a}	2.12 ± 0.08^{h}	0.52 ± 0.03^{cde}	0.54 ± 0.01^{cdef}	0.023 ± 0.002^{de}
Site 11	271.15 ± 0.82^{g}	17.58 ± 0.06^{d}	6.70 ± 0.17^{bc}	4.26 ± 0.06^{bcd}	0.48 ± 0.01^{de}	0.50 ± 0.03^{ef}	0.030 ± 0.002^{bcd}
Site 12	339.24 ± 0.73^{d}	14.63 ± 0.40^{e}	6.00 ± 0.03^{c}	3.49 ± 0.06^{ef}	0.59 ± 0.01^{cde}	0.56 ± 0.02^{bcde}	0.024 ± 0.001^{de}
Site 13	310.29 ± 2.63^{e}	3.51 ± 0.04^{k}	6.65 ± 0.19^{bc}	3.22 ± 0.09^{fg}	0.59 ± 0.01^{cde}	0.42 ± 0.02^{f}	0.037 ± 0.001^{ab}
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Means with the same letter in a column are not statistically significantly different at p=0.05.

Table 6: Mean (±SE) concentrations of micronutrients (mg/kg) in soil across the study sites.

Ni concentrations varied between 0.42 ± 0.02 mg/kg at Site 13 and 0.70 ± 0.02 mg/kg at Site 1. Mo levels ranged from 0.019 ± 0.002 mg/kg at Site 2 to 0.040 ± 0.002 mg/kg at Site 6.

Principal Component Analysis of Physicochemical Properties and Plant Nutrients from Soil Across the Study Sites

Figure 2i (left) and ii (right): Principal Component Analysis (PCA) biplots showing variation in soil physicochemical properties, plant nutrients across study sites. Panel A shows the first two principal components (PC1 and PC2), explaining 43.5% of the total variance, while Panel B shows PC3 and PC4, which explain an additional 27.4%. Sites are represented as blue points with labels, while soil properties are represented as red arrows. Together, the first four components capture 70.9% of the total variance.

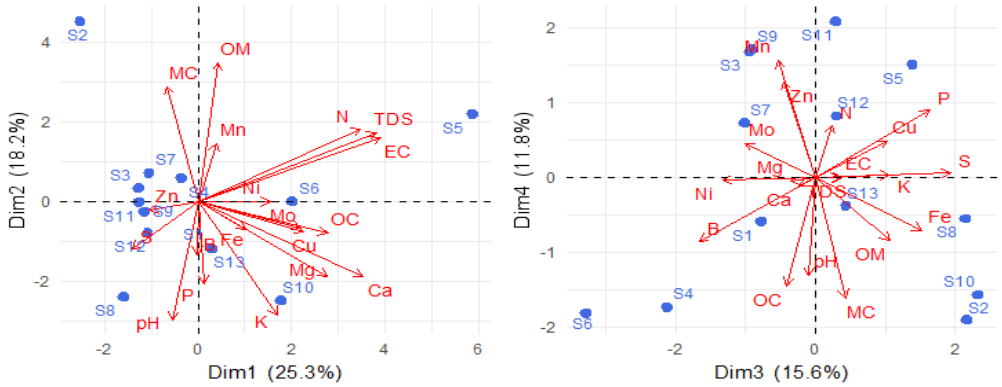

Figure 2i and ii: PCA biplot of physicochemical properties and plant nutrients

The PCA biplot (PC1 vs PC2) illustrates the spatial separation of sites based on soil physicochemical properties and nutrient concentrations. PC1, explaining 25.3% of variance, is primarily associated with electrical conductivity (EC), total dissolved solids (TDS), nitrogen (N), and potassium (K). Site S5 is strongly aligned with these variables, indicating elevated salinity and nutrient levels. In contrast, PC2 (18.2%) is influenced by organic matter (OM) and moisture content (MC), which separates Site S2 from the others. The remaining sites cluster near the origin, suggesting relatively similar soil conditions. The clear divergence of S5 and S2 highlights localized management practices or environmental factors affecting soil composition.

The PCA biplot for PC3 versus PC4 captures secondary variation in soil characteristics, explaining 27.4% of the total variance. Sites S2 and S10 are positioned on the far right of PC3, driven by high levels of phosphorus (P), potassium (K), electrical conductivity (EC), and copper (Cu). Conversely, sites S3, S9, and S11 are strongly associated with manganese (Mn) and zinc (Zn), reflecting different fertility characteristics. Organic matter (OM), moisture content (MC), and pH cluster together, indicating strong interrelationships. This plot highlights additional dimensions of variability that complement the patterns observed in PC1 and PC2, bringing the cumulative explained variance to 70.9%.

Pesticides Analysis in Soil

Table 7: Pesticides detected across the study site in Pwani University Farm

Pesticide	Detected In Sites	Mean ± SD (ppb)	Min-Max
Carbendazim	S5, S9, S10	0.21 ± 0.06	0.02-1.12
Atrazine	S1, S2, S3, S5, S6, S7, S8, S9	0.13 ± 0.07	0.01-0.623
Diazinon	S1, S2, S3, S4, S5, S6, S7, S8, S9, S10	91.80 ± 43.20	0.03- 486.82
Buprofezin	S3, S5, S9, S10	0.03 ± 0.019	0.01 - 0.087
Chlorpyrifos	S1, S2, S4, S5, S6, S9, S10	1.97 ± 0.71	0.104 - 5.94
Chlofenvinphos	S4, S5, S6, S9, S10	159.66 ± 86.26	4.13- 624.86

A total of six pesticides were detected across thirteen sampling sites, with varying frequencies and concentrations (Table 7). Diazinon was the most prevalent compound,

present in sites (S1–S10) with a mean concentration of 91.80 ± 43.20 ppb and a range of 0.03–486.82 ppb, indicating widespread and intensive use. Chlorfenvinphos had the highest mean concentration among all pesticides (159.66 ± 86.26 ppb; 4.13–624.86 ppb) and was detected in five sites (S4, S5, S6, S9, and S10).

Chlorpyrifos was found in seven sites with a mean of 1.97 ± 0.71 ppb and concentrations ranging from 0.104 to 5.94 ppb, while Carbendazim and Buprofezin were sporadically detected at relatively low mean levels (0.21 ± 0.06 ppb and 0.03 ± 0.019 ppb, respectively). Atrazine was present in eight (8/13) sites with a mean of 0.13 ± 0.07 ppb and a range of 0.01–0.623 ppb.

DISCUSSION

Method Validation

The analytical method exhibited strong validation performance, confirming its suitability for accurate quantification of the detected pesticide residues in soil. The calibration curves demonstrated excellent linearity with correlation coefficients (R^2) between 0.9872 to 0.9995 for all analytes, indicating a proportional detector response across the tested concentration range. Such linearity reflects the precision of the chromatographic system and the absence of matrix-induced signal suppression or enhancement. The low LODs (0.002–0.008 ng/mL) and LOQs (0.007–0.05 ng/mL) achieved indicate high analytical sensitivity suitable for trace-level detection of residues in environmental samples. Intra-day precision values fall within the recommended limit of ≤20% for trace analysis, demonstrating excellent method repeatability and reproducibility [20]. This consistency reflects the stability of the instrument response and sample preparation protocol. Mean accuracy/recoveries ranging between 82.69–105.31% indicate acceptable accuracy and minimal matrix interference. Slightly lower recoveries for highly hydrophobic pesticides (e.g., chlorpyrifos) could be attributed to their strong adsorption to soil organic matter and lower extractability, consistent with previous studies [21].

Physicochemical Properties of Soil

The soil physicochemical properties differed significantly across the study sites, reflecting diverse soil conditions caused by variations in land use, management practices, and underlying soil features. Analysis of variance (ANOVA) showed significant differences ($p < 0.05$) for most parameters, including pH, EC, TDS, OM, and OC, whereas MC did not differ significantly. This indicates that although soil water content was relatively consistent during sampling, other essential soil quality indicators were heavily affected by site-specific factors.

Soil pH ranged from slightly acidic to moderately alkaline (6.87–7.96), generally supporting nutrient availability and crop growth. The study's findings align with Karuma (2019), showing that soil pH in the Galana region of Coastal Kenya varies from 7.3 to 8.3, indicating moderately alkaline conditions. The slightly alkaline pH observed at some sites may reflect high base cation saturation and irrigation water quality, both of which influence nutrient solubility and microbial activity. At site 5, slightly acidic conditions could decrease phosphorus availability, while at site 10, alkaline conditions might hinder the uptake of

essential micronutrients, such as iron and zinc. These nutrient imbalances could negatively impact crop productivity, especially for crops sensitive to pH changes [3].

EC and TDS showed great variation, with higher values evident at Site 5. Notably, although it had a lower pH (pH 6.87), it had the highest values for both EC and TDS. This implies that although alkalinity can increase ion solubility, other components, such as salt deposition due to irrigation water, fertilisers, waste disposal and low leaching fluxes, might be increasing ion concentrations. The high levels of EC and TDS represent salt enrichment in soil, which is not dependent on soil pH. Also significant is the regression between EC and TDS, which was confirmed by Tukey's HSD test. Indeed, it showed that both EC and TDS presented comparable variation. This corresponds with literature suggesting that both variables strongly correlate because both measure similar components—the overall ion concentration in soil [22]. The variance in values is contrary to Karuma (2019), which reported overall EC levels to be 2.62-5.71 dS/m in Galana soils along Kenya's coast. High salinity concentration in soil causes osmoregulatory stress due to reduced soil water uptake by plant roots. Non-saline soils would be below 2000 µS/cm.2000 µS/cm can easily facilitate growth for plant species [3].

Organic matter and organic carbon varied significantly among sites. Soils with high OM and OC likely benefit from regular additions of organic residues or manure, which enhance soil structure, moisture retention, and nutrient cycling. The SOM findings presented herein stand in contrast to those of Karuma (2019), who reported a low range of SOM between 0.34% and 0.86%. In contrast, low OM levels at certain sites indicate continuous cultivation without residue return, leading to rapid organic matter depletion and reduced soil resilience.

Unlike in EC and TDS, SOM and SOC revealed a lack of positive correlation based on the compact display letters (CDL) done by Tukey's HSD test and therefore the study contradicts with previous research by Sakin (2012), which found a strong positive correlation between soil organic matter (SOM) and soil organic carbon (SOC) in uniform soils of arid and semi-arid regions. The lack of correlation may be due to the heterogeneous nature of the sampling sites, which encompassed various land uses, including crop cultivation, vegetable gardening, cattle dipping, milking areas, fish ponding, unused water troughs, cattle resting areas, pig housing, and waste disposal. These diverse land uses result in site-specific differences that affect organic input, residue management, and microbial activity, thereby influencing the dynamics of soil organic matter (SOM) and soil carbon (SOC).

The significant variability in pH, salinity, and organic matter has critical implications for soil management and agrochemical behaviour. Soils with higher OM can adsorb nutrients and pesticides, reducing leaching but potentially prolonging pesticide persistence [23]. Conversely, saline soils may experience inhibited microbial activity, slowing pesticide degradation [24]. These dynamics underscore the need for site-specific interventions to mitigate salinity, restore organic matter, and sustain long-term soil productivity.

Plant Nutrients in Soil Across the Study Sites

Macronutrients Across the Study

The concentrations of both primary (N, P, K) and secondary macronutrients (Ca, Mg, S) varied significantly across the study sites ($p < 0.001$), reflecting differences in land use, soil

management, and inherent soil properties. In this study, P levels were consistent with those reported by Kenyanya et al (2013), while K concentrations were higher but followed the same trend. In contrast, N levels in this study were lower than the referenced values.

Nitrogen (N) showed the greatest variability, with Site 5 recording extremely high levels, likely due to intensive fertiliser or manure application. Conversely, Sites 4, 8, 10, and 11 had very low N, suggesting losses through leaching or insufficient replenishment [25]. Similar trends were reported by Liu et al. [26], who observed rapid nitrogen depletion in sandy soils under high rainfall [26]. Phosphorus was highest at Sites 8, 10, and 3, possibly from targeted fertiliser inputs, while Sites 4 and 6 had deficient levels, potentially due to fixation in acidic soils. This aligns with the findings of Agegnehu et al. [27], who highlighted pH as a major determinant of P availability. Potassium (K) was highest at Sites 10 and 8 and lowest at Sites 2 and 7. Elevated K may be linked to mineral-rich parent material or direct fertilisation, as also observed by Harper et al. [28] in irrigated agricultural systems.

From Table 5, higher levels of Ca were observed at Sites 5, 6, and 10, while Sites 2, 3, 11, and 12 exhibited lower concentrations. The lower Ca contents observed could reflect depletion through continuous cropping, leaching losses in sandy soils, or limited external supplementation. The results of this study align with the findings presented by Omwakwe et al. (2023) in their research on the macro and micronutrient status of selected soils in Kenya. They reported a mean concentration of calcium (Ca) at 1397.39 mg/kg.

Mg concentrations also varied markedly, with the lowest content recorded at Site 2 and the highest at Site 10. Like Ca, Mg availability is strongly influenced by parent material and soil management [29]. Elevated levels at Sites 6, 10, and 12 suggest enrichment from fertilisers or organic inputs, while the low values at Sites 2, 3, and 8 may indicate leaching losses, especially in coarse-textured soils. The results of this study are consistent with those of Omwakwe et al. (2023), who reported a mean concentration of Mg of 163.98 mg/kg in Kenyan soils.

S concentration was lowest at Site 6 and highest at Site 8, with elevated levels also observed at Sites 7 and 10. Sulfur is an essential nutrient, but is prone to spatial variation due to its mobility in soils and dependence on both organic matter mineralization and atmospheric deposition [8]. Higher sulfur (S) levels at Site 8 might be due to local organic matter decomposition, S-containing agrochemicals, or livestock activity. In contrast, low S values at Sites 4 and 6 could result from leaching in well-drained soils, as indicated by Aspel et al. [30].

Micronutrients Across the Study

The distribution of plant nutrients across the study sites showed statistically significant differences ($p < 0.05$) for all micronutrients analysed, indicating strong spatial variability. This variation is influenced by factors such as soil type, organic matter content, land use history, and management practices. Such heterogeneity is common in tropical agricultural systems and has been widely reported in previous studies [31].

Fe and Mn were generally abundant, consistent with findings in tropical soils, where intense weathering releases these elements from parent materials [32]. However, their levels can fluctuate depending on drainage and redox conditions. Notably, the Fe concentrations recorded here contrast with those reported in a study by Ahogle et al. (2023),

conducted in Nairobi, where much higher values were observed (20196 – 333658 ppm), likely reflecting differences in parent material, soil chemistry, and land use intensity. Excessive concentrations of these elements may lead to antagonistic effects, particularly by suppressing the uptake of other micronutrients such as zinc and copper [33].

The concentrations of Cu and Zn varied significantly across sites ($p < 0.001$). Still, all remained above deficiency thresholds and well below toxicity levels, indicating that the soils are generally adequate in micronutrients. Comparison with findings by Chiteva et al. (2022) in Kwale and Bungoma counties shows consistency in Mn (10.86 – 190.77 mg/kg) and Zn (0 – 20.70 mg/kg) concentrations, while Cu (0 – 1.88 mg/kg) levels in this study differ, suggesting site-specific or management-related influences. The discrepancy in Cu levels compared with Chiteva et al. (2022) may reflect differences in soil type, land-use history, or agrochemical practices, highlighting the importance of localised assessments before making broad management recommendations.

Agronomically, these micronutrients are critical for crop growth and productivity. Mn is essential in photosynthesis and enzyme activation, Cu is important for lignin formation and reproductive development, while Zn supports enzyme function and auxin metabolism [34]. In plants, the optimum concentration of these micronutrients, Mn, Cu, and Zn, is 50, 6, and 20 mg/kg of dry matter, respectively [35]. Deficiencies in these nutrients can lead to interveinal chlorosis, stunted growth, poor grain set, and reduced yields [36]. For toxicity, the FAO/WHO set the maximum permissible limits of Mn, Cu, and Zn in soil at 500mg/kg, 270mg/kg, and 600mg/kg, respectively [37].

The observed variations in B, Ni, and Mo highlight spatial heterogeneity influenced by soil parent material, organic matter, and possible anthropogenic inputs [35]. B is essential for cell wall formation, sugar transport, and reproductive development; Ni plays a role in urease activity and nitrogen metabolism; and Mo is required for nitrate reduction and nitrogen fixation [34]. Deficiencies in B may cause flower sterility and poor grain set, Ni deficiency can impair urea metabolism and nitrogen utilisation, while Mo deficiency often leads to nitrogen deficiency-like symptoms in legumes [38].

Principal Component Analysis of Soil Across the Study Sites

Multivariate analysis using Principal Component Analysis (PCA) was applied to evaluate the interrelationships among soil physicochemical properties and plant nutrients across the study sites. PCA is widely recognised for its ability to reduce complex datasets into a few key components, thereby identifying dominant factors influencing soil quality [39]. This approach has been effectively used in soil fertility and environmental studies to reveal patterns and classify sites based on shared characteristics [40].

The PCA biplots (Figure 1) provide a multivariate perspective on the interactions between soil nutrients, physicochemical properties, and study sites. The first four principal components explained 70.9% of the total variance, with PC1 and PC2 accounting for 43.5%, and PC3 and PC4 contributing an additional 27.4%. This cumulative variance indicates a strong discriminatory power of the PCA, enabling effective visualisation of site-specific nutrient dynamics and underlying soil processes [41].

PC1 (25.3% variance) is characterised by strong positive loadings of N, EC, TDS, and OC, indicating a fertility and salinity gradient. Elevated N levels correlate with higher

soluble salts and organic inputs, suggesting intensive fertilizer use or organic amendments. Sites like S5 are notably enriched in nutrients due to continuous disposal of agrochemical wastes. Ca and Mg are positively correlated with salinity and base saturation, as indicated by their loading on PC1. This relationship aligns with Chen et al. (2021), who found that the accumulation of Ca and Mg is often associated with saline irrigation and liming practices in intensively cultivated soils.

PC2 accounts for 18.2% of the total variance and is linked to OM and micronutrients such as Mn, Zn, and Ni. High OM and trace metal concentrations were observed at sites S2 and S8, likely due to organic residue or parent material influences. This aligns with findings by Dhaliwal et al. (2024) on the role of organic matter in micronutrient retention. Sites S1, S3, S7, S9, S11, S12, and S13 show balanced nutrient levels, indicating moderate soil fertility. In contrast, sites S5, S2, S4, S6, S8, and S10 exhibit spatial heterogeneity influenced by management intensity, soil type, and hydrological conditions [42].

PC3, accounting for 15.6% the total variance, is linked to macronutrients P, K, and S, reflecting fertiliser application patterns and soil fertility. Site S8 shows targeted enrichment in P and K. PC4, explaining 11.8% variance, focuses on micronutrients Zn, Mn, and Mo, influenced by pH and redox conditions [43]. Sites S6 and S4 reveal nutrient depletion and potential deficiency hotspots, indicating concerns for crop productivity.

Pesticides Analysis in Soil Across the Study Sites

The detection of multiple pesticide residues across the study sites highlights the extent of agrochemical use and its persistence in agricultural soils [44]. Diazinon and chlorfenvinphos were detected at high concentrations at all sites, suggesting heavy application. The widespread presence is also linked to intensive farming systems, where continuous use and limited microbial degradation led to its persistence. Most pesticides are stable at neutral pH [45]. Chlorfenvinphos levels are significant due to historical and possibly unregulated use. This compound has been restricted or banned in many areas because of its environmental persistence and toxicity [46].

Chlorpyrifos was moderately detected in several sites, aligning with studies in comparable tropical agricultural systems where organophosphates remain common due to their effectiveness and affordability [47]. The presence of carbendazim and buprofezin at relatively low concentrations suggests episodic application, consistent with their use in crop protection for specific pest outbreaks rather than continuous treatment [48]. Atrazine, a commonly used herbicide, was detected at low to moderate levels across various sites, indicating its current usage and environmental mobility. Bamal et al. [49] reported similar findings, noting atrazine residues in non-target areas due to leaching and runoff.

Pesticide degradation decreases when organic matter (OM) content exceeds 3 – 5% because strong sorption limits microbial access and slows chemical hydrolysis. High organic matter may also reduce pesticide mineralisation due to sorption effects [50]. This accounts for the high detection frequency and diversity of pesticide residues in all sites, suggesting potential cumulative effects on soil health and risks to nearby ecosystems. Concentrations of diazinon and chlorfenvinphos at some sites exceeded international soil guideline values, raising concerns about their potential entry into the food chain and long-term ecological impacts [13]. Differences in residue levels across sites are influenced by variations in

pesticide application practices, soil organic matter content, and degradation dynamics, as highlighted in other agricultural soil studies [51].

CONCLUSION AND RECOMMENDATIONS

The study assesses soil quality by examining physicochemical properties, plant nutrients, and pesticide residues at various agricultural sites. It finds significant spatial variability in key fertility indicators like pH, organic matter, and macronutrient levels. Multivariate analysis using PCA identifies distinct clusters influenced by soil fertility gradients and nutrient availability, highlighting the impact of land management practices on soil health.

The detection of high levels of pesticide residues, particularly diazinon and chlorfenvinphos, indicates excessive and possibly careless agrochemical use. Some concentrations surpassed international soil safety limits, raising concerns about environmental impact and food chain contamination. The findings highlight the link between soil degradation, excessive pesticide use, and nutrient imbalances, which jeopardise soil productivity and ecosystem health.

To promote sustainable agriculture and protect soil health, it's essential to implement integrated pest management (IPM) that minimises synthetic pesticide use through biological control, crop rotation, and the use of resistant varieties. Strengthening soil fertility management with tailored nutrient plans based on soil testing will optimise fertiliser use and enhance organic matter. Policy measures should include stricter oversight of pesticide use and routine soil residue monitoring to adhere to safety standards. Investing in farmer education and capacity building is crucial for safe pesticide handling and responsible land management. Lastly, long-term research is necessary to assess changes in soil quality and the interactions between pesticide residues, nutrients, and microbial activity, enabling informed interventions.

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REFERENCES

[1] L. Bondareva and N. Fedorova, "Pesticides: Behavior in agricultural soil and plants.," *Molecules,* vol. 26, no. 17, p. 5370, 2021.

[2] S. Sharma, B. Lishika and S. Kaushal, "Soil Quality Indicators: A Comprehensive Review," *International Journal of Plant & Soil Science,* vol. 35, no. 22, pp. 315 - 325, 2023.

[3] S. K. Dewangana, N. Kashyapb, D. Tiggab and N. Tirkeyb, “THE ROLE OF PHYSICO-CHEMICAL PROPERTIES IN SOIL FUNCTIONALITY: A LITERATURE REVIEW,” *EPRA International Journal of Research and Development (IJRD),* vol. 9, no. 12, 2024.

[4] S. K. Mishra, K. M. Tripathi and S. Pandey, “Effects of Chemical Pesticides on Soil Health and its Physio-chemical Properties,” *Novel perspectives of Geography, environment and earth sciences,* vol. 8, pp. 156-167, 2023.

[5] R. M. Shepherd and A. M. Oliverio, “Micronutrients modulate the structure and function of soil bacterial communities.,” *Soil Biology and Biochemistry,* vol. 192, p. 109384, 2024.

[6] H. Tiwari, R. Bhatt, P. K. Singh, D. Das, S. Vihan, T. Tomar and S. Kumar, “Micronutrients in the Plant-Soil-Environment Continuum: A Comprehensive Review.,” *European Journal of Nutrition & Food Safety,* vol. 16, no. 7, pp. 171-178, 2024.

[7] I. Zewide and Y. Reta, “Review on the role of soil macronutrient (NPK) on the improvement and yield and quality of agronomic crops,” *Journal of Agriculture and Food Research,* vol. 9, no. 1, pp. 7-11, 2021.

[8] P. Niazi and A. Monib, “Function of macronutrients in plant growth and human,” *IJSDR Res. J,* vol. 8, no. 4, p. 1265., 2023.

[9] S. Kumar, T. Korra, R. Thakur, R. Arutselvan, A. S. Kashyap, Y. Nehela and C. Keswani, “Role of plant secondary metabolites in defence and transcriptional regulation in response to biotic stress,” *Plant stress,* vol. 8, p. 100154, 2023.

[10] T. K. Faraj, M. H. EL-Saeid, M. M. Najim and M. Chieb, “The impact of pesticide residues on soil health for sustainable vegetable production in arid areas,” *Separations,* vol. 11, no. 2, p. 46, 2024.

[11] B. Sujatha, S. Sahoo and V. Kumar, “Effect of Pesticides on Soil Health,” *Agriculture and Food: E-Newsletter,* 2021.

[12] J. Kamau, N. Ngisiange, O. Ochola, J. Kilionzi, A. Kimeli, S. B. Mahongo and M. Osore, “Factors influencing spatial patterns in primary productivity in Kenyan territorial waters.,” *Western Indian Ocean Journal of Marine Science,* pp. 9-18, 2020.

[13] FAO, “Pesticides use and trade,” 2023.

[14] B. Habibu, O. Olawale, Y. O. Ejeh, M. A. Abah, T. Olalekan, E. A. Eneojo and A. M. Gbadebo, “Heavy Metals Speciation and Health Risk Analysis of Arable Farmlands In Ardo-Kola, Bali and Wukari Local Government Areas of Taraba State, Nigeria,” *Asian Journal of Biological Sciences,* vol. 17, no. 4, pp. 587-598, 2024.

[15] M. Salem, D. Bedade, L. Al-Ethawi and S. Al-Waleed, “Assessment of physiochemical properties and concentration of heavy metals in agricultural soils fertilized with chemical fertilizers,” *Heliyon,* vol. 6, no. 10, 2020.

[16] W. Li, B. C. O’Kelly, K. Fang and M. Yang, “Briefing: Water content determinations of peaty soils using the oven-drying method,” *Environmental Geotechnics,* vol. 9, no. 1, pp. 3-11, 2022.

[17] K. L. Sahrawat and J. R. Burford, “Modification of the alkaline permanganate method for assessing the availability of soil nitrogen in upland soils,” *Soil Science,* vol. 133, no. 1, pp. 53-57, 1982.

[18] S. Ghada, E. G. Alaa and A. A. H. Eman, "The use of experimental design for optimisation of QuEChERS extraction of commonly used pesticides in Egyptian soil and drainage water and their determination by GC/MS," *International Journal of Environmental Analytical Chemistry,* vol. 102, no. 16, pp. 4238-4249, 2022.

[19] K. Mastovska, J. Zulkoski, E. Deal, L. Vaclavik, U. Koesukwiwat, J. F. Halbardier and T. Gluaner, "Improved LC/MS/MS Pesticide Multiresidue Analysis Using Triggered MRM and Online Dilution," *Application note (Agilent)(accessed April 9, 2024),* pp. 5991-7193., 2017.

[20] R. H. Singh and H. P. Singh, "Analytical Method Validation: Principles, Techniques, and Applications," *Chemistry Research Journal,* vol. 10, no. 4, pp. 140-143, 2025.

[21] S. Y. Gebremariam, M. W. Beutel, D. R. Yonge, M. Flury and J. B. Harsh, "Adsorption and desorption of chlorpyrifos to soils and sediments," *Reviews of environmental contamination and toxicology,* pp. 123-175, 2011.

[22] S. A. Shahid, M. Zaman and L. Heng, "Introduction to soil salinity, sodicity and diagnostics techniques," in *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques*, Cham: Springer International Publishing, 2018, pp. 1-42.

[23] G. Pérez-Lucas, A. El Aatik, N. Vela, J. Fenoll and S. Navarro, "Exogenous organic matter as strategy to reduce pesticide leaching through the soil," *Archives of Agronomy and Soil Science,* vol. 67, no. 7, pp. 934-945, 2021.

[24] M. Khouni, C. Hammecker, O. Grunberger and H. Chaabane, "Effect of salinity on the fate of pesticides in irrigated systems: a first overview," *Environmental Science and Pollution Research,* vol. 30, no. 39, pp. 90471-90488., 2023.

[25] H. Liang, S. Gao, Z. Qi, K. Hu and J. Xu, "Leaching loss of dissolved organic nitrogen from cropland ecosystems," *Environmental Reviews,* vol. 29, no. 1, pp. 23-30, 2021.

[26] G. Liu, J. Sun, C. Liu, H. Shi, Y. Fey, C. Wang and H. Wang, "Progress and trends in research on soil nitrogen leaching: A bibliometric analysis from 2003 to 2023," *Sustainability,,* vol. 17, no. 1, p. 339, 2025.

[27] G. Agegnehu, T. Amede, G. Desta, T. Erkossa, G. Legesse, T. Gashaw and S. Schulz, "Improving fertilizer response of crop yield through liming and targeting to landscape positions in tropical agricultural soils," *Heliyon,* vol. 9, no. 6, 2023.

[28] C. A. Harper, B. K. Strickland, M. A. Lashley, M. A. Turner, J. S. Nanney, M. Colter Chitwood and G. M. Street, "Soil quality does not predict plant nutrition available to white-tailed deer.," *The Journal of Wildlife Management,* vol. 89, no. 3, p. e22722, 2025.

[29] R. O. Enesi, M. Dyck, S. Chang, M. S. Thilakarathna, X. Fan, S. Strelkov and L. Y. Gorim, "Liming remediates soil acidity and improves crop yield and profitability-a meta-analysis.," *Frontiers in Agronomy,* vol. 5, p. 1194896, 2023.

[30] C. Aspel, P. N. Murphy, M. J. McLaughlin and P. J. Forrestal, "Sulfur fertilization strategy affects grass yield, nitrogen uptake, and nitrate leaching: A field lysimeter study#," *Journal of Plant Nutrition and Soil Science,* vol. 185, no. 2, pp. 209-220, 2022.

[31] P. Tittonell, A. Muriuki, C. J. Klapwijk, K. D. Shepherd, R. Coe and B. Vanlauwe, "Soil heterogeneity and soil fertility gradients in smallholder farms of the East African highlands," *Soil Science Society of America Journal,* vol. 77, no. 2, pp. 525-538, 2013.

[32] U. C. Sharma, M. Datta and V. Sharma, "Global Status and extent of acid soils," in *Soil Acidity: Management Options for Higher Crop Productivity*, Cham: Springer Nature Switzerland, 2025, pp. 49-119.

[33] S. Rai, P. K. Singh, S. Mankotia, J. Swain and S. B. Satbhai, "Iron homeostasis in plants and its crosstalk with copper, zinc, and manganese," *Plant Stress,* vol. 1, p. 100008, 2021.

[34] S. K. Dewangan, S. K. Shrivastava, D. Kehri, A. Minj and V. Yadav, "A Review of the Study Impact of Micronutrients on Soil Physicochemical Properties and Environmental Sustainability," *International Journal of Agriculture and Rural Economic Research (ARER),* vol. 11, no. 6, 2023.

[35] D. Saya, D. Roveni, M. M. Ariina Shulee, A. N. Baite and Zohlunpua, "Micronutrient: Status and Management," *Justagriculture,* vol. 2, no. 3, pp. 1-13, 2021.

[36] A. Sagwal, P. Wadhwa, Shubham and S. Kaushal, "Essentiality of micronutrients in soils: A review," *International Journal of Plant and Soil Science,* vol. 65, no. 24, pp. 56-65, 2023.

[37] Y. Sexona, S. Lokhol, M. Premchand, L. Premjit and M. Paingam, "A quantitative analysis of essential heavy metals (iron, copper, zinc and manganese) in soils and vegetables grown at Machi sub-division, Tengnoupal District, Manipur," *Pharma Innovation,* vol. 14, no. 7, pp. 227-232, 2025.

[38] P. Shrivastav, "Role of Nutrients in Plant Growth and Development," in *Contaminants in Agriculture*, Springer, Cham, 2020, pp. 43-59.

[39] M. K. Abdel-Fattah, E. S. Mohamed, E. M. Wagdi, S. A. Shahin, A. A. Aldosari, R. Lasaponara and M. A. Alnaimy, "Quantitative evaluation of soil quality using Principal Component Analysis: The case study of El-Fayoum depression, Egypt," *Sustainability,* vol. 13, no. 4, p. 1824, 2021.

[40] J. Chen, M. Qu, J. Zhang, E. Xie, B. Huang and Y. Zhao, "Soil fertility quality assessment based on geographically weighted principal component analysis (GWPCA) in large-scale areas.," *Catena,,* vol. 201, p. 105197, 2021.

[41] M. Sharma, S. Goel and A. A. Elias, "Predictive modeling of soil profiles for precision agriculture: a case study in safflower cultivation environments," *Scientific Reports,* vol. 15, no. 1, p. 44, 2025.

[42] A. Walche, W. Haile, A. Kiflu and D. Tsegaye, "Spatial analysis and mapping of intensity and types of agricultural salt-affected soils around Abaya and Chamo Lakes, South Ethiopia Rift Valley," *Heliyon,* vol. 10, no. 13, 2024.

[43] Y. Pan, G. F. Koopmans, L. T. Bonten, J. Song, Y. Luo, E. J. Temminghoff and R. N. Comans, "Influence of pH on the redox chemistry of metal (hydr) oxides and organic matter in paddy soils.," *Journal of Soils and Sediments,* vol. 14, no. 10, pp. 1713-1726, 2014.

[44] C. Froger, C. Jolivet, H. Budzinski, M. Pierdet, G. Caria, N. P. Saby and A. Bispo, "Pesticide residues in French soils: occurrence, risks, and persistence," *Environmental Science & Technology,* vol. 57, no. 20, pp. 7818-7827, 2023.

[45] S. Dehghan Abkenar, N. Khakipour and M. R. Ganjali, "Analytical Methods for Extraction, Determination and Degradation of Diazinon in Soil Samples," *Pollution,* vol. 9, no. 4, pp. 1538-1553, 2023.

[46] F. Alam, K. Maroof, N. Choon Ming, M. I. Khalil and S. H. Gan, “Other Possible Contaminants, Toxic Compounds, and Microbial Growth,” *Honey: Composition and Health Benefits*, pp. 167-185, 2023.

[47] M. A. Gomez-Arguello, “Study of the Dynamics and Risk of the Organophosphate Pesticide Chlorpyrifos and its Degradation Product TCP in La Fe Reservoir, Antioquia,” 2024.

[48] M. P. Hill, S. Macfadyen and M. A. Nash, “Broad-spectrum pesticide application alters natural enemy communities and may facilitate secondary pest outbreaks,” *PeerJ*, vol. 5, p. e4179, 2017.

[49] D. Bamal, A. Duhan, A. Pal, R. K. Beniwal, P. Kumawat, S. Dhanda and R. Yadav, “Herbicide risks to non-target species and the environment: A review,” *Environmental Chemistry Letter*, vol. 22, no. 6, pp. 2977-3032, 2024.

[50] E. C. Devitt and M. R. Wiesner, “Dialysis Investigations of Atrazine-Organic Matter Interactions and the Role of a Divalent Metal,” *Environ. Sci. Technol*, vol. 32, p. 232–237, 1998.

[51] M. Yasir, A. Hossain and A. Pratap-Singh, “Pesticide degradation: Impacts on soil fertility and nutrient cycling,” *Environments*, vol. 12, no. 8, p. 272, 2025.