

Agrochemical residues in soil and foliage of date palm (*Phoenix dactylifera* L.) and their association with macrofaunal and microbial diversity under agrisilvicultural system in Yobe State, Nigeria

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ABSTRACT: The widespread use of agrochemicals in semi-arid agricultural systems raises concerns about their persistence, mobility, and effects on non-target organisms and ecosystem health. This study assessed the agrochemical footprint in soil and foliage of date palm (*Phoenix dactylifera* L.) and its effects on macrofaunal and microbial diversity under agrisilvicultural practice in Damaturu, Yobe State, Nigeria. The plantation was stratified into high-, medium-, and low-growth sites based on observed growth variability. Soil samples were collected at 0–60 and 61–90 cm depths for physicochemical analysis, pesticide residue determination using Gas Chromatography-Mass Spectrometry (GC-MS), and microbial enumeration. Foliar samples were also analysed for pesticide residues, while macro-invertebrates were sampled using 20 m × 20 m plots and 1 m × 1 m quadrats. Results showed that soils were sandy loam with slightly acidic pH (6.06–6.40), low total nitrogen (0.12–0.15%), and low water-holding capacity (10.93–11.28%). The high-growth site recorded superior nutrient status, including available phosphorus (11.23 mg kg⁻¹), calcium (5.47 cmol kg⁻¹), and magnesium (2.42 cmol kg⁻¹). Pesticide residues detected included chlorpyrifos (0.17 µg/kg), dichlorvos (0.44 µg/kg), 2,4-D (0.42 µg/kg), alachlor (0.33 µg/kg), cypermethrin (0.34 µg/kg), butachlor (0.16 µg/kg), and atrazine (0.08 mg/kg). Residues were also detected at 61–90 cm, indicating downward mobility through infiltration. Macro-invertebrate abundance was highest at the high-growth site (365 individuals), representing 14 taxa, while the medium-growth site recorded the highest Shannon-Wiener diversity ($H' = 1.823$) and evenness ($J = 0.4763$). Microbial populations varied significantly ($p \leq 0.05$), with the medium site recording the highest bacterial (54.8 cfu/ml) and fungal (50.6 cfu/ml) populations, whereas the low site had elevated actinomycetes (140 cfu/ml) and reduced bacterial counts (33.0 cfu/ml). The study concludes that agrochemical contamination influences soil quality and biological community dynamics, particularly at the low-growth site. Integrated pest management, routine monitoring, organic matter amendment, conservation practices, and strengthened regulatory enforcement are recommended for sustainable date palm production in semi-arid environments.

Keywords: Agrochemical footprint, Date palm, Pesticide residues, Macro-invertebrate diversity, Microbial communities, and agrisilviculture.

INTRODUCTION

Agriculture is an important economic activity in Nigeria and provides food, employment, and income for a large proportion of the population. In the semi-arid environment

of northern Nigeria, including Damaturu in Yobe State, agricultural production is constrained by low and irregular rainfall, high temperatures, poor soil fertility, pest attacks,

and periodic drought. These challenges have encouraged farmers to adopt agrochemicals such as inorganic fertilisers, herbicides, insecticides, fungicides, and other crop-protection products to improve plant growth and reduce losses. Umar *et al.* (2026) state that agrochemicals can increase agricultural productivity, their repeated and sometimes inappropriate use may produce undesirable effects on soil quality, vegetation, non-target organisms, and the wider environment (Meena *et al.*, 2020).

Sibalekile *et al.* (2025) describe the term agrochemical footprint as referring to the cumulative environmental pressure resulting from the application, persistence, movement, and biological effects of agricultural chemicals. This footprint may be influenced by the type and quantity of chemical applied, frequency of application, method of application, soil characteristics, climatic conditions, irrigation practices, and the level of chemical management by farmers. Agrochemicals may enter the soil directly during application or indirectly through drift, runoff, leaching, and the decomposition of treated plant materials. Once present in the soil, some compounds may persist for considerable periods, while others may be transformed into metabolites that can also affect soil organisms and plant health (Sibalekile *et al.*, 2025).

Soil is a biologically active ecosystem containing bacteria, fungi, protozoa, nematodes, arthropods, earthworms, termites, and other organisms. These organisms perform essential functions that support agricultural productivity. Soil macrofauna, including earthworms, termites, ants, beetles, millipedes, centipedes, and other large soil-dwelling invertebrates, contribute to litter decomposition, soil aggregation, aeration, nutrient cycling, organic matter incorporation, and the formation of channels that improve water infiltration. They also serve as indicators of soil disturbance because their abundance, composition, and diversity respond to changes in soil moisture, organic matter, pH, vegetation cover, and chemical contamination (Potts *et al.*, 2023; De Menezes *et al.*, 2023).

Microorganisms are equally important components of soil fertility and ecosystem functioning. Soil bacteria and fungi decompose organic residues and facilitate the cycling of carbon, nitrogen, phosphorus, and sulphur. Certain microorganisms participate in nitrogen fixation, phosphate solubilization, production of plant-growth-promoting substances, and suppression of soil-borne pathogens (Colagiero *et al.*, 2024). The composition and diversity of microbial communities are influenced by environmental conditions and agricultural practices. Agrochemicals can alter these communities by inhibiting sensitive species, favouring tolerant organisms, changing microbial competition, or modifying the chemical and physical properties of the soil. Such changes may affect decomposition processes, nutrient availability, soil respiration, and the long-term productivity of agricultural land (Meena *et al.*, 2020; Sibalekile *et al.*, 2025).

Date palm, *Phoenix dactylifera* L., is an important fruit

crop in arid and semi-arid regions. It is valued for its nutritional, economic, cultural, and ecological significance. Date palms are relatively well adapted to high temperatures and water stress, making them suitable for parts of northern Nigeria, including Yobe State (Usman *et al.*, 2025). In addition to producing dates, date palms provide shade, reduce wind speed, protect the soil surface, and may contribute to the development of a more favourable microclimate beneath their canopy. The area under a date palm can accumulate fallen leaves, fruit residues, and other organic materials, which may support a distinct community of soil macrofauna and microorganisms compared with exposed or non-cultivated soil (Almansor, 2023).

However, date palm production may involve the use of agrochemicals to control insect pests, diseases, weeds, and nutrient deficiencies. Chemicals applied to the foliage may be deposited on leaves and fruits, washed onto the soil by rainfall or irrigation, or transferred through fallen plant materials. Fertilisers and pesticides applied around the palm basin may also influence the chemical characteristics of the soil and the organisms living within it (Al-Hadidi *et al.*, 2024). The foliage therefore represents an important component of the agrochemical pathway, while the soil serves as a major reservoir and medium through which chemical effects may be expressed. The interaction between chemical residues on date palm foliage and biological communities in the soil is consequently relevant to both crop protection and environmental sustainability.

The effects of agrochemicals on soil macrofauna and microbial diversity are not always uniform. Some products may have short-term effects, while others may persist and produce cumulative impacts after repeated application. Broad-spectrum insecticides, for example, may affect beneficial arthropods in addition to target pests. Herbicides may indirectly influence soil organisms by reducing plant cover and the quantity of organic residues returned to the soil (Potts *et al.*, 2023). Fertilisers can increase nutrient availability, but excessive use may cause soil acidification, salinity, nutrient imbalance, or changes in microbial community structure (Al-Hadidi *et al.*, 2024). The response of soil organisms may also vary according to chemical concentration, exposure duration, organism type, soil texture, organic matter content, temperature, and moisture conditions (Meena *et al.*, 2020; De Menezes *et al.*, 2023).

Damaturu presents a relevant setting for investigating these relationships. The area is characterised by a hot semi-arid climate, seasonal rainfall, high evaporation, and soils that may be vulnerable to nutrient depletion and degradation. Farmers may depend on agrochemical inputs to maintain crop productivity under challenging environmental conditions (Usman *et al.*, 2025). At the same time, limited information may be available on the types and quantities of agrochemicals used in date palm production, their accumulation in soil and foliage, and their effects on non-target biological communities. Local

environmental conditions can influence the persistence, movement, and toxicity of agrochemicals; therefore, findings from other ecological zones cannot always be directly applied to Damaturu (Umar *et al.*, 2026).

Evaluating macrofauna and microbial diversity provides a useful approach for determining the ecological consequences of agrochemical use. A decline in macrofaunal abundance or the disappearance of sensitive groups may indicate soil disturbance, habitat degradation, or chemical stress. Similarly, changes in microbial richness, diversity, and community composition may reveal alterations in soil functioning before visible changes in crop performance become apparent (Potts *et al.*, 2023; Sibalekile *et al.*, 2025). Measurements of soil physicochemical properties, agrochemical residues, macrofaunal abundance, and microbial diversity can therefore provide an integrated assessment of the agrochemical footprint associated with date palm production.

Despite the importance of soil biodiversity for sustainable agriculture, environmental assessments of agrochemical use often focus mainly on crop yield and pest control. Less attention is given to the effects of chemical inputs on beneficial soil organisms and the biological processes that maintain soil fertility (Meena *et al.*, 2020; Colagiero *et al.*, 2024). In addition, information linking agrochemical residues in date palm foliage and soil with macrofaunal and microbial diversity in the Damaturu environment is limited. This creates a need for site-specific research that considers both the chemical dimension of agricultural practices and their biological consequences (Umar *et al.*, 2026).

The study of the agrochemical footprint on date palm soil and foliage in relation to macrofauna and microbial diversity is therefore important for several reasons. It can generate baseline information on agrochemical contamination and biological diversity in date palm production systems. It can also help identify whether current chemical-use practices are associated with reductions or changes in beneficial soil organisms. The findings may support the development of integrated pest management, improved fertiliser and pesticide application practices, safer handling of agrochemicals, and conservation strategies for soil biodiversity. Ultimately, understanding these relationships can contribute to the sustainable production of date palm, protection of soil health, and environmental management in Damaturu and other semi-arid regions of Nigeria.

MATERIALS AND METHODS

The study area

Damaturu Local Government Area of Yobe State, Nigeria, lies approximately between 11°39'30"–11°47'00" N and 11°54'00"–12°02'00" E and falls within the Sudano-

Sahelian savanna zone. The vegetation consists mainly of scattered drought-tolerant trees, shrubs, grasses and seasonal herbs. Common woody species include *Balanites aegyptiaca*, *Ziziphus mauritiana*, *Faidherbia albida*, *Tamarindus indica* and *Azadirachta indica*. Vegetation density and composition vary with rainfall, soil conditions and human activities such as farming, grazing, fuelwood collection and urban expansion. Overall, the vegetation is generally open and discontinuous, with greater herbaceous cover during the rainy season and sparse vegetation during the dry season.

Yobe State is located in the northeastern part of Nigeria. It lies between latitude 12 and 22°N of the equator and longitude 11 and 42°E of the green wish meridian. its share boundaries with Gombe State in the south and west, Bauchi State in the north, Jigawa State in the east, and Borno State; it has an international boundary with the Niger Republic. The total land area of Yobe State is 4,660,900ha (46,609 km²), of which 386,710 ha constitute the area covered by forest reserves. Moreover, the total population in Yobe is 2,321,339. It was divided into 17 local government areas (Figure 1; Gujja *et al.*, 2024). Yobe state falls under the Sudan savannah type of vegetation and experiences distinct dry and wet reason, with temperature and humidity varying with season s. the wet or rainy season fall between May and October, which is characterized by a single maximum in August and September during this season the moisture laden south west trade wind from the Atlantic ocean blows over area, seventy percent of the total rain fall in the area happen to fall within four month from May to September (Gujja *et al.*, 2024)blows area has an average of 62 rainy days, while the average amount of rainfall recorded in the area is 972mm. The harmattan period was between December to march, and this period was characterised by dry, dusty and hazy northern trade winds that blow over the area from the Sahara Desert. The temperature within the area varies with the season. Although the temperature is relatively high almost all year round, the temperature of the area ranges from 27 to 34°C. December and January are the coldest month an average temperature of 28°C (Gujja *et al.*, 2024). The natural vegetation of the area is Sudan savannah and Sahel type, which is characterised by scattered vegetation. The vegetation has a wide variety of savannah tree species, among which are *Acacia spp*, *Adansonia digitata*, and *Anogeissus leocarpus* (Gujja *et al.*, 2024).

Rainfall and relative humidity

The mean annual rainfall pattern in the state shows that it ranges from 400 mm in the north-south part to 1600 mm in the southern part. Generally, mean annual rainfall is less than 1200mm in the Damaturu and east-western parts of the state, including Fune, Potiskum, Fika, and Nangere local government areas; on the other hand, the north-south

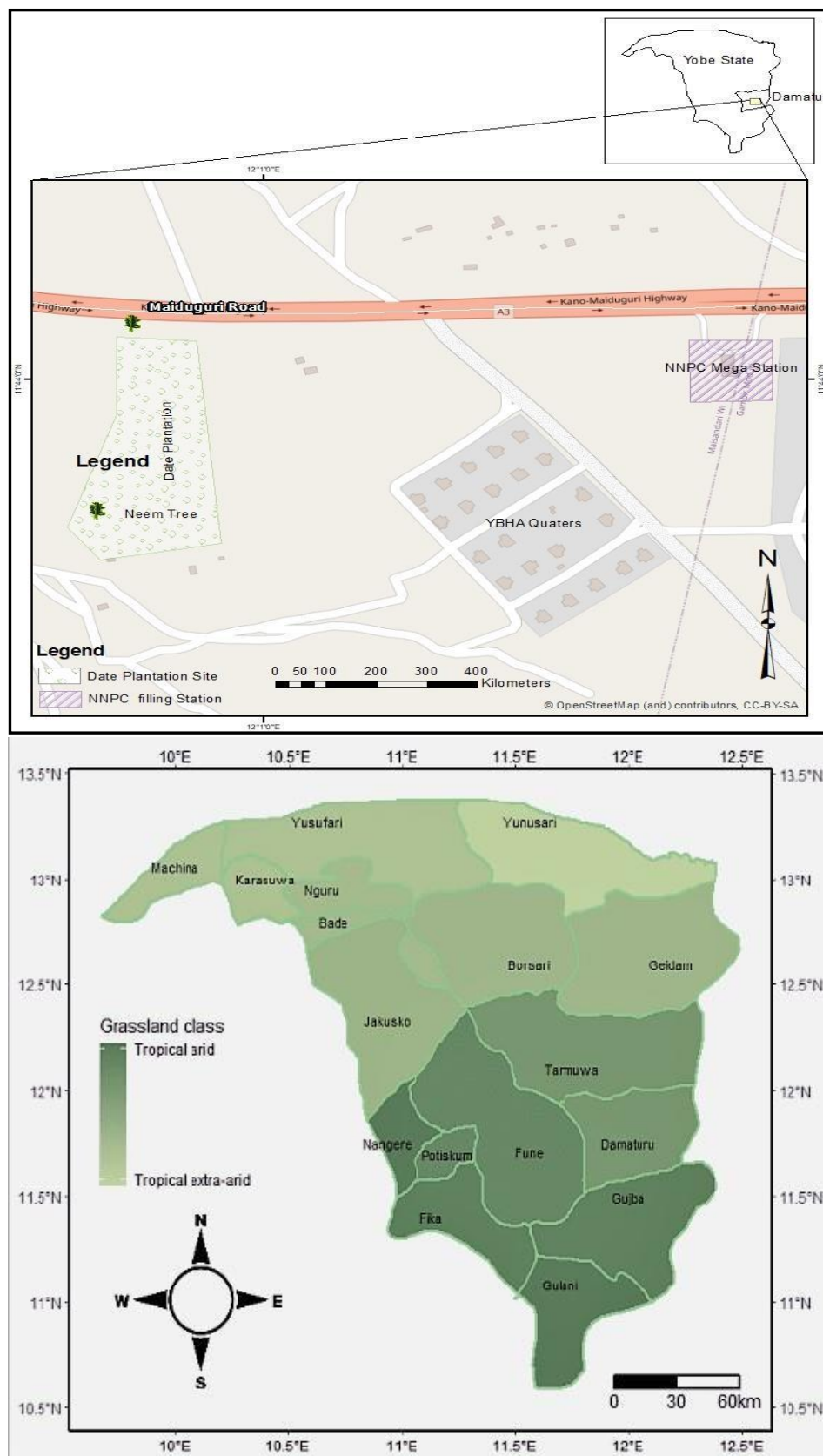


Figure 1. Map of Damaturu and Yobe State Nigeria (Source: GIS Laboratory, Geography Department Yobe State University, Damaturu (2026).

strip and southern part have over 1800 mm. The mean length of the rainy season is about 120 days in the state. The lowest relative humidity in the state (20 – 30%) is recorded between December and February. It starts increasing from April and reaches its peak (about 80%) in August and September. This is due to the influence of the humid maritime air mass which covers the whole state during this period. Relative humidity starts to decline again in October following the cessation of the rains. Generally, there is a north-south increase in relative humidity values in the state (Gujja *et al.*, 2024).

Temperature

An air temperature characteristic in Yobe State is typically of the West African savannah climate. Temperature in this climatic region is high throughout the year because of high radiation income, which is relatively evenly distributed throughout the year. However, there is usually a seasonal temperature change. There is a gradual increase in temperature from March to May. There is a distinct drop in temperature at the onset of rains due to the effect of cloudiness. Maximum temperature in the state can reach 40°C, particularly in April, while minimum temperature in the state ranges from 16 to 23°C (Gujja *et al.*, 2024).

Sampling design and data collection

Soil sample collection for physicochemical properties

A reconnaissance survey of the date palm plantation revealed variation in date palm tree growth. Therefore, the plantation was divided into three areas according to these variabilities (low, medium, and high growth). Five auger points were made, and soil samples were collected from the surface and subsurface layers in each of the areas (0-60 cm and 61- 90 cm), respectively. These were appropriately labelled in polythene bags and taken to the Soil Science Laboratory of Yobe State University, Damaturu, for analysis of micro- and macronutrients.

Foliar sample collection for pesticide/ herbicide extraction

Date palm leaves were collected by hand from Mai Sandari ward date palm plantation in Damaturu. The plantation was divided according to growth variabilities observed (upper, middle, and lower slopes) based on growth performance, and ten (10) leaves from each tree were collected and sterilised, appropriately labelled, placed in a polythene bag and taken to the Analytical Laboratory of Yobe State University, Damaturu, for analysis of pesticide/herbicide extraction.

Laboratory analysis

Soil Macro Nutrients

Total nitrogen (TN): Total nitrogen was determined by the micro Kjeldahl technique (Bremmer and Mulvaney, 1982). One (1) gram of soil was digested with 10 mls of concentrated sulphuric acid; the digested solution was then diluted with 100 mL of distilled water. 10 mls of the aliquot was distilled with sodium hydroxide. The distillate was then titrated with 0.01N H₂SO₄ to a pink endpoint.

Available phosphorus (AVP): Available phosphorus was determined following the procedure described by IITA (1979) using the Bray-1 extraction method (Bray and Kurtz, 1945). Available phosphorus was extracted from ten (10) grams of soil using ammonia fluoride in hydrochloric acid. Phosphorus in solution was then determined calorimetrically by the modified single solution procedure using ascorbic acid (Murphy and Riley, 1962).

Available Potassium (K₂O): This was estimated by using normal neutral ammonium acetate as an extractant, and the extractant was analysed using a flame photometer (Jackson, 1973).

Exchangeable cations: Exchangeable cations (Ca and Mg) were determined using the NH₄OAc saturation method at pH 7.0 as described by Thomas (1982). Five (5) grams of soil samples were leached with NH₄OAc, and the solution was determined using the titrimetric method.

Soil micronutrients

Micronutrients (Zn, Fe, Cu, Mn, Mo, and Cl) were analysed according to Lindsay and Norvell (1978). Available micronutrients in soil were removed using 0.005 M diethylene triamine pentaacetic acid (DTPA) + 0.01 M calcium chloride + 0.1 M triethanolamine (pH 7.3) and estimated using an atomic absorption spectrophotometer (Analytik Jena ZEE nit 700).

Assessment of species of soil micro- and macroinvertebrates

Assessment of macrofauna species was carried out using plots of 20 m × 20 m, which were randomly selected from all plots for the assessment of macrofaunal diversity using Dishan *et al.* (2018) methods. A quadrat of 1m × 1m was laid at random within each of the plots. Topsoil for biological assessment of soil samples was collected using trowels at depths ranging from 0- 40 cm. The soil samples were immediately spread on a board of about 60cm² and sorted for the presence of macrofauna (earthworms, crickets, termites, scorpions, spiders, mites, centipedes, millipedes, ants, beetles, etc.). The soil macroinvertebrates

encountered in each of the sites were counted and recorded. Identification was done using the literature. Pictures of unidentified soil macroinvertebrates were taken for identification. The computation of species diversity indices per study site was done.

Soil sampling process for microbial isolates

Soil samples were taken at each auger point in the date palm plantation. A composite sample was obtained after mixing the sample thoroughly, and sterile polythene bags were used to convey samples to the laboratory within 24 hours of collection for analysis of soil bacteria, fungi, and actinomycetes at the Department of Microbiology of Yobe State University, Damaturu.

Culture

Bacteria population were estimated by the method of Vieira (2005) using nutrient agar medium at 10^5 dilutions. The inoculated Petri dishes were incubated at $30^\circ\text{C} \pm 10^\circ\text{C}$ for 2-5 days for bacteria colonies. The laboratory analysis involved adding 1g of soil into 9ml of sterile water in a test tube, followed by vigorous shaking, and then serial dilutions were done in four test tubes before being transferred into the Petri dish. However, molten agar/media was poured into the Petri dish.

For isolation and characterisation of fungi and actinomycetes, the dilution plate method was used; Sabouraud dextrose agar for fungi and Actinomycetes selected media for Actinomycetes were used as basal medium to isolate species. The inoculated Petri dish was incubated at 25°C for 5-7 days to grow the fungi and Actinomycetes colonies. Representative isolates of fungi were identified under the microscope with the help of standard manuals (Naher *et al.* 2013). Representative isolates of bacteria were also identified under the microscope. Fungi identification was done based on the appearance and pigmentation of spores on agar, and actinomycetes were identified based on their appearance on agar plates.

Identification of the compounds

Gas chromatography/mass spectrometry (GC-MS)

Principle: The Gas Chromatography/Mass Spectrometry (GC/MS) instrument separates chemical mixtures (the GC component) and identifies the components at a molecular level (the MS component). It is one of the most accurate tools for analysing environmental samples. The GC works on the principle that a mixture can be separated into individual substances when heated. The sample is injected into the GC inlet, where it is vaporized and swept into a

chromatographic column by the carrier gas (helium). The sample flows through the column, and the compounds comprising the mixture of interest are separated by their relative interaction with the coating of the column (stationary phase) and the carrier gas (mobile phase). The latter part of the column passes through a heated transfer line and ends at the entrance to the ion source, where compounds eluting from the column are converted to ions. A beam of electrons ionises the sample molecules, resulting in the formation of molecular ions and smaller ions with characteristic relative abundances that provide a 'fingerprint' for that molecular structure. The mass analyser separates the ions, and is then detected (Shimadzu, 2020).

Method: Compounds present in the most active subfraction were identified by GC-MS at the analytical laboratory, Yobe State University, Damaturu. The injection volume was 2 μL , and the carrier gas was helium at 1.22 mL/min. GC column oven temperature was 50°C for 3 min, 230°C for 5 min, and finally 260°C for 18 min.

1. Data on the residue of pesticide and herbicide accumulation in date palm foliage and soil were determined by the compounds, names, and percentage abundance, and were presented in tabular form.
2. Data on macrofaunal diversity were analysed using the Shannon Diversity Index. This is illustrated as follows (Yager *et al.*, 2017):

$$H^1 = -\sum_{i=1}^s P_i \ln(P_i)$$

Where: H^1 = Shannon Diversity Index, n_i = number of individuals in species, N = total number of all individuals, P_i = relative abundance of each species, calculated as the proportion of individuals of a given species to the total number of individuals in the community: n_i/N , and $\ln$ = natural logarithm (Yager *et al.*, 2017).

RESULTS

Soil physicochemical properties

The physicochemical properties of soils collected from different landscape positions (Low, Middle, and Upper sites) are presented in Table 1. The results showed variations in soil pH, total nitrogen (TN), available phosphorus (AvP), and exchangeable cations (calcium, potassium, and magnesium) across the three sites. The soil pH ranged from 6.06 to 6.40, indicating that soils at all three sites were slightly acidic. This pH range is generally considered favourable for the growth of date palm and most agrisilvicultural crops because it promotes the

Table 1. Soil chemical properties across the three study sites.

Parameter	Low site	Middle site	Upper site
Ph	6.06	6.40	6.18
Total Nitrogen (TN %)	0.13	0.12	0.15
Available phosphorus (AvP mg/kg)	9.40	9.23	11.23
Calcium (Ca, cmol/kg)	3.56	4.24	5.47
Potassium (K, cmol/kg)	0.65	0.55	0.62
Magnesium (mg cmol/kg)	1.84	2.34	2.42

Source: Laboratory analysis (2026).

Table 2. Physical properties of soils according to variability.

Site	Sand	Silt	Clay	Bulk.Dg/cm ³	Particle D	Total Porosity%	WHC
Low	67.20	9.00	17.60	1.44	2.50	43.40	11.28
Middle	68.00	9.60	17.46	1.57	2.61	42.70	10.93
Upper	70.24	6.20	17.80	1.52	2.60	41.20	11.00

Source: Laboratory Analysis, 2026.

availability of essential nutrients, while minimising aluminium toxicity. The middle site (pH 6.40) was closest to neutral, suggesting slightly better nutrient availability than the low and upper sites. The small differences among sites may reflect variations in organic matter decomposition, fertiliser application, and soil parent material. Total nitrogen (TN), available phosphorus (AvP), calcium (Ca), potassium (K), and magnesium (Mg) varied across the three study sites, indicating differences in soil fertility status. Total nitrogen ranged from 0.12–0.15%, with the upper site recording the highest value (0.15%), followed by the low site (0.13%) and the middle site (0.12%), suggesting greater organic matter accumulation and nutrient cycling at the upper site. Available phosphorus ranged from 9.23–11.23 mg kg⁻¹, with the highest concentration also observed at the upper site (11.23 mg kg⁻¹), indicating better conditions for root development, energy transfer, flowering, and fruit production.

Exchangeable calcium increased from 3.56 cmol kg⁻¹ at the low site to 5.47 cmol kg⁻¹ at the upper site, reflecting improved soil fertility and base saturation. Exchangeable potassium showed only slight variation, ranging from 0.55–0.65 cmol kg⁻¹, with the highest value at the low site, indicating generally adequate potassium availability across all sites. Similarly, exchangeable magnesium ranged from 1.84–2.42 cmol kg⁻¹, with the upper site recording the highest concentration, suggesting enhanced photosynthetic potential and nutrient availability. Overall, the upper site exhibited superior nutrient status compared with the low and middle sites, indicating more favourable soil conditions for supporting vigorous date palm growth and productivity.

Table 2 shows the physical properties of the soil at the low study site, which indicated a sandy loam texture,

comprising 67.20% sand, 9.00% silt, and 17.60% clay. The high sand content promotes good drainage, aeration, and root penetration but also reduces the soil's ability to retain water and nutrients due to increased leaching. The relatively low silt content limits moisture retention, while the moderate clay fraction provides some capacity for nutrient and water storage. The soil had a bulk density of 1.44 g cm⁻³, indicating acceptable compaction that is unlikely to restrict root growth, and a particle density of 2.50 g cm⁻³, which is typical of mineral soils with some organic matter influence. The total porosity of 43.40% suggests adequate pore space for water movement, aeration, and microbial activity, creating favourable conditions for plant growth. However, the water-holding capacity, which ranged from 10.93% to 11.28% (mean $\approx$ 11.07%), was relatively low, reflecting the sandy nature of the soil and indicating that irrigation and proper soil management may be required to maintain adequate moisture and nutrient availability for optimal date palm growth under the agrisilvicultural system.

The soil at the middle growth site contained 68.00% sand, 9.60% silt, and 17.60% clay, indicating a sandy loam textural class. This soil texture is characterised by good drainage, adequate aeration, and favourable conditions for root penetration and plant growth. The soil recorded a bulk density of 1.57 g cm⁻³, suggesting moderate compaction that is still suitable for root development. The particle density was 2.61 g cm⁻³, which is within the normal range for mineral soils and reflects a predominance of mineral particles. The total porosity of 42.70% indicates a balanced distribution of pore spaces for air and water movement, while the water-holding capacity of 10.93% suggests a moderate ability to retain soil moisture for plant uptake. Overall, the physical properties of the middle growth site indicate a well-drained sandy loam soil with moderate

Table 3. Leaves pesticide/ herbicide concentrations ($\mu\text{g/kg}$) low growth site.

RT(Minutes)	Compound Names	Upper leaves($\mu\text{g/kg}$)	Medium leaves($\mu\text{g/kg}$)	Low leaves ($\mu\text{g/kg}$)
5.0 -6.0	Dichlorvos	0.12	0.28	0.44
8.2 – 9.0	2,4 – D	0.28	0.35	0.42
10.0 – 10.9	Alachlor	0.33	0.225	0.12

Source: Laboratory Analysis (2026).

moisture retention and favourable conditions for date palm growth.

The soil at the upper growth site comprised 70.24% sand, 6.20% silt, and 17.80% clay, indicating a sandy loam textural class dominated by sand particles. This texture promotes good drainage, adequate soil aeration, and favourable root penetration while retaining sufficient fine particles for nutrient storage. The bulk density was 1.52 g cm^{-3} , suggesting low to moderate soil compaction and providing a suitable environment for root growth. The particle density of 2.60 g cm^{-3} falls within the normal range for mineral soils, reflecting a predominance of mineral constituents. The soil exhibited a total porosity of 41.20%, indicating adequate pore spaces for air and water movement, while the water-holding capacity of 11.00% suggests a moderate ability to retain moisture for plant use. Overall, the physical properties indicate that the middle growth site has a well-drained sandy loam soil with favourable structural characteristics for supporting healthy date palm growth (Table 2).

Pesticide /herbicide detection in date palm leaves

Gas chromatography-mass spectrometry (GC-MS) analysis was employed to quantify agrochemical residues in the leaf samples. The chromatograms revealed the presence of four distinct compounds, which were identified by comparison with the National Institute of Standards and Technology (NIST) mass spectral library. The detected compounds and their respective retention time ranges were as follows: Dichlorvos (5.0–6.0 min), 2,4-D (8.2–9.0 min), and alachlor (10.0 – 10.9 min)."

Table 3 presents the concentrations of pesticide and herbicide residues detected in the leaves of date palm (*Phoenix dactylifera* L.) at the low-growth study site. Three compounds, namely Dichlorvos, 2,4-D, and Alachlor, were detected at trace concentrations, all below $1 \mu\text{g/kg}$. Dichlorvos recorded concentrations of 0.12, 0.28, and 0.44 $\mu\text{g/kg}$ in the upper, medium, and lower leaves, respectively, with the highest concentration occurring in the lower leaves. Similarly, 2,4-D was detected at 0.28, 0.35, and 0.42 $\mu\text{g/kg}$ in the upper, medium, and lower leaves, respectively. Alachlor showed concentrations of 0.33, 0.225, and 0.12 $\mu\text{g/kg}$ in the upper, medium, and lower leaves, respectively. Overall, Dichlorvos had the highest concentration (0.44 $\mu\text{g/kg}$), followed closely by 2,4-

D (0.42 $\mu\text{g/kg}$), while Alachlor recorded the lowest concentration (0.12 $\mu\text{g/kg}$). The variation in residue concentrations among leaf positions may reflect differences in pesticide deposition, absorption, translocation, degradation, and exposure to environmental factors. The detection of these compounds, although at trace levels, indicates that the date palm foliage had been exposed to agrochemical inputs and highlights the importance of continued monitoring of pesticide and herbicide residues within the plantation ecosystem.

Pesticide residues detected in soil samples at 0-30 cm and 31-60 cm depths in the low-growth site of the date palm plantation

The laboratory analysis of soil samples from the date palm plantation revealed multiple pesticide residues with varying persistence and mobility across soil depths: at 0-60 cm, dichlorvos (0.20 $\mu\text{g/kg}$), chlorpyrifos (0.17 $\mu\text{g/kg}$), butachlor (0.16 $\mu\text{g/kg}$), and cypermethrin (0.34 $\mu\text{g/kg}$) were detected, while at 61-90 cm, chlorpyrifos (0.30 $\mu\text{g/kg}$) and atrazine (0.08 mg/kg) were found, indicating downward migration through infiltration (Table 4). When compared against WHO/FAO maximum residue limits (0.10 $\mu\text{g/kg}$ for dichlorvos, 0.50 $\mu\text{g/kg}$ for chlorpyrifos, 0.10 $\mu\text{g/kg}$ for butachlor, and 0.05 $\mu\text{g/kg}$ for atrazine), the levels of dichlorvos, butachlor, and atrazine exceeded recommended thresholds, indicating over-application or slow degradation under semi-arid conditions, while cypermethrin's presence at 0.34 $\mu\text{g/kg}$ in subsurface layers reflects its stability and limited biodegradation influenced by soil texture, organic matter, and pH. These findings demonstrate that pesticide residues are not confined to topsoil but can migrate vertically, posing potential risks to soil organisms, nutrient cycling, and groundwater quality, thereby underscoring the urgent need for sustainable pest management practices and routine monitoring to prevent pesticide buildup and maintain the long-term ecological integrity of date palm plantation soils (Table 4).

Table 4 shows comparative analysis of pesticide residues in date palm plantation soils against regulatory standards reveals that all detected compounds chlorpyrifos (0.17 $\mu\text{g/kg}$), dichlorvos (0.44 $\mu\text{g/kg}$), and atrazine (0.03 $\mu\text{g/kg}$) fall far below their respective permissible limits (EPA SSL of 15,000 $\mu\text{g/kg}$ for chlorpyrifos, EU-MRL of 100

Table 4. Compound detected in date palm plantation soil.

Retention Time	Compound name	Concentration detected $\mu\text{g/kg}$	Soil depth cm
5.0 - 6.0	Dichlorvos	0.20	0 - 60
6.0 - 7.0	Chlorpyrifos	0.17	0 - 60
16.8 - 17.3	Butachlor	0.16	0 - 60
19.7 - 20.5	Cypermethrin	0.34	0 - 60
15.0 - 15.8	Atrazine	0.03	61 - 90
6.0 - 7.0	Chlorpyrifos	0.30	61 -90

Source: Laboratory analysis, (2026).

Table 5. Comparative analysis with regulatory standards.

Pesticide	Matrix	Detected ($\mu\text{g/kg}$)	Regulatory limit ($\mu\text{g/kg}$)	compliance
Chlorpyrifos	Soil (MGS 0-60)	0.17	EPA SSL:15,000	Compliant
Dichlorvos	Foliage point	0.44	EU MRL:100(dates)	Compliant

Source: Laboratory analysis, (2026).

Table 6. Some macro-fauna species of the study area.

S/N	English Name	Scientific Name
1	Earthworm	<i>Lumbricina terrestris</i>
2	Ant	<i>Monomorium minimum</i>
3	Subterranean Termite	<i>Heterotermes species</i>
4	Millipede	<i>Eurymerodesmidae spp</i>
5	Giant centipede	<i>Scolopendra gigantea</i>
6	Crickets	<i>Gryllus assimillis</i>
7	Grasshopper	<i>Conozoa hyaline</i>
8	Ground Beetle	<i>Scaritinae clivinini</i>
9	Brow marmorated stink bug	<i>Halyomorpha halys</i>
10	Snail	<i>Achatina spp</i>
11	common centipede	<i>Scutigera coleoptrata</i>
12	Black ant	<i>Lasius niger</i>
13	Soil mites	<i>Unidentified</i>
14	Spider	<i>Achaeranea tepideariorum</i>
15	Rove beetle	<i>Staphylius caesareus</i>

Source: Field data, (2026).

$\mu\text{g/kg}$ for dichlorvos, and Codex MRL of 50 $\mu\text{g/kg}$ for atrazine), indicating that all concentrations are within safe environmental thresholds and pose no immediate risk to soil health, crop safety, groundwater quality, or soil organisms. These low residue levels, representing less than 1% of regulatory limits, reflect minimal pesticide accumulation and compliance with international safety standards, attributable to factors such as moderate application practices, rapid degradation through microbial and photolytic processes, favourable soil conditions, and the limited environmental persistence of these organophosphate and herbicide compounds (Table 5).

Diversity of macro invertebrate species in the study areas

Table 6 shows a checklist of macro-invertebrate species assemblages of the study areas. A total of 365, 139 and 153 individual species belonging to 14, 13 and 10 Taxa from the studied sites were recorded, respectively. Species encountered included; Earthworm (*Lumbricina terrestris*), Ant (*Monomorium minimum*), Subterranean Termite (*Heterotermes species*), Millipede (*Eurymerodesmidae spp*), Giant centipede (*Scolopendra gigantea*), Crickets (*Gryllus assimillis*), Ground Beetle

Table 7. Diversity indices of macro fauna in the study site.

Variables	Low	Middle	Upper
Taxa_S	10	13	14
Individuals	153	139	365
Dominance	0.1977	0.235	0.5113
Simpson_1-D	0.8023	0.765	0.4887
Shannon_H	1.838	1.823	1.252
Evenness_e^H/S	0.6283	0.4763	0.2499
Brillouin	1.73	1.686	1.189
Menhinick	0.8085	1.103	0.7328
Margalef	1.789	2.432	2.203
Equitability	0.7982	0.7108	0.4745
Fisher alpha	2.397	3.51	2.888
Berger-Parker	0.281	0.3885	0.7068
Total	174.27	165.13	389.69

Source: Field data, (2026).

Table 8. Mean separation of soil microorganism based on growth performance in the study area.

Site	Bacteria (cfu ⁻¹)	Fungi (cfu ⁻¹)	Actinomycetes (cfu ⁻¹)
High	33.0	40.4	14.8
Medium	54.8	50.6	126
Low	33	51.2	140
SE	8.03	9.48	18.7

Means with different letters(s) along the column are significantly different ($p \leq 0.05$) (**Source:** laboratory analysis, 2026).

(*Scaritinae clivinini*) Brown marmorated stink Bug (*Halyomorpha halys*), Spider (*Araneus angulatus*), Giant Snail (*Achatina fulina*), common centipede (*Scutigera coleoptrata*) and small snail (*Helix pomatia*).

Shannon-Wiener Diversity Index, Dominance, Evenness and Equitability index values of macro-invertebrate species for the studied sites are presented in Table 7. The values followed the order: Shannon-Wiener Diversity Index $1.383 > 1.823 > 1.252$, Dominance values $0.511 > 0.235 > 0.198$, Evenness values $0.628 > 0.476 > 0.249$, and Equitability index values were $0.798 > 0.710 > 0.474$, respectively.

Soil microorganisms (cfu⁻¹) in the study areas

The soil microbial analysis across the date palm plantation revealed the presence of diverse bacterial, fungal, and actinomycete species, including *Staphylococcus aureus*, *Escherichia coli*, *Bacillus subtilis*, *Aspergillus niger*, *Pseudomonas aeruginosa*, and various *Actinomyces* and *Streptomyces* species. Colony counts varied by site: at the high-growth site, bacteria ranged from $3.0\text{--}5.0 \times 10^4$ cfu/ml, fungi from $3.0\text{--}5.4 \times 10^4$ cfu/ml, and actinomycetes from

$9.0\text{--}19.0 \times 10^4$ cfu/ml; at the medium-growth site, bacteria ranged $3.8\text{--}6.8 \times 10^4$ cfu/ml, fungi $4.6\text{--}6.0 \times 10^4$ cfu/ml, and actinomycetes $6.0\text{--}21.0 \times 10^4$ cfu/ml; while at the low-growth site, bacteria ranged $3.0\text{--}4.5 \times 10^4$ cfu/ml, fungi $3.0\text{--}6.7 \times 10^4$ cfu/ml, and actinomycetes $9.0\text{--}18.0 \times 10^4$ cfu/ml. Table 8 shows variations in soil microbial populations among high-, medium-, and low-growth sites. Bacteria were highest at the medium-growth site (54.8 cfu⁻¹), while fungi (51.2 cfu⁻¹) and actinomycetes (140 cfu⁻¹) were highest at the low-growth site. The high-growth site recorded the lowest fungal (40.4 cfu⁻¹) and actinomycete (14.8 cfu⁻¹) populations, while bacterial abundance was lowest at both the high- and low-growth sites (33.0 cfu⁻¹). These variations may reflect differences in soil nutrients, organic matter, moisture, and other environmental conditions among the sites. Actinomycetes showed the greatest variability, as indicated by the highest standard error (18.7), compared with bacteria (8.03) and fungi (9.48). Overall, the results indicate that microbial abundance varied with date palm growth performance. The standard errors (SE) were 8.03 for bacteria, 9.48 for fungi, and 18.7 for actinomycetes, indicating greater variability in actinomycete counts among samples compared with bacteria and fungi.

DISCUSSION

Soil physicochemical properties and their influence on date palm growth

The physicochemical analysis revealed slightly acidic soils (pH 6.06–6.40) across all sites, which is optimal for date palm cultivation and nutrient availability. This result conformed with studies of Alebidi and Abdel-Sattar (2024). Total nitrogen was low (0.12–0.15%), with the upper site showing the highest value due to greater organic matter accumulation, indicating a need for nitrogen supplementation as observed by Okorie *et al.* (2024). Available phosphorus (9.23–11.23 mg kg⁻¹) and exchangeable calcium (3.56–5.47 cmol kg⁻¹) increased from low to upper sites, reflecting improved fertility at higher elevations, while potassium showed minimal variation (0.55–0.65 cmol kg⁻¹) and magnesium ranged from 1.84–2.42 cmol kg⁻¹, with the upper site recording the highest concentrations (Baidoo, 2024). Generally, the upper site exhibited superior nutrient status, indicating more favourable conditions for supporting vigorous date palm growth, consistent with observed growth performance differences among sites.

The soils across all sites consistently exhibited a sandy loam texture with sand content ranging from 67.20% to 70.24%, which promotes good drainage, adequate aeration, and favourable root penetration but also limits water retention and increases nutrient leaching susceptibility (Bhatt *et al.*, 2025). Bulk density (1.44–1.57 g cm⁻³) and particle density (2.50–2.61 g cm⁻³) indicated low to moderate compaction suitable for root development, while total porosity (41.20–43.40%) provided adequate pore spaces for air and water movement, as observed by Vani (2024). However, water-holding capacity was relatively low (10.93–11.28%) across all sites, reflecting the sandy nature of the soils and necessitating careful irrigation management, organic matter amendment, and mulching practices to maintain adequate moisture for optimal date palm growth (Zhang *et al.*, 2023).

GC-MS analysis revealed multiple pesticide residues in both leaf and soil samples, with chlorpyrifos (0.17 µg/kg) and dichlorvos (0.44 µg/kg) detected in leaves, and soil samples showing dichlorvos (0.20 µg/kg), chlorpyrifos (0.17 µg/kg), butachlor (0.16 µg/kg), cypermethrin (0.34 µg/kg) at 0–60 cm, and atrazine (0.08 mg/kg) and chlorpyrifos (0.30 µg/kg) at 61–90 cm depth, indicating significant downward mobility through infiltration (Li *et al.*, 2026). While the medium growth site complied with international regulatory standards (EPA SSL of 15,000 µg/kg for chlorpyrifos and EU-MRL of 100 µg/kg for dichlorvos), the low growth site showed exceedances for dichlorvos, butachlor, and atrazine against WHO/FAO limits, indicating over-application or slow degradation under semi-arid conditions. These studies conform with those of Njewa *et al.* (2023). The detection of pesticides at deeper soil layers raises serious concerns about

groundwater contamination, while the presence of cypermethrin in subsurface layers reflects its stability and limited biodegradation, collectively underscoring the urgent need for sustainable pest management practices, routine monitoring, and adoption of integrated pest management strategies (Kumar *et al.*, 2024; Zhang *et al.*, 2024).

The macro-invertebrate survey recorded 365 individuals at the high-growth site, 153 at the low site, and 139 at the medium site, representing 14, 13, and 10 taxa, respectively, with species including earthworms, ants, termites, millipedes, centipedes, crickets, ground beetles, and spiders; this result conformed with studies of Lavelle *et al.*, (2021). Diversity indices revealed that the medium site exhibited the highest Shannon-Wiener diversity ($H' = 1.823$) and species evenness ($J = 0.4763$), while the high site showed the greatest dominance (Berger-Parker = 0.7068) and the low site demonstrated the most equitable species distribution ($J = 0.6283$), consistent with the intermediate disturbance hypothesis; these results conform to those of Kumar *et al.* (2022). The presence of diverse functional groups including decomposers, predators, herbivores, and detritivores indicates that the plantation supports essential ecosystem services such as nutrient cycling, soil structure formation, and natural pest regulation, as observed by Decaëns *et al.* (2023).

The soil microbial analysis revealed diverse bacterial, fungal, and actinomycete species, including *Staphylococcus aureus*, *Escherichia coli*, *Bacillus subtilis*, *Aspergillus niger*, *Pseudomonas aeruginosa*, and various *Actinomyces* and *Streptomyces* species, with colony counts varying significantly across sites, as observed by Sadiqi *et al.* (2022). Statistical analysis (ANOVA, $p \leq 0.05$) confirmed significant differences in bacterial and actinomycete counts among sites but no significant variation in fungal counts, with the medium site showing the highest bacterial (54.8 cfu/ml) and fungal (50.6 cfu/ml) populations, while the low site exhibited the highest actinomycete count (140 cfu/ml), and the finding conformed with studies of Sadiqi *et al.* (2022) and Bai *et al.* (2024). The elevated actinomycete populations at the low site, where pesticide residues exceeded regulatory limits, suggest an adaptive enrichment of these organisms due to their metabolic versatility and xenobiotic-degrading capabilities (Sadiqi *et al.*, 2022), while the suppression of bacterial populations at the same site indicates greater sensitivity to pesticide contamination, highlighting the differential sensitivity of microbial groups and the potential role of fungi and actinomycetes in natural attenuation of pesticide residues (Jiang *et al.*, 2023).

The integrated assessment reveals a clear gradient in soil quality and ecosystem health across the three sites, with the upper site exhibiting superior nutrient status, favourable physical properties, lower pesticide contamination, and the presence of sensitive indicator species such as earthworms, representing the most favourable conditions for date palm growth and ecosystem

functioning as observed by Li *et al.* (2026). The medium site demonstrated intermediate conditions with compliance with pesticide regulatory standards, moderate nutrient availability, and the highest microbial and macro-invertebrate diversity, indicating that balanced management practices can maintain productivity while preserving ecosystem integrity. In contrast, the low site presented the most concerning scenario, with exceedance of regulatory limits for multiple pesticides, suppressed bacterial populations, elevated actinomycete counts, reduced macro-invertebrate species richness, and evidence of vertical pesticide migration, indicating significant environmental stress and potential risks to groundwater quality, nutrient cycling, and long-term soil sustainability that necessitate immediate intervention through integrated pest management, organic matter amendment, and regular monitoring; this finding conformed with studies of Silva *et al.* (2022).

The findings highlight the critical need for site-specific management approaches that account for spatial variability in soil fertility, pesticide contamination, and biological communities, as uniform recommendations are inadequate for addressing the diverse conditions across landscape positions in this agrisilvicultural system as described by Yadav *et al.* (2023). The exceedance of pesticide residue limits at the low site underscores deficiencies in current regulatory enforcement and monitoring programs, while the detection of multiple pesticide residues in both soil and leaves raises concerns about food safety, cumulative exposure effects, and potential groundwater contamination that require strengthened institutional capacity and adoption of the precautionary principle in pesticide regulation (Oliveira *et al.*, 2025). Policy recommendations include promoting integrated pest management, precision application techniques, organic amendments, buffer zones, regular soil and water quality monitoring, agroecological practices such as intercropping and cover cropping, and farmer education on safe pesticide handling, all of which are essential for achieving sustainable intensification and protecting environmental and human health in semi-arid agrisilvicultural systems, as observed in their studies (Kumar *et al.*, 2024; de Oliveira *et al.*, 2021).

Conclusion

This study revealed a clear gradient in soil quality, pesticide contamination, and biological community dynamics across landscape positions in the date palm agrisilvicultural system. The upper growth site exhibited the most favourable conditions with superior nutrient status, favourable physical properties, and lower pesticide contamination, supporting vigorous date palm growth and diverse biological communities. The medium growth site demonstrated intermediate conditions with compliance with international pesticide regulatory standards (chlorpyrifos $0.85 \mu\text{g/kg} < \text{EPA SSL of } 15,000 \mu\text{g/kg}$;

dichlorvos $0.44 \mu\text{g/kg} < \text{EU-MRL of } 100 \mu\text{g/kg}$), the highest microbial populations, and greatest macro-invertebrate diversity (Shannon $H' = 1.823$), indicating that balanced management practices can maintain both productivity and ecosystem integrity. Similarly, the low growth site presented the most concerning scenario, with pesticide residues exceeding WHO/FAO limits for dichlorvos, butachlor, and atrazine, suppressed bacterial populations (33.0 cfu/ml), elevated actinomycete counts (140 cfu/ml), and reduced species richness, confirming that pesticide contamination and management intensity significantly affect soil faunal and microbial communities. The detection of pesticides at subsurface depths (61-90 cm) demonstrated significant downward mobility, posing risks to groundwater quality, while the spatial variability across sites underscores the need for site-specific management approaches. Generally, the findings emphasise the urgent need for integrated pest management, regular monitoring, and sustainable soil management practices to balance agricultural productivity with ecological sustainability in tropical agrisilvicultural systems.

Recommendations

1. Implement integrated nutrient management with organic amendments to enhance soil organic matter, water-holding capacity, and address low nitrogen levels across all sites.
2. Adopt integrated pest management (IPM) with precision application and routine monitoring to reduce contamination, particularly at the low site where dichlorvos, butachlor, and atrazine exceed regulatory limits.
3. Promote organic matter addition and biostimulation to enhance beneficial microbial populations while harnessing actinomycetes for natural pesticide degradation and restoring suppressed bacterial communities.
4. Implement conservation agriculture practices (cover cropping, mulching, reduced tillage) and vegetative buffer zones to protect and enhance macro-invertebrate diversity and ecosystem services.
5. Strengthen regulatory enforcement, establish farmer training programs, promote agroecological approaches, and conduct long-term monitoring to ensure compliance, protect human health, and maintain ecological integrity.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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