Biological and Biomedical Journal

Journal homepage: https://bbj.journals.ekb.eg

Influence of soil and water physicochemical parameters on the biodiversity of nematodes and soil microarthropods near drainage canals in El Beheira Governorate, Egypt

Aml I. Barakat[1], Mohamed F. Ageba*[,2]

[1]Zoology Department, Faculty of Science, Damanhur University, Egypt
[2]Zoology Department, Faculty of Science, Tanta University, Egypt

ARTICLE INFO

Received:25/6/2025
Revised: 7/8/2025
Accepted:27/8/2025

***Corresponding author:**
Mohamed F. Ageba, Ph.D
E-mail: mohamed.ageba@science.tanta.edu.eg
Mobile: 01013813701

P-ISSN: 2974-4334
E-ISSN: 2974-4342
DOI: 10.21608/BBJ.2025.407429.1121

ABSTRACT

The Nile Delta faces a critical challenge of environmental degradation due to the pollution of its soil and water from industrial and agricultural effluents. This study investigated the influence of soil and water physicochemical parameters, including heavy metal concentrations, on the biodiversity of nematodes and soil microarthropods near drainage canals in Egypt's El Beheira Governorate. Water and soil samples were collected from five sites in Kafr El-Dawar, El Delingat, Abo Hommos, El Mahmodia, and Nobaria and analyzed for macronutrients, pH, electric conductivity, and heavy metals (Zn, Cr, Al, Cd, Pb). The extracted nematode and microarthropod communities were identified and evaluated using diversity indices. The results revealed significant spatial variations in environmental conditions, with several water samples exceeding WHO/FAO safety limits for Cr, Cd, and Pb, while soil metal levels remained within safe thresholds. Multivariate analyses demonstrated that factors like salinity (EC, Na, Cl), pH, organic matter, and specific heavy metals were significant drivers of community structure. Sites with higher contamination, like Nobaria and El Mahmodia exhibited lower faunal diversity and dominance by tolerant species, while less polluted sites supported richer, more balanced communities. The findings conclusively demonstrate that nematode and microarthropod communities are highly sensitive bioindicators, effectively reflecting anthropogenic pollution stress and providing a valuable tool for monitoring ecological health in agricultural drainage ecosystems.

Keywords: Bioindicators, Drainage canals, Egypt, Heavy metals, Microarthropods, Nematode diversity, Oribatid mites, Soil and water quality.

1. Introduction

Ecosystem services are essential for maintaining soil and water quality, improving soil structure, enhancing water retention, facilitating nutrient cycling, suppressing pests and diseases, and promoting beneficial biodiversity. These services are tightly linked to soil health, which in turn influences plant productivity, animal health, and environmental sustainability (Melakeberhan et al., 2021). However, maintaining these services becomes increasingly difficult in the face of pollution and land degradation, especially in intensively used agricultural areas.

Soil is part of the dynamic, living, natural terrestrial ecosystem. In practical terms, soil consists of four major components: mineral materials, organic matter, water, and air. Soil health is a complex attribute encompassing physical, chemical, and biological components to sustain plant output, maintain animal health, and enhance air and water quality, representing a rapidly growing field of study (Saraswathi et al., 2021). Among these, biological health is the least understood due to the limited development and application of reliable biological indicators. While chemical and physical measures are commonly used, there is growing interest in developing sensitive and integrative biological indicators that reflect ecosystem functioning, particularly the roles played by soil microbiota and fauna (Bünemann et al., 2018).

Soil organic matter (SOM) is one of the most important indicators of soil quality. It influences many soil properties, including nutrient supply, cation exchange capacity, adsorption of pollutants, infiltration and retention of water, soil structure, and soil color, most of which in turn affect soil temperature. SOM consists of microbial cells, plant and animal residues at various stages of decomposition, is a major consistent of soil C pools, and has a major implication on soil physical and chemical properties (Bashir et al., 2021). Water quality is equally critical to ecosystem stability. Defined by its physical, chemical, and biological characteristics, water quality determines the suitability of freshwater ecosystems for both human use and aquatic life. Rivers are essential and fragile freshwater ecosystems crucial for the maintenance of all living forms. Rivers are streams of significant strategic importance globally, serving as primary water supplies (He et al., 2021).

In Egypt, the deterioration of water quality, especially in the Nile River and its associated drainage canals, poses a significant environmental and public health concern. Despite regulatory efforts by the Egyptian Environmental Affairs Agency (EEAA), pollution persists due to the discharge of untreated or inadequately treated industrial and domestic wastewater, pesticide and fertilizer runoff, and increasing urbanization. These contaminants negatively impact the river and drainage ecosystems by altering species growth rates and disrupting the food chain or public health (Sarhan, 2021). The severity of water quality issues in Egypt differs across various water bodies, influenced by population density, industrialization, sanitation system availability, and the prevailing social and economic situations around the water source and soil. The release of untreated or inadequately treated industrial and household wastewater, the leaching of pesticides and fertilizer residues, and navigation frequently influence water quality (El-Zeiny, 2022).

Toxic chemicals such as heavy metals and organic micropollutants primarily adhere to suspended materials, with a significant portion accumulating in sludge inside aquatic ecosystems, where their concentration escalates through biomagnification. Consequently, this may result in the pollution of surface and groundwater, as well as soil in proximity to these resources (Singh et al., 2021). Heavy metals are regarded as a primary source of environmental contamination due to their substantial impact on ecological quality. The primary causes of heavy metal contamination in the environment are anthropogenic activities, including fossil fuel burning, mining operations, industrial wastewater discharges, and waste disposal (Ali et al., 2021). Elevated concentrations of heavy metals in sediments and soils can migrate to the aquatic environment, groundwater, and vegetation via transfer mechanisms, ultimately affecting animals and people. Consequently, the utilization of straightforward and precise techniques for detecting heavy metals has significant relevance in environmental investigations (Chen et al., 2021).

Soil fauna, particularly nematodes, are key indicators of ecosystem health. These abundant, non-segmented worm-like invertebrates are sensitive to changes in soil and water quality, and their diversity and roles in nutrient cycling make them valuable bioindicators (Melakeberhan et al., 2021). Nematodes are grouped into trophic guilds, including bacterivores, fungivores, plant parasites, predators, and omnivores, each reflecting specific ecological niches and contributing to nutrient cycling and maintaining healthy soils. Change in nematode population dynamics is an excellent indicator of changes in soil and global ecosystems. Soil nematodes are numerous; their many morphological species can be readily distinguished, they are relatively immobile, and they play a significant role in ecosystem functions (Ramteke et al., 2024). Similarly, soil mesofauna such as Acari (oribatid mites) and Collembola (springtails) play essential roles in decomposition, nutrient cycling, and soil structure maintenance. Their abundance and diversity respond to soil pollution and management practices, making them reliable indicators of ecological disturbance (Lü et al., 2023).

In El-Beheira Governorate of Egypt, water bodies, particularly those near industrial and agricultural zones, are experiencing significant pollution levels. For instance, Kafr El-Dawar, a major industrial city, discharges untreated wastewater directly into canals, affecting both aquatic and adjacent terrestrial environments (Fouda, 2021). The Mahmodia Canal also receives domestic and municipal waste, introducing pathogens and nutrients that further degrade water and soil quality (Abdelrazek and El Naka, 2022). These conditions pose serious risks to human health, agricultural productivity, irrigation, fisheries, and ecological balance (El-Degwy et al., 2023). Given these environmental concerns, the current study aims to evaluate the influence of selected physicochemical parameters of soil and water on the diversity and distribution of nematodes and soil microarthropods across five drainage canal sites in El Beheira Governorate. By identifying key environmental factors affecting soil fauna communities, the research seeks to contribute to the development of effective biological indicators for monitoring ecosystem health in polluted agricultural landscapes.

2. Materials and Methods

Sampling sites

Soil and water samples were collected from five locations within El-Beheira Governorate, Egypt: Kafr El-Dawar, El Delingat, Abo Hommos, El Mahmodia, and Nobaria in January 2025 (Figure 1). Site selection was based on the distribution of vegetation physiognomy and the presence of industrial activities along the governorate. Sampling was conducted during the dry winter season in January, when the average temperature was approximately 20°C. All samples were collected once from each location for subsequent physical and chemical analysis. At each site, three soil cores were collected as replicates within each quadrat. Sampling coordinates were as follows: El Delengat (N°30.827, E°30.535), Abu Hummus (N° 30.311, E°31.097), El Mahmoudia, N° 30.5245, E°31.1835, Kafr El Dawwar (N° 30.1297, E° 31.1338), Nobaria (N° 30.5833, E° 30.1667)

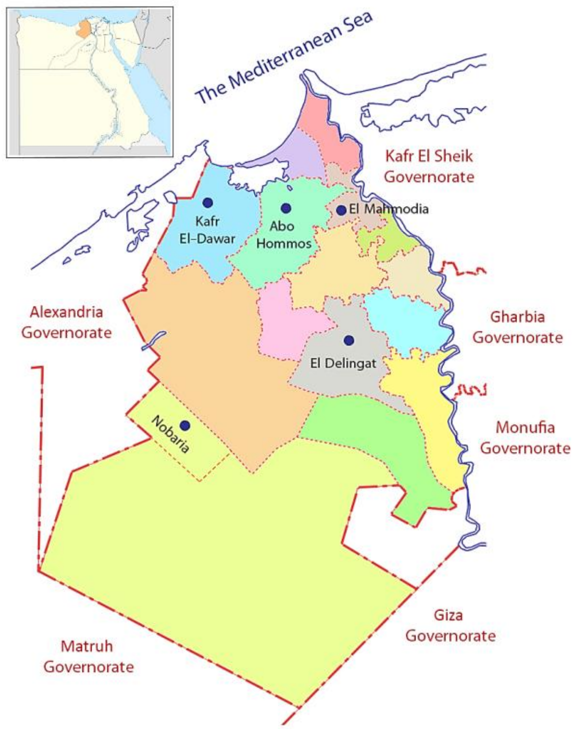

Figure 1. Map of the study sites in El-Beheira Governorate, Egypt

Soil sample collection and preparation for physicochemical analysis.

Soil samples were collected from a depth of 10–30 cm using a screw auger from both the left and right sides of alfalfa fields (*Medicago sativa*). Surface debris was removed before collection. Samples were randomly collected following a zigzag pattern, with subsampling points spaced 1.0 m apart to ensure representation. From each site, five subsamples spaced 10 m apart were taken and combined to obtain a representative composite sample with uniform composition (Even et al., 2025). Collected samples were air-dried in the shade and then further dried in an oven at 70°C at the Directorate of Agriculture Rural Development Laboratory, Damanhour, El-Beheira Governorate. The dried soil was crushed using a wooden roller, passed through a 2 mm stainless steel sieve, and stored in clean polyethylene bags. Samples were kept in an ice-box during transport to the laboratory for physical and chemical analyses.

Soil digestion procedure

To prepare soil samples for physicochemical analysis, acid digestion was conducted following the U.S. Environmental Protection Agency (EPA) Method 3050B (Güven and Akıncı, 2011). One gram of air-dried soil was placed in a 250 ml glass digestion flask and heated to 95°C. Concentrated nitric acid was added without boiling. After cooling, the sample was refluxed with repeated additions of 65% nitric acid until the brown fumes subsided, and the volume was reduced to approximately 5 ml by evaporation. After cooling, 10 ml of 30% hydrogen peroxide was added gradually to avoid sample loss. The mixture was then refluxed with 10 ml of 37% hydrochloric acid at 95°C for 15 minutes. The resulting solution was filtered through a 0.45 µm filter paper, diluted to 100 ml with deionized water, and stored at 40°C until further analysis.

Water sample collection and preparation

Water samples were collected from various surface water bodies across El-Beheira Governorate using a 50 cm stainless steel sampler. Clean polyethylene bottles (500 ml) were pre-acidified with 2 ml of 10% HNO_3 to prevent microbial activity. In total, 25 water samples were collected, labeled, and transported under refrigerated conditions at 4°C. Before analysis, all samples were filtered using Whatman No. 42 filter paper in accordance with APHA guidelines (Banerjee and Prasad, 2020).

Determination of pH and electric conductivity in soil and water samples

The pH of each sample was measured in 2 ml of soil extract or water. The sample was shaken and allowed to stand for 30 minutes before inserting the electrode of a calibrated pH meter (Model 181, Serial No. 0708149, UK) into the supernatant to record the pH (Abdelrazek and El Naka, 2022). EC was measured using a conductivity meter equipped with an EC probe. Readings were taken electronically, and the mean of three measurements was recorded for each sample (Abdelrazek and El Naka, 2022).

Determination of macronutrients in soil and water samples

Macronutrients, including calcium (Ca) and sodium (Na) were determined using a flame photometer (FP902, Model 1382, S/N 1208037). Calcium was detected at a wavelength of 622 nm, and sodium at 589 nm, following standard calibration procedures (Gupta, 2007).

Determination of Potassium (K) in soil and water samples

Potassium was determined using a flame photometric method. Soil and water samples were extracted using a neutral 1.0 N ammonium acetate solution. The extracting solution was prepared by adding 58 ml of glacial acetic acid to 600 ml of distilled water, followed by 70 ml of concentrated ammonia. The pH was adjusted to 7.0. A standard potassium solution was prepared by dissolving 1.9 g of potassium chloride in distilled water. Potassium content was measured by flame photometer after proper calibration (Ullah et al., 2022).

Determination of sulphate in soil and water samples

For sulfate (SO_4^{-2}) analysis, 10 ml of soil extract or water sample was transferred into a conical flask. The pH was adjusted to mildly acidic using concentrated HCl, and the solution was heated to boiling. Barium chloride solution (N/4) was added dropwise until sulfate precipitation was complete and a slight excess remained. The solution was then neutralized using ammonium hydroxide, and the excess barium chloride was titrated with potassium chromate (N/4) as the titrant. If necessary, silver nitrate was used as an external indicator to confirm the endpoint (Pillai et al., 2007).

Determination of nitrogen in soil and water samples

The Kjeldahl method (digestion-distillation-titration) was used to determine the ammonium (NH_4^+) (Sáez-Plaza et al., 2013).

Determination of phosphorus in soil and water samples

Available phosphorus in soil samples was determined using the sodium bicarbonate extraction method (pH 8.5). A 5 cm³ soil sample was extracted with 100 cm³ of 0.5 M sodium bicarbonate along with 3 g of activated charcoal. The mixture was shaken for 30 minutes and then filtered. The filtrate (5 ml) was treated with 5 N sulfuric acid and ascorbic acid for colorimetric analysis. For water samples, phosphorus was determined through acid digestion followed by colorimetric determination. The method involved simultaneous oxidation and hydrolysis of meta-, pyro, and organic phosphates to orthophosphate in an acidic medium (D'Angelo et al., 2001).

Determination of bicarbonates in soil and water samples

Bicarbonate (HCO_3^-) concentration was quantified by titrating a 10 ml aliquot of soil extract or water sample with 0.01 N hydrochloric acid (HCl) using methyl orange as an indicator. The endpoint was indicated by a color change to light brown (Moursy et al., 2022).

Determination of soil organic matter

Soil organic matter (SOM) was determined using the Walkley-Black wet oxidation method. One gram of air-dried soil sample was weighed into a 500 ml conical flask and mixed with 1.0 ml of 1.0 N $K_2C_2O_7$ and concentrated H_2SO_4 containing Ag_2SO_4. The mixture was left to stand for 30 minutes, then diluted with 200 mL of NaF and 2 mL of diphenylamine. The solution was titrated until a brilliant green color appeared. A blank solution without soil was run simultaneously (Tabatabai, 1996).

Heavy metals analysis in soil and water samples

Concentrations of heavy metals; zinc (Zn), chromium (Cr), aluminum (Al), cadmium (Cd), and lead (Pb), in soil extracts and water samples were analyzed using an atomic absorption spectrophotometer (GCB-Avanta). The average values from three replicates were recorded for each determination (Gbaa et al., 2023).

Examination of nematodes in soil samples

Nematodes were extracted using a combination of elutriation and centrifugal sugar flotation techniques, following the method described by Martin et al. (2022). Soil samples were first processed through an elutriator to separate nematodes from soil particles. The resulting suspension was subjected to centrifugal flotation using a sugar solution to concentrate the nematodes in the supernatant. Nematode abundance was quantified by counting individuals under a dissecting microscope at 50× magnification. All observed nematodes were classified as either free-living or plant-pathogenic.

Examination of microarthropods in soil samples

Soil samples for microarthropod analysis were collected using a metal core sampler (10 cm × 10 cm). Microarthropods were extracted over 5 days using a modified Berlese-Tullgren funnel equipped with a 1.0 mm mesh. Specimens were collected into vials containing 70% ethanol. Adult oribatid mites were cleared in 70% lactic acid before identification. Species-level identification was conducted using the keys of Balogh and Mahunka (1983), Balogh and Balogh (1992), and the checklist of Egyptian oribatids by Al-Assiuty and Khalil (1991).

Statistical analysis

Descriptive statistics (mean ± standard deviation) were calculated for physicochemical parameters and biological data across the five sampling sites. One-way analysis of variance (ANOVA) was applied to test for significant differences in soil and water parameters. Post hoc comparisons were conducted using Tukey's HSD test to identify pairwise differences at a significance level of $p < 0.05$.

Biodiversity indices for nematodes and oribatid mites, including Shannon-Wiener diversity (H'), Simpson's index (1-D), dominance (D), evenness (e^H/S), and equitability (J), were calculated using PAST software. Multivariate relationships between species abundance and environmental parameters were explored using Canonical Correspondence Analysis (CCA). This method allowed identification of the environmental gradients that most strongly influenced nematode and mite assemblages. Hierarchical cluster analysis (Bray-Curtis similarity index) was also used to assess similarities in community composition across sites. All data were tested for normality and homogeneity of variances before conducting parametric analyses. All statistical analyses were performed using IBM SPSS Statistics version 27 and PAST version 4.03.

Ethical clearance

Ethical clearance was obtained from the Ethics Committee of the Faculty of Science, Damanhur University (License Code: DMU-SCI-CSRE-25-01-08).

3. Results

Physicochemical properties of water samples

One-way ANOVA revealed significant spatial variation in heavy metals and physicochemical parameters among the study sites ($p < 0.05$). The most pronounced differences were observed in EC ($F = 584.12$, $p < 0.001$) and sodium concentrations ($F = 559.80$, $p < 0.001$) (Table 1). Abo Hommos samples recorded the highest EC (644 ± 10 ppm), followed by El Delingat samples (515.67 ± 7.09 ppm), while samples collected from El Mahmodia showed the lowest EC (220 ± 11.27 ppm). Nobaria samples recorded the highest concentrations of Na (522 ± 18.2 ppm), Mg (48 ± 6.56 ppm), Ca (58.67 ± 6.43 ppm), SO_4 (44.67 ± 4.51 ppm), P (1.87 ± 0.11 ppm), and N/NH_4^+ (89.67 ± 1.53 ppm).

In contrast, Abo Hommos samples had the lowest Na (132.33 ± 10.5 ppm) and P (0.74 ± 0.14 ppm), but the highest K (54.67 ± 3.51 ppm) and pH (8.22 ± 0.12). Kafr El-Dawar samples generally showed lower values across most parameters (e.g., Mg: 14.4 ± 0.7 ppm; Cl: 70.67 ± 4.51 ppm), whereas El Delingat samples were characterized by elevated Cl (91.87 ± 1.6 ppm) and Na (383.33 ± 6.03 ppm).

All measured parameters varied significantly among the sites ($p < 0.007$), and post hoc comparisons (denoted by superscript letters in Table 1) revealed distinct groupings among locations.

Table 1. Average values of physical and chemical parameters of water samples from the studied sites.

Parameters	Study sites					ANOVA	
	Kafr El-Dawar	El Delingat	Abo Hommos	El- Mahmodia	Nobaria	F-value	*p*-value
pH	7.57 ± 0.21^{b}	7.32 ± 0.19^{b}	8.22 ± 0.12^{a}	$7.67 \pm 0.25^{a,b}$	8.13 ± 0.25^{a}	10.03	0.002
EC dS/m	412.33 ± 8.74^{c}	515.67 ± 7.09^{b}	644 ± 10^{a}	220 ± 11.27^{e}	334 ± 18.2^{d}	584.12	< 0.001
Na (ppm)	247 ± 6.24^{c}	383.33 ± 6.03^{c}	132.33 ± 10.5^{e}	422.67 ± 10.5^{b}	522 ± 18.2^{a}	559.80	< 0.001
K (ppm)	$42 \pm 3^{b,c}$	43 ± 2^{b}	54.67 ± 3.51^{a}	35.33 ± 2.08^{c}	43 ± 2^{b}	21.62	< 0.001
Mg (ppm)	14.4 ± 0.7^{c}	22 ± 3^{c}	36 ± 6.08^{b}	13.33 ± 1.53^{c}	48 ± 6.56^{a}	36.44	< 0.001
Ca (ppm)	$33.67 \pm 2.08^{c,d}$	$41.67 \pm 2.08^{b,c}$	25.67 ± 4.73^{d}	$52 \pm 2.65^{a,b}$	58.67 ± 6.43^{a}	33.73	< 0.001
Cl (ppm)	70.67 ± 4.51^{c}	91.87 ± 1.6^{a}	$82 \pm 5.29^{a,b}$	$74 \pm 3^{b,c}$	84.33 ± 3.51^{a}	14.80	< 0.001
HCO_3^- (ppm)	$186.67 \pm 9.07^{a,b}$	$183.67 \pm 7.02^{a,b}$	154.67 ± 8.14^{c}	$167 \pm 9.17^{b,c}$	203.33 ± 6.81^{a}	16.09	< 0.001
SO_4^{2-} (ppm)	24 ± 2^{b}	27.17 ± 1.04^{b}	23.33 ± 3.21^{b}	23.67 ± 2.08^{b}	44.67 ± 4.51^{a}	31.19	< 0.001
P (ppm)	1.21 ± 0.04^{b}	1.13 ± 0.09^{b}	0.74 ± 0.14^{c}	1.3 ± 0.07^{b}	1.87 ± 0.11^{a}	53.90	< 0.001
N/NH_4^+ (ppm)	69.33 ± 3.06^{b}	69.67 ± 1.53^{b}	74 ± 11.36^{b}	73 ± 3.61^{b}	89.67 ± 1.53^{a}	6.74	0.007

Data presented as Mean ± SD. F-value = value of one-way ANOVA test, p-value < 0.001 is considered highly significant. Means that do not share the same letter are significantly different (Tukey's test, $p < 0.05$)

Physicochemical Properties of Soil Samples

Table (2 summarizes the physicochemical properties of soil samples collected from five sites. The results showed highly significant spatial variability (one-way ANOVA, $p < 0.05$). EC and Na showed the most substantial differences among sites, with extremely high F-values (EC: $F = 8995.3$; Na: $F = 4407.38$; both $p < 0.001$). El Delingat site recorded the highest values for EC (1889 ± 10.6 ppm), Na (1811.7 ± 11 ppm), and nitrogen/ammonium (N/NH_4^+: 488.33 ± 11.59 ppm). In contrast, Nobaria samples exhibited the lowest levels of EC (221.7 ± 17.9 ppm), Na (214 ± 7.81 ppm), Cl (102 ± 3.61 ppm), and SO_4 (21.33 ± 2.52 ppm). The Abo Hommos site showed the highest K concentration (84.07 ± 2.69 ppm) but the lowest HCO_3 (58.33 ± 3.06 ppm). El Mahmodia site had the highest concentrations of Ca (121.67 ± 11.6 ppm), Mg (46 ± 4.36 ppm), and SOM (7.53 ± 0.57%). All measured parameters varied significantly among the study sites ($p < 0.02$), and post hoc comparisons in Table (2) confirmed statistically distinct groupings.

Table 2. Average values of physical and chemical parameters of soil samples from the studied sites.

Parameters	Study sites					ANOVA	
	Kafr El-Dawar	**El Delingat**	**Abo Hommos**	**El- Mahmodia**	**Nobaria**	**F-value**	***p*-value**
pH	8.66 ± 0.11 ^{a}	8.31 ± 0.12 ^{a,b}	8.07 ± 0.06 ^{b}	8.4 ± 0.27 ^{a,b}	8.63 ± 0.12 ^{a}	7.8	0.004
pH	1277.3 ± 9.29 ^{c}	1889 ± 10.6 ^{a}	817.33 ± 16.0 ^{d}	1747 ± 3 ^{b}	221.7 ± 17.9 ^{e}	8995.3	< 0.001
EC dS/m	1739 ± 35.8 ^{b}	1811.7 ± 11 ^{a}	219.33 ± 15.8 ^{d}	1549.7 ± 23.8 ^{c}	214 ± 7.81 ^{d}	4407.38	< 0.001
Na (ppm)	48.67 ± 1.53 ^{c}	25.27 ± 2.26 ^{e}	84.07 ± 2.69 ^{a}	75.67 ± 4.16 ^{b}	36.57 ± 0.93 ^{d}	289.00	< 0.001
K (ppm)	9.2 ± 0.4 ^{c}	44.33 ± 4.04 ^{a}	33.67 ± 2.08 ^{b}	46 ± 4.36 ^{a}	13.33 ± 1.53 ^{c}	105.22	< 0.001
Mg (ppm)	23.67 ± 0.58 ^{c}	79.33 ± 2.08 ^{b}	94.33 ± 6.03 ^{b}	121.67 ± 11.6 ^{a}	20 ± 2 ^{c}	166.68	< 0.001
Ca (ppm)	492 ± 4.36 ^{b}	518.67 ± 16.26 ^{a}	140 ± 6.24 ^{c}	492.33 ± 4.51 ^{b}	102 ± 3.61 ^{d}	1839.54	< 0.001
Cl (ppm)	127.67 ± 6.03 ^{a}	110 ± 5 ^{b}	58.33 ± 3.06 ^{c}	128.33 ± 6.03 ^{a}	122 ± 3 ^{a,b}	111.82	< 0.001
HCO_3^- (ppm)	92.33 ± 3.21 ^{a}	92.67 ± 3.79 ^{a}	42 ± 7.94 ^{c}	62.67 ± 3.79 ^{b}	21.33 ± 2.52 ^{d}	135.50	< 0.001
SO_4^{2-} (ppm)	1.46 ± 0.15 ^{b}	1.79 ± 0.22 ^{a,b}	2.06 ± 0.12 ^{a}	1.65 ± 0.27 ^{a,b}	1.5 ± 0.17 ^{b}	4.80	0.020
P (ppm)	108.67 ± 10.02 ^{b}	488.33 ± 11.59 ^{a}	105 ± 6 ^{b}	101.67 ± 3.06 ^{b}	91.33 ± 3.51 ^{b}	1536.46	< 0.001
SOM	1.32 ± 0.09 ^{c}	3.2 ± 0.31 ^{b}	1.06 ± 0.12 ^{c}	7.53 ± 0.57 ^{a}	3.03 ± 0.25 ^{b}	201.10	< 0.001

Data represented as Mean ± SD. F-value = value of one-way ANOVA test, *p*-value < 0.001 is considered highly significant. Means that do not share the same letter are significantly different (Tukey's test, $p < 0.05$)

Heavy metal concentrations in water samples

The results, presented in Table (3), indicate statistically significant variation across all sites for each metal ($p < 0.001$). For context, the table also includes the permissible limits for each metal based on the World Health Organization/Food and Agriculture Organization (WHO/FAO) and the Egyptian Code of Practice (ECP) standards.

Zinc concentrations were highest in Kafr El-Dawar (0.36 ± 0.007 mg/l) and El Delingat (0.35 ± 0.003 mg/l), while the lowest concentration was recorded in Abo Hommos (0.11 ± 0.02 mg/l). Despite these variations, Zn levels across all sites remained well below the permissible threshold of 2.0 mg/l. In contrast, chromium concentrations exceeded permissible limits in El-Mahmodia (0.36 ± 0.01 mg/l), significantly surpassing the WHO/FAO and ECP limit of 0.1 mg/l. Other sites exhibited lower Cr values ranging from 0.12 to 0.14 mg/l.

Aluminum concentrations were notably elevated in Nobaria (9.6 ± 0.8 mg/l), exceeding the recommended limit of 5.0 mg/l. A relatively high concentration was also observed in El-Mahmodia (4.60 ± 1.6 mg/l), while AH and El Delingat recorded the lowest Al levels. Cadmium concentrations were greatest in Kafr El-Dawar (0.40 ± 0.001 mg/l), followed by El- Mahmodia (0.34 ± 0.006 mg/l) and Nobaria (0.30 ± 0.001 mg/l). These values substantially exceeded the WHO/FAO and ECP permissible limit of 0.01 mg/l in all sites except Abo Hommos and El Delingat.

Lead concentrations were highest in El Delingat (6.62 ± 0.1 mg/l), exceeding both the WHO/FAO limit of 5.0 mg/l and the much stricter ECP limit of 0.1 mg/l. Similarly, Kafr El-Dawar recorded a high Pb concentration of 5.31 ± 0.1 mg/l. The lowest concentrations were observed in Abo Hommos and El- Mahmodia. These findings raise concern about potential ecological and health risks due to elevated Pb levels in surface waters at these sites.

In summary, the water quality analysis revealed exceedances of international safety limits for chromium, cadmium, and lead at several sites. El Mahmodia sites exhibited critically high Cr concentrations, Nobaria site showed excessive Al levels, and both El Mahmodia and Kafr El-Dawar sites demonstrated significantly elevated Pb levels. These results suggest localized contamination sources and warrant further investigation into the environmental and anthropogenic factors driving heavy metal pollution.

Table 3. Average concentration of heavy metals in water samples from the five studied sites

Site	Zn (mg/l)	Cr (mg/l)	Al (mg/l)	Cd (mg/l)	Pb (mg/l)
Kafr El-Dawar	0.36 ± 0.007[a]	0.14 ± 0.01[b]	2.66 ± 0.6 [b,c]	0.40 ± 0.001[a]	5.31 ± 0.1[b]
El Delingat	0.35 ± 0.003 [a]	0.14 ± 0.004[b]	1.53 ± 0.16[c]	0.16 ± 0.006[d]	6.62 ± 0.1[a]
Abo Hommos	0.11 ± 0.02[c]	0.13 ± 0.01[b]	1.28 ± 0.18[c]	0.14 ± 0.004[d]	2.68 ± 0.3[d]
El Mahmodia	0.25 ± 0.01[b]	0.36 ± 0.01[a]	4.60 ± 1.6[b]	0.34 ± 0.006[b]	2.33 ± 0.008[d]
Nobaria	0.23 ± 0.002[b]	0.12 ± 0.002[b]	9.6 ± 0.8 [a]	0.30 ± 0.0011[c]	4.34 ± 0.3[c]
F-value	277.6	488.44	48.7	396.3	241.8
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
WHO/FAO*	2.0	0.1	5	0.01	5
ECP**	2.0	0.1	-	0.01	0.1

Data represented as Mean ± SD. *Ayers & Westcot (1994). FAO: Food and Agriculture Organization of the United Nations. **Egyptian Code of Practice for the Safe Agricultural Use of Treated Municipal Wastewater (ECP 501-2015). F-value of one-way ANOVA test, p-value < 0.001 is considered highly significant. Means that do not share the same letter are significantly different (Tukey's test, $p < 0.05$)

Heavy metal concentrations in the soil samples

Table (4) summarizes the average concentrations of the same heavy metals (Zn, Cr, Al, Cd, and Pb) in soil samples from the study sites. Similar to the water samples, all measured metals showed statistically significant differences across the sites (p < 0.001). However, in contrast to the water samples, all soil metal concentrations were below the permissible thresholds established by WHO/FAO and ECP guidelines, indicating minimal immediate risk from heavy metal contamination in the soils.

Zinc concentrations were highest in Kafr El-Dawar (0.76 ± 0.04 mg/kg) and lowest in El Mahmodia (0.13 ± 0.03 mg/kg), well below the maximum allowable limit of 300 mg/kg. Chromium concentrations were most elevated in Nobaria (0.78 ± 0.01 mg/kg), while other sites reported lower values. All sites remained well under the permissible Cr threshold of 100 mg/kg. The highest aluminum concentration was recorded in El Mahmodia (8.35 ± 1.3 mg/kg), followed by KD (5.58 ± 0.2 mg/kg), with Nobaria registering the lowest value (3.38 ± 0.18 mg/kg). Cadmium concentrations were highest in Kafr El-Dawar (0.19 ± 0.009 mg/kg), although all values across the study sites were markedly below the WHO/FAO and ECP threshold of 3 mg/kg. Lead concentrations were highest in El Mahmodia (6.82 ± 0.1 mg/kg) and El Delingat (5.60 ± 0.2 mg/kg), while the lowest concentrations were found in Kafr El-Dawar and Abo Hommos. All Pb concentrations remained far below the regulatory limits, which range from 100 to 300 mg/kg.

Table 4. Average concentration of heavy metals in soil samples from the five studied sites.

Site	Zn (mg/kg)	Cr (mg/kg)	Al (mg/kg)	Cd (mg/kg)	Pb (mg/kg)
Kafr El-Dawar	0.76 ± 0.04 [a]	0.29 ± 0.005 [b]	5.58 ± 0.2 [b]	0.19 ± 0.009 [a]	3.23 ± 0.2 [d]
El Delingat	0.13 ± 0.03 [d]	0.22 ± 0.017 [c]	4.31 ± 0.8 [b,c]	0.15 ± 0.01 [b]	5.60 ± 0.2 [b]
Abo Hommos	0.41 ± 0.02 [c]	0.18 ± 0.02 [c]	4.68 ± 0.16 [b,c]	0.11 ± 0.002 [c]	3.17 ± 0.3 [d]
El Mahmodia	0.37 ± 0.04 [c]	0.19 ± 0.03 [c]	8.35 ±1.3 [a]	0.15 ± 0.008 [b]	6.82 ± 0.1 [a]
Nobaria	0.63 ± 0.01 [b]	0.78 ± 0.01 [a]	3.38 ± 0.18 [c]	0.12 ± 0.002 [c]	4.84 ± 0.17 [c]
F-value	194.35	806.84	22.28	58.10	176.3
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
WHO/FAO*	300	100	-	3	100
ECP**	300	100	-	3	100-300

Data represented as Mean ± SD. *Ayers & Westcot (1994). FAO: Food and Agriculture Organization of the United Nations. **Egyptian Code of Practice for the Safe Agricultural Use of Treated Municipal Wastewater (ECP 501-2015). F-value = value of one-way ANOVA test, p-value < 0.001 is considered highly significant. Means that do not share the same letter are significantly different (Tukey's test, $p < 0.05$)

Overall, the soil samples reflected generally safe levels of heavy metal accumulation. While concentrations varied spatially, likely influenced by site-specific factors such as irrigation practices, industrial proximity, and soil composition, they remained within acceptable environmental limits. This contrasts with the water samples, where multiple exceedances of heavy metal limits were observed. The differences between water and soil contamination levels underscore the importance of monitoring both environmental compartments when assessing ecosystem health and pollution risks.

Diversity of nematodes in the study sites

The results reveal distinct differences in the composition and abundance of nematode species among the study sites, suggesting that each location supports a unique nematode community. *M. javanica*, a root-knot nematode, was present at all sites, with the highest density recorded at Abo Hommos (85 ± 21.21 individuals), followed by Kafr El-Dawar (71 ± 8.49), while Nobaria and El Mahmodia showed very low levels (12.5 ± 14.85 and 16.5 ± 9.19, respectively). *A. buetschlii*, a free-living or facultative nematode, was completely absent from El Mahmodia but showed its highest abundance at Kafr El-Dawar (69.5 ± 13.44). Similarly, *C. emarginatus* was most abundant in Kafr El-Dawar (79 ± 12.73), nearly absent in El Delingat, and moderately present in Abo Hommos. Notably, *Ditylenchus destructor* was found only at Kafr El-Dawar and El Delingat, with no detection in the remaining sites (Table 5).

Lesion nematodes also varied in distribution: *P. penetrans* was most abundant in Abo Hommos (56.5 ± 28.99) and absent in Nobaria, while *P. vulnus* was most prominent in El Mahmodia (55 ± 7.07), indicating a clear species-specific pattern. *Nacobbus*, a nematode often associated with root galls, showed high populations in El Mahmodia (73 ± 4.24) and El Delingat (63.5 ± 13.44), but was absent from Abo Hommos and Nobaria (Table 5). The general *Pratylenchus* group was present at all sites but was particularly high in Nobaria (45 ± 15.56). Lastly, the free-living nematode *Caenorhabditis elegans* was found in low densities across all sites, with slightly elevated numbers in El Delingat (16 ± 8.49) and El Mahmodia (11 ± 8.49). These results underscore the spatial heterogeneity of nematode communities, likely shaped by environmental conditions, host plant presence, and soil properties at each location.

Multivariate analysis of nematode abundance in relation to environmental and heavy metal gradients

Figure (2) illustrates the results of a CCA biplot and the Bray-Curtis similarity hierarchical cluster dendrogram, which together reveal the relationship between nematode diversity and environmental variables across the study sites.

The analysis highlights clear associations between specific environmental factors and nematode distributions. Cr and Zn were found to influence nematode communities at Nobaria and El Delingat sites, while pH showed a strong association with Abo Hommos sites. EC, Na, Cl, and (SO_4^{2-}) were collectively associated with El Delingat and Kafr El-Dawar samples. Conversely, a separate group of variables—including HCO_3^-, P, Mg, Ca, Al, and N/$NH_4^+$was associated with El Mahmodia and Nobaria sites.

The distribution of nematode species further supports these environmental associations. *P. vulnus*and *A. buetschlii* were most closely aligned with Nobaria and El Delingat and were strongly influenced by Cr and Zn concentrations. *M. javanica* and *C. emarginatus* were linked to Kafr El-Dawar and El Delingat, primarily influenced by salinity-related factors such as EC, Na, Cl, and SO_4^{2-}. *D. destructor* appeared relatively isolated in the ordination space, suggesting it may be influenced by unmeasured factors or possesses a broad environmental tolerance. Other taxa such as *Nacobbus* spp. and *C. elegans* were associated with El Mahmodia and Nobaria, corresponding to higher concentrations of bicarbonate, nutrients, and metals. *P. penetrans* and *P. vulnus* occupied intermediate positions, indicating they may have broader ecological niches or respond to a combination of environmental factors.

The hierarchical cluster dendrogram revealed two distinct site clusters based on nematode community composition. El Mahmodia and El Delingat formed one closely related cluster, suggesting strong similarity in their nematode assemblages. A second cluster comprised Kafr El-Dawar and Abo Hommos sites, while Nobaria was more distinct but eventually grouped with this cluster at a lower similarity level. These patterns indicate that both environmental gradients and geographic proximity influence the structure and similarity of nematode communities. Sites with similar physicochemical properties tend to support more comparable nematode communities.

Table 5. List of nematode species, their abundance, and diversity from the five studied sites.

Species	Studied sites				
	Kafr El-Dawar	El Delingat	Abo Hommos	El- Mahmodia	Nobaria
Root-knot nematodes					
Meloidogyne javamica	71 ± 8.49	43.5 ± 13.44	85 ± 21.21	16.5 ± 9.19	12.5 ± 14.85
Acrobeloides buetsehlii	69.5 ± 13.44	52.5 ± 3.54	28 ± 7.07	0 ± 0	49.5 ± 21.92
Cephalenchus emarginatus	79 ± 12.73	1.5 ± 2.12	55.5 ± 20.51	4 ± 4.24	17 ± 8.49
Ditylenchus destructor	57 ± 2.83	17 ± 8.49	0 ± 0	0 ± 0	0 ± 0
Lesion nematode					
Pratylenchus penetrans	32.5 ± 14.85	38.5 ± 9.19	56.5 ± 28.99	28 ± 5.66	0 ± 0
Pratylenchus vulnus	19.5 ± 9.19	4.5 ± 6.36	27 ± 5.66	55 ± 7.07	24.5 ± 13.44
Nacobbus	22.5 ± 14.85	63.5 ± 13.44	0 ± 0	73 ± 4.24	0 ± 0
Pratylenchus	1 ± 1.41	17 ± 7.07	17 ± 8.49	14 ± 2.83	45 ± 15.56
Free living					
Caenorhabditis elegans	3 ± 1.41	16 ± 8.49	5.5 ± 0.71	11 ± 8.49	2 ± 2.83
Taxa (S)	9	9	7	7	6
Individuals	357	257	276	202	152
Dominance (D)	0.17	0.17	0.20	0.24	0.24
Simpson (1-D)	0.83	0.83	0.80	0.76	0.76
Shannon (H')	1.89	1.92	1.74	1.64	1.55
Evenness (e^H/S)	0.74	0.76	0.81	0.74	0.79
Equitability (J)	0.86	0.87	0.89	0.84	0.86

Data presented as Mean ± SD

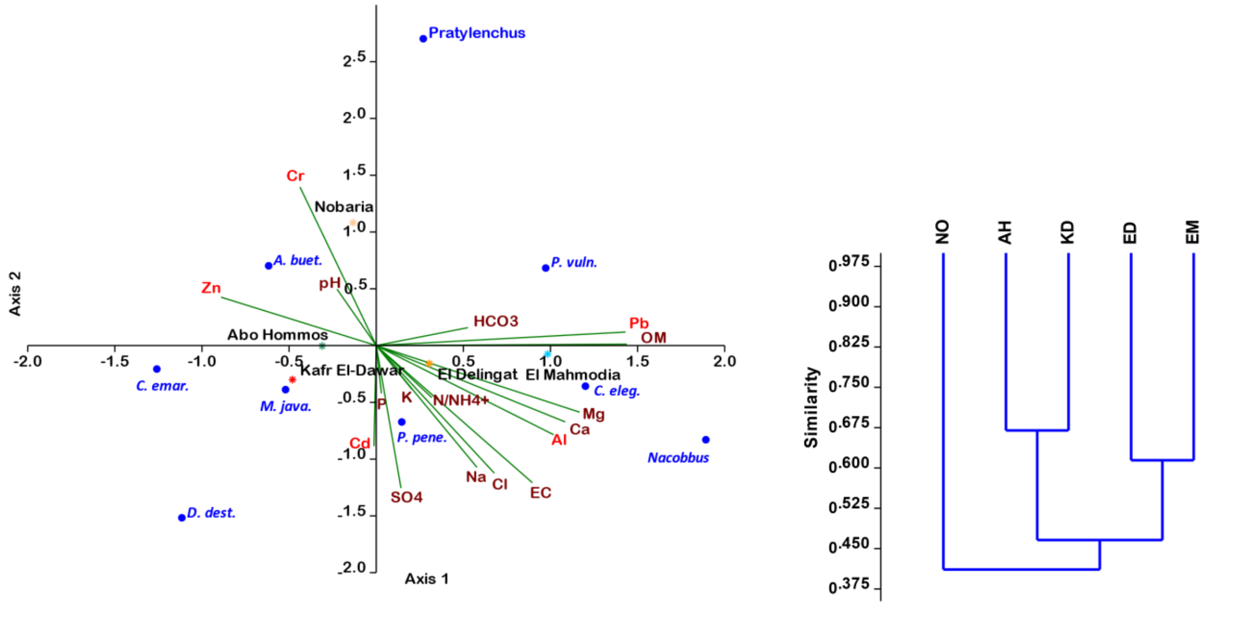

Figure 2. CCA Biplot and cluster dendrogram showing the relationship between nematode abundance, environmental variables, and heavy metals concentration across the five study sites.

Diversity and abundance of oribatid mites and other soil microarthropods in the studied sites

A total of 1572 individuals were collected across all locations, Nobaria site showed the highest abundance of individuals (1199), followed by site El Delingat site (226). In contrast, Abo Hommos, El Mahmodia, and Kafr El-Dawar sites had markedly lower populations, with 62, 51, and 4 individuals, respectively. The highest taxonomic richness (S) was recorded in El Delingat site with 9 taxa, while the lowest was in Kafr El-Dawar with only 4 taxa identified (Table 6).

Nobaria samples was characterized by extremely high dominance (D = 0.98) and consequently, very low diversity (Shannon H = 0.08) and equitability (J = 0.04). This was primarily due to the overwhelming abundance of a single species, *L. hispaniola*, which had a mean count of 237 ± 149.2 at this location. El Mahmodia site also showed high dominance (D = 0.85), with *A. aegyptica* being the most prevalent species (9.4 ± 4.74). Conversely, Kafr El-Dawar despite its low number of individuals, exhibited the highest diversity (Shannon H = 1.76) and perfect equitability (J = 1.00), indicating an even distribution of individuals among the few taxa present. El Delingat also showed moderate diversity (Shannon H = 0.98) and was numerically dominated by *S. laevigatus* (33.2 ± 22.2). In Abo Hommos sites, the community was largely dominated by *A. aegyptica* (10.4±3.67), resulting in high dominance (D = 0.71) and low diversity (Shannon H = 0.65).

Table 6. Relative abundance of oribatid mites and other soil fauna from the five studied sites.

species	Study sites				
	Kafr El-Dawar	**El Delingat**	**Abo Hommos**	**El-Mahmodia**	**Nobaria**
Family Epilohmanniidae					
Epilohmannia c. cylindrica	0.2 ± 0.2	0.4 ± 0.4	-	-	0.6 ± 0.4
Lohmanniidae					
Lohmannia hispaniola	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.2	-	237 ± 149.2
Lohmannia loebli	-	7 ± 4.14	-	-	-
Achipteriidae					
Anachipteria aegyptica	-	0.6 ± 0.24	10.4 ± 3.67	9.4 ± 4.74	0.2 ± 0.2
Malaconothridae					
Rhysotritia a. ardua	-	1.2 ± 0.58	-	-	-
Scheloribatidae					
Scheloribates laevigatus	-	33.2 ± 22.2	-	-	1 ± 0.63
Scheloribates pallidulus	-	-	1.2 ± 0.97	0.2 ± 0.2	0.6 ± 0.4
Scheloribates confundatus	-	-	-	0.2 ± 0.2	-
Galumnidae					
Galumna tarsipennata	-	1 ± 0.77	-	-	-
Oppiidae					
Oppia variance	-	0.8 ± 0.8	-	-	0.2 ± 0.2
Collembola	-	-	0.2 ± 0.2	-	-
Mesostigmata	-	0.8 ± 0.37	0.4 ± 0.24	-	0.2 ± 0.2
Prostigmata	0.2 ± 0.2	-	-	0.2 ± 0.2	-
Other Microarthropds	0.2 ± 0.2	-	-	0.2 ± 0.2	-
Taxa (S)	4	9	5	5	7
Individuals	4	226	62	51	1199
Dominance (D)	0.00	0.56	0.71	0.85	0.98
Simpson (1-D)	1.00	0.44	0.29	0.15	0.02
Shannon (H')	1.76	0.98	0.65	0.42	0.08
Evenness (e^H/S)	1.46	0.30	0.38	0.31	0.16
Equitability (J)	1.00	0.44	0.38	0.24	0.04

Data represented as mean ± SD

Multivariate analysis of oribatid mites abundance in relation to environmental and heavy metal gradients.

Figure (3) displays a CCA biplot and a corresponding dendrogram that summarize the distribution of microarthropod species in relation to environmental variables across the study sites. The biplot reveals clear environmental gradients influencing microarthropod community composition, similar to the nematode patterns. Environmental factors such as K, Al, P, Mg, and Ca were associated with El Delingat and Abo Hommos. EC, Pb, Na, and Ammonium (N/NH_4^+) also played a prominent role at ED. Meanwhile, HCO_3^-, Cd, Cr, and pH were more strongly associated with Kafr El-Dawar, while Zn and OM were key drivers in Nobaria and El Mahmodia sites.

Species-level associations were also evident. Several oribatid mites, including *L. loebli*, *G. tarsipennata*, *R. a. ardua*, *S. laevigatus*, and *O. varians*, were most strongly associated with El Delingat site, influenced by a broad range of soil parameters including metals and nutrients. *A. aegyptica* and *S. pallidulus* were linked to Abo Hommos and El Mahmodia sites, under the influence of OM and Zn. *E. cylindrica* was primarily found at Kafr El-Dawar samples, associated with HCO_3^-, Cd, Cr, and pH. In contrast, *L. hispaniola* showed a strong preference for Nobaria samples, associated with elevated OM and Zn. *S. confundatus* was relatively isolated in the ordination, suggesting its distribution is governed by factors not well represented in the current environmental dataset.

The dendrogram of site similarity based on microarthropod communities identified two main clusters. The first cluster included El Delingat and Kafr El-Dawar sites, indicating a high degree of similarity in species composition. The second cluster grouped Abo Hommos and El Mahmodia, with Nobaria sites again forming a distinct site but related sub-cluster. These findings reinforce the idea that environmental parameters, particularly soil chemical composition and organic matter content, play a critical role in structuring microarthropod communities across different habitats.

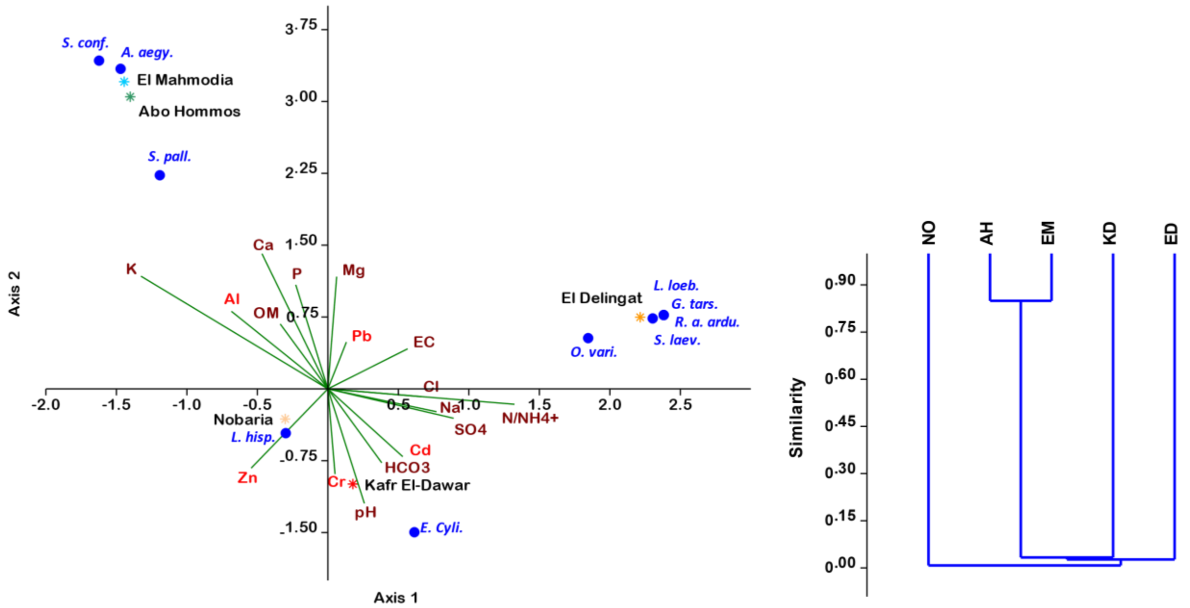

Figure 3. CCA Biplot and cluster dendrogram showing the relationship between oribatid mites' abundance, environmental variables, and heavy metals concentrations across the study sites

4. Discussion

The present study revealed significant variations in the physicochemical properties of both water and soil across the five drainage canal sites in El Beheira Governorate, Egypt. These variations are crucial as environmental factors, particularly water and soil characteristics, are known to exert a profound influence on the distribution, abundance, and diversity of aquatic and soildwelling organisms, including nematodes and microarthropods (Kitagami et al., 2021; Guo et al., 2022).

Water quality parameters such as pH, EC, and ion concentrations (Na, K, Mg, Ca, Cl, HCO_3^-, SO_4^{-2}, P, N/NH_4^+) varied considerably among the sites. For instance, water samples from Nobaria generally exhibited higher concentrations of most measured parameters in water, while samples from Abo Hommos showed the highest EC and K but the lowest Na, Ca, HCO_3^-, and P. These differences can be attributed to various factors, including agricultural runoff, industrial discharges, and geological characteristics of the surrounding areas. Elevated levels of certain ions and EC can indicate increased salinity, which is a critical stressor for many aquatic organisms (Núñez Salazar et al., 2020). Research by Mola et al. (2025) highlights the drastic effects of precipitation and soil moisture on soil nematode abundance, composition, and diversity, underscoring the sensitivity of these organisms to water-related parameters. Similarly, a study by Ayers and Westcot (1994) emphasizes the importance of water quality for agricultural use, providing guidelines for various parameters that can indirectly affect the health of aquatic ecosystems and the organisms within them.

Soil physicochemical properties also showed considerable heterogeneity across the sites. Sol samples from El Delingat and El Mahmodia generally had higher soil EC, Na, and Cl, suggesting higher soil salinity. Conversely, Nobaria had the lowest soil EC. Soil pH ranged from slightly acidic to alkaline, with samples from Kafr El-Dawar, El Mahmodia, and Nobaria exhibiting higher pH values. SOM content was highest in El Mahmodia and lowest in Abo Hommos. These soil characteristics are fundamental drivers of soil biological activity and community structure (Neher and Barbercheck, 2019). For example, soil pH is a predominant factor influencing various trophic groups of soil nematodes, with changes in pH affecting the food resources available to them (Yang et al., 2024). Studies have consistently shown that soil physicochemical properties significantly shape nematode assemblage patterns and microarthropod communities (Kitagami et al., 2021; Wu et al., 2024). The availability of food and water resources, coupled with suitable temperature, is considered a principal factor controlling nematode populations.

The analysis of heavy metal concentrations in both water and soil samples revealed important insights into potential environmental contamination. While soil heavy metal levels were generally well below permissible limits, several heavy metals in water samples exceeded established guidelines, raising concerns about water quality in the drainage canals. Specifically, Cr, Cd, and Pb concentrations in water samples at certain sites surpassed the permissible limits set by (WHO/FAO) and ECP. For instance, Cr at El Mahmodia, Al at Nobaria, Cd at most sites, and Pb at El Delingat and Kafr El-Dawar were found in concerning concentrations. Heavy metal pollution in aquatic environments is a significant global issue, as these elements are non-biodegradable and can accumulate in the food chain, posing risks to aquatic organisms and human health (Houmani et al., 2023). Studies have shown that heavy metals can directly impact the diversity and community structure of aquatic invertebrates, including nematodes and microarthropods, by causing toxicity, altering habitat, and reducing food availability (Niño-de-Guzman-Tito and Lima-Medina, 2023; Finnan et al., 2025). In contrast, Nobaria samples, which exhibited extremely high levels of Al and Cr in soil and Pb in water, showed very low nematode diversity. This supports previous research indicating that Al and Cr are particularly toxic to soil invertebrates, disrupting their development and survival (Bongers and Ferris, 1999; Li et al., 2020). Free-living nematodes like *C. elegans* were also scarce across all sites, which is consistent with findings from Korthals et al. (1996), who demonstrated that microbial-feeding nematodes are highly sensitive to metal pollution due to indirect effects on microbial biomass. In El Mahmodia, although some species such as *P. vulnus* and *Nacobbus* were abundant, overall diversity was low, indicating that species-specific tolerance may allow a few opportunistic taxa to dominate contaminated environments. Moreover, Abo Hommos and El Delingat exhibited intermediate levels of both contamination and nematode diversity, highlighting that moderate pollution levels may selectively filter nematode communities, favoring more resilient species. This pattern aligns with the work of Ekschmitt et al. (2001), who reported that heavy metal contamination alters nematode community structure by reducing sensitive taxa and favoring tolerant ones, thus shifting the ecological balance. The presence of root-knot and lesion nematodes in highly contaminated areas may also be related to plant root stress and damage, which enhances host susceptibility and nematode proliferation (Neher, 2001).

Conversely, heavy metal concentrations in soil samples were largely within safe limits. This discrepancy between water and soil concentrations might suggest that while the water in the drainage canals is affected by heavy metal inputs, the soil's buffering capacity or other environmental processes might be mitigating their accumulation in the soil to hazardous levels. However, continuous monitoring is essential, as long-term exposure to even low levels of heavy metals can lead to their accumulation in soil and subsequent transfer to plants and the wider ecosystem (Yuda et al., 2021).

Soils have great biological, biochemical, chemical complexity, and the biodiversity below ground may be orders of magnitude higher than that above ground. The diversity and community structure of nematodes and microarthropods are highly sensitive to environmental conditions, making them valuable bioindicators of soil and water health (Qiaofang et al., 2020; Young and Unc, 2023). Soil nematodes are numerous; their many morphological species can be readily distinguished, they are relatively immobile, and they contribute to ecosystem functions (Creamer et al., 2022).

The present study's findings on nematode and microarthropod communities align with existing literature, demonstrating the intricate relationships between these organisms and their physicochemical surroundings. In the past 30 years, studies on the composition of soil nematode faunae have been ecologically centered with identifications to genus or functional group. This may also occur within plant-parasitic nematodes, e.g., Meloidogyne species are more numerous and cause problems to crops in the tropics (Du Preez et al., 2022).

The study results indicated that Kafr El-Dawar and El Delingat sites generally supported a higher number of nematode species and individuals, along with higher diversity indices. This suggests that the environmental conditions in these sites, despite variations in water and soil parameters, were more conducive to a diverse nematode community. The spatial variation in nematode diversity observed across the study sites is closely linked to the chemical composition of water and soil, particularly the concentrations of heavy metals such as Zn, Cr, Al, Cd, and Pb. Generally, nematode community structure appeared to respond negatively to elevated heavy metal levels, although species-specific tolerances were evident. For instance, Kafr El-Dawar, despite high concentrations of Zn and Pb in water and soil, supported the highest nematode richness, including high populations of *M. javanica*, *C. emarginatus*, and *A. buetschlii*. These results suggest potential adaptive tolerance mechanisms in some nematode taxa. Similar findings have been reported by Sánchez-Moreno et al. (2006), who observed that certain nematode genera, especially plant-parasitic types, can persist or even increase under moderate heavy metal stress due to reduced competition and predator pressure. Also, Renčo et al. (2022), observed that certain nematode genera can persist or even thrive under moderate heavy metal stress due to reduced competition and predator pressure. In contrast, Nobaria samples, with extremely high levels of Al and Cr in soil and Pb in water, showed very low nematode diversity. This aligns with studies indicating that Al and Cr are particularly toxic to soil invertebrates, disrupting their development and survival (Renčo et al., 2022). Free-living nematodes like *C. elegans* were scarce across all sites, consistent with findings from Park et al. (2016), who demonstrated that microbial-feeding nematodes are highly sensitive to metal pollution due to indirect effects on microbial biomass.

El Mahmodia, despite some species like *P. vulnus* and *Nacobbus* being abundant, had overall low diversity, indicating that species-specific tolerance may allow a few opportunistic taxa to dominate contaminated environments. This pattern is supported by findings from Park et al. (2016), who reported that heavy metal contamination alters nematode community structure by reducing sensitive taxa and favoring tolerant ones, thus shifting ecological balance. Abo Hommos and El Delingat sites exhibited intermediate levels of both contamination and nematode diversity, highlighting that moderate pollution levels may selectively filter nematode communities, favoring more resilient species. This pattern aligns with the work of Martinez et al. (2018), who reported that heavy metal contamination alters nematode community structure by reducing sensitive taxa and favoring tolerant ones, thus shifting ecological balance.

In contrast, Nobaria appears as the most ecologically distinct site, clustering with the rest only at a low similarity index. This distinction is reflected in its lower taxa richness species, individual count, and diversity, alongside the absence of certain taxa like *D. destructor* and *Nacobbus*. These differences may stem from unique environmental stressors, soil amendments, or land use patterns that shape nematode community composition (Zhao et al., 2021). The dominance of *Pratylenchus* and relatively low abundance of root-knot nematodes further highlight its deviation from the other locations. Overall, the data suggest that while some nematode species may thrive in contaminated environments, heavy metal pollution is generally associated with reduced diversity and altered community composition. Species richness and evenness decline in sites with extreme levels of metals like Al, Cr, and Pb. Furthermore, the type of nematode also plays a role in sensitivity, as free-living species like *C. elegans* were consistently low in abundance, possibly due to their sensitivity to metal stress or reduced microbial prey under contamination. This highlights the potential of nematode community structure as a bioindicator of soil and water quality and underscores the need for integrative assessments when evaluating environmental pollution impacts on soil biota.

Multivariate analyses using CCA biplot for nematodes further elucidated these relationships. It showed that certain nematode species, such as *M. javanica* and *C. emarginatus*, were associated with sites characterized by higher EC, Na, Cl, and SO_4^{-2} in water. This could imply a tolerance or even preference of these species for such conditions, or that these parameters are correlated with other unmeasured factors favorable to their growth. Conversely, *Pratylenchus* and *A. buetsehlii* were linked to sites with higher Cr and Zn, suggesting their adaptability to these heavy metals. Previous research has consistently highlighted the significant impact of soil chemical characteristics on nematode communities **(**Shokoohi and Masoko, 2024). Factors like soil pH, moisture, and nutrient availability are known to influence nematode diversity and trophic group distribution (Choudhary et al., 2023, Li et al., 2024).

The Bray-Curtis similarity results and the clustering of sites further supports the idea that similar environmental conditions lead to similar nematode assemblages. Overall, the Bray-Curtis similarity analysis is strongly supported by species-level data and diversity metrics, offering a robust understanding of the ecological relationships among the studied sites. For instance, the close clustering of El Mahmodia and El Delingat sites in terms of nematode diversity suggests shared environmental drivers, further reflect their community resemblance, a pattern often observed in agroecosystems with shared management histories (Kassie et al., 2022). Such regional similarities in nematode assemblages have been linked to edaphic and climatic variables, as well as host plant associations (Wang et al., 2023).

The current findings reaffirm the bioindicator value of nematodes and emphasize that both nematode abundance and species composition can reflect the level of chemical pollution in terrestrial ecosystems. Site-specific differences in metal contamination are key determinants of nematode community dynamics, consistent with earlier studies in various polluted habitats (Sánchez-Moreno & Navas, 2007; Yeates, 2003).

Similar to nematodes, the distribution and abundance of oribatid mites and other soil fauna varied significantly across the sites. Nobaria exhibited an exceptionally high abundance of *L.*

hispaniola, leading to high dominance and low diversity, suggesting that specific environmental conditions in Nobaria might favor this particular species, potentially at the expense of others. In contrast, El Mahmodia showed the highest species richness with high diversity and evenness for microarthropods, indicating a more balanced community structure. The CCA biplot for microarthropods provided further insights into these associations. It revealed that species like *L. loebli*, *G. tarsipennata*, and *S. laevigatus* were associated with El Delingat, influenced by parameters such as K, Al, P, Mg, Ca, EC, Pb, Na, and N/NH_4^+. This indicates that the specific combination of these soil physicochemical properties in El Delingat supports a particular microarthropod community. The strong association of *L. hispaniola* with Nobaria and its correlation with SOM and Zn further emphasizes the species-specific responses to environmental factors. Soil microarthropods are known to be sensitive indicators of soil health, and their community characteristics are influenced by various edaphic factors (Tabaglio et al., 2009, Gutiérrez-López et al., 2010, Wu et al., 2024). The similarity dendrogram showing the clustering of sites based on microarthropod diversity, reinforces the notion that environmental similarity drives community resemblance. For example, the close relationship between El Delingat and Kafr El-Dawar in terms of microarthropod diversity suggests shared environmental influences.

Conclusion

In conclusion, the study underscores the critical role of both water and soil physicochemical parameters, including heavy metal concentrations, in shaping the diversity and community structure of nematodes and microarthropods in drainage canal ecosystems. The observed variations in these biotic communities across the sites are a direct reflection of the heterogeneous environmental conditions. These findings contribute to a better understanding of the ecological dynamics in such environments and highlight the importance of considering a wide range of environmental factors when assessing the health and biodiversity of aquatic and terrestrial ecosystems.

5. Reference

Abdelrazek SA, El Naka A, 2022. Study the impact of the change of water quality in El Mahmoudia Canal on the chemical properties of the agricultural environment. Alexandria Science Exchange Journal, 43, 565–570.

Ageng'o FO, Waruiru RM, Wanja DW, Nyaga PN, Hamisi MM, Ndegwa JM, Ali SE, Chadag MV, Mbuthia PG, 2025. Parasites of farmed and wild Tilapine fishes from selected farms and Lake Jipe in Taita Taveta County, Kenya. Aquaculture, Fish and Fisheries, 5(1), Article e70042.

Al-Assiuty AI, Khalil MA, 1991. The Egyptian soil Acarina of suborder Oribatei with description of two new species of family Galumnidae (Jacot, 1925). Journal of the Egyptian German Society of Zoology, 6B, 491–502.

Ali MM, Hossain D, Al-Imran A, Khan M, Begum M, Osman M, 2021. Environmental pollution with heavy metals: A public health concern. Heavy Metals - Their Environmental Impacts and Mitigation, 771–783.

Ayers RS, Westcot DW, 1994. Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29, Rev. 1. FAO, Rome.

Balogh J, Balogh P, 1992. The oribatid mites genera of the world. Hungarian Natural History Museum, Budapest, Vol. I, 263 pp.; Vol. II, 375 pp.

Balogh J, Mahunka S, 1983. Primitive oribatids of the Palaearctic region. Akadémiai Kiadó, Budapest.

Banerjee P, Prasad B, 2020. Determination of concentration of total sodium and potassium in surface and ground water using a flame photometer. Applied Water Science, 10, 1–7.

Bashir O, Ali T, Baba ZA, Rather G, Bangroo S, Mukhtar SD, Naik N, Mohiuddin R, Bharati V, Bhat RA, 2021. Soil organic matter and its impact on soil properties and nutrient status. Microbiota and Biofertilizers, Vol. 2, 129–159.

Bongers T, Ferris H, 1999. Nematode community structure as a bioindicator in environmental monitoring. Trends in Ecology & Evolution, 14(6), 224–228.

Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, De Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, 2018. Soil quality–A critical review. Soil Biology and Biochemistry, 120, 105–125.

Chen YG, Huang JH, Luo R, Ge HZ, Wołowicz A, Wawrzkiewicz M, Gładysz-Płaska A, Li B, Yu QX, Kołodyńska D, 2021. Impacts of heavy metals and medicinal crops on ecological systems, environmental pollution, cultivation, and production processes in China. Ecotoxicology and Environmental Safety, 219, 112336.

Choudhary F, Bhardwaj A, Sayeed I, Rather SA, Khan MAH, Shah AA, 2023. Elevational patterns of soil nematode diversity, community structure and metabolic footprint in the Trikuta mountains of Northwestern Himalaya. Frontiers in Forests and Global Change, 6, 1135219.

Creamer R, Barel J, Bongiorno G, Zwetsloot M, 2022. The life of soils: Integrating the who and how of multifunctionality. Soil Biology and Biochemistry, 166, 108561.

D'Angelo E, Crutchfield J, Vandiviere M, 2001. Rapid, sensitive, microscale determination of phosphate in water and soil. Journal of Environmental Quality, 30, 2206–2209.

Du Preez G, Daneel M, De Goede R, Du Toit MJ, Ferris H, Fourie H, Geisen S, Kakouli-Duarte T, Korthals G, Sánchez-Moreno S, 2022. Nematode-based indices in soil ecology: Application, utility, and future directions. Soil Biology and Biochemistry, 169, 108640.

Ekschmitt K, Stierhof T, Dauber J, Kreimes K, Wolters V, 2001. On the quality of soil biodiversity indicators: Abiotic and biotic parameters as predictors of nematode diversity. Applied Soil Ecology, 17(1), 15–36.

El-Degwy AA, Negm NA, El-Tabl AS, Goher ME, 2023. Assessment of heavy metal pollution in water and its effect on Nile tilapia (*Oreochromis niloticus*) in Mediterranean Lakes: a case study at Mariout Lake. Applied Water Science, 13, 50.

El-Zeiny AM, 2022. Review of land-use impacts on surface water quality in Egypt. Journal of the Indian Society of Remote Sensing, 50, 987–1001.

Even RJ, Machmuller MB, Lavallee JM, Zelikova TJ, Cotrufo MF, 2025. Large errors in soil carbon measurements attributed to inconsistent sample processing. Soil, 11, 17–34.

Fouda MM, 2021. Report on the baseline situation for IMAP common indicator 15 "Location and extent of the habitats potentially impacted by hydrographic alterations" in Egypt.

Gbaa D, Tanee F, Albert E, 2023. Impact analysis of soil flushing remediation technique on chemical properties and metals contents of hydrocarbon-contaminated mudflat in Bodo Creek, Rivers State, Nigeria. Journal of Applied Sciences and Environmental Management, 27, 229–236.

Guo Y, Chang H, Liu Y, Zhang Y, 2022. Response of soil microarthropod community to seasonal changes in Urat Desert Steppe, Inner Mongolia. Frontiers in Environmental Science, 10, 893913.

Gupta B, 2007. Soil, plant, water and fertilizer analysis. Agrobios, India.

Gutiérrez-López M, Jesús JB, Trigo D, Fernández R, Novo M, Díaz-Cosín DJ, 2010. Relationships among spatial distribution of soil microarthropods, earthworm species and soil properties. Pedobiologia, 53(6), 381–389.

Güven D, Akıncı G, 2011. Comparison of acid digestion techniques to determine heavy metals in sediment and soil samples. Gazi University Journal of Science, 24, 29–34.

He F, Wu X, Gao J, Wang Z, 2021. Solar-driven interfacial evaporation toward clean water production: burgeoning materials, concepts and technologies. Journal of Materials Chemistry A, 9, 27121–27139.

Houmani M, Bendali-Saoudi F, Soltani N, 2023. Impact of physicochemical parameters of water on the biodiversity of the invertebrate fauna from Echatt Lake (Northeast Algeria). Biodiversitas, 24(1), 258–268.

Kassie BT, Singh H, Wesemael W, 2022. Soil and cropping system effects on plant-parasitic nematode communities: A review. Applied Soil Ecology, 177, 104510.

Kitagami Y, Kawai K, Ekino T, 2021. Soil physicochemical properties shape distinct nematode communities in serpentine ecosystems. Pedobiologia, 85–86, 150725.

Korthals GW, Bongers T, van der Meulen H, Kammenga JE, 1996. Long-term effects of copper and pH on the nematode community in an agroecosystem. Environmental Toxicology and Chemistry, 15(6), 979–985.

Li L, Luo Z, Nian L, Li L, Niu Y, Prasath BB, Haider FU, Zhang Y, He R, Liu J, 2024. Response of soil nematode community structure and metabolic footprint to nitrogen addition in alfalfa fields on the Loess Plateau. Scientific Reports, 14, 17640.

Li X, Liu Y, Zhang W, 2020. Effects of soil heavy metals on nematode communities: A meta-analysis. Ecotoxicology and Environmental Safety, 188, 109887.

Lu Q, Liu T, Wang N, Dou Z, Wang K, Zuo Y, 2020. A review of soil nematodes as biological indicators for the assessment of soil health. Frontiers of Agricultural Science and Engineering, 7(3), 275–281.

Lü Y, Xue W, Wan X, 2023. Changes in the soil biotic community are associated with variation in Illicium verum productivity. Plant and Soil, 486, 323–336.

Martin T, Wade J, Singh P, Sprunger CD, 2022. The integration of nematode communities into the soil biological health framework by factor analysis. Ecological Indicators, 136, 108676.

Martinez JG, Torres MA, dos Santos G, Moens T, 2018. Influence of heavy metals on nematode community structure in deteriorated soil by gold mining activities in Sibutad, Southern Philippines. Ecological Indicators, 91, 712–721.

Melakeberhan H, Bonito G, Kravchenko AN, 2021. Application of nematode community analyses-based models towards identifying sustainable soil health management outcomes: a review of the concepts. Soil Systems, 5, 32.

Mola M, Stratilaki E, Mourouzidou S, Kougias PG, Statiris E, Papatheodorou EM, Malamis S, Monokrousos N, 2025. Seasonal dynamics and functional diversity of soil nematode communities under treated wastewater irrigation in abandoned agricultural soils. Journal of Environmental Management, 375, 124231.

Moursy A, Hassan M, Elhefny T, 2022. Sampling and analysis of soil and water: A review. International Journal of Geography Geology and Environment, 4, 34–41.

Neher DA, 2001. Role of nematodes in soil health and their use as indicators. Journal of Nematology, 33(4), 161–168.

Neher DA, Barbercheck ME, 2019. Soil microarthropods and soil health: Intersection of decomposition and pest suppression in agroecosystems. Insects, 10(12), 414.

Niño-de-Guzman-Tito M, Lima-Medina I, 2023. Bioindicator nematodes in relation to an abiotic stress gradient in soils influenced by mining. Scientia Agropecuaria, 14(1), 59–66.

Núñez Salazar R, Aguirre C, Soto J, Salinas P, Salinas C, Prieto H, Paneque M, 2020. Physicochemical parameters affecting the distribution and diversity of the water column microbial community in the high-altitude Andean lake system of La Brava and La Punta. Microorganisms, 8(8), 1181.

Park BY, Lee JK, Ro HM, Kim YH, 2016. Short-term effects of low-level heavy metal contamination on soil health analyzed by nematode community structure. Plant Pathology Journal, 32(4), 329–339.

Pillai A, Abraham B, Sridharan A, 2007. Determination of sulphate content in marine clays. Research Applications (IJERA), 1, 1012–1016.

Ramteke S, Dewangan M, Ali M, Thiske S, 2024. A brief review on biodiversity of soil nematode.

Renčo M, Čerevková A, Hlava J, 2022. Life in a contaminated environment: How soil nematodes can indicate long-term heavy-metal pollution. Journal of Nematology, 54(1), 20220053.

Sáez-Plaza P, Michałowski T, Navas MJ, Asuero AG, Wybraniec S, 2013. An overview of the Kjeldahl method of nitrogen determination. Part I. Early history, chemistry of the procedure, and titrimetric finish. Critical Reviews in Analytical Chemistry, 43, 178–223.

Sánchez-Moreno S, Minoshima H, Ferris H, Jackson LE, 2006. Linking soil properties and nematode community composition: Structural and functional indices applied to soil management systems. Applied Soil Ecology, 33(2), 253–265.

Sánchez-Moreno S, Navas A, 2007. Nematode diversity and food web conditions in heavy metal contaminated soils in the Iberian Peninsula. Applied Soil Ecology, 37(2–3), 219–229.

Saraswathi VS, Johnson M, Kumaraguru A, 2021. Review on water holding capacity of soil across the tropical and subtropical forests in India. Indian Journal of Ecology, 48, 641–648.

Sarhan A, 2021. Towards a blue economy in Egypt: Economic assessment of environmental degradation of marine and coastal resources. Journal of Environmental Science, 50, 63–83.

Shokoohi E, Masoko P, 2024. Association of plant-parasitic nematodes and soil physicochemical properties in tomatoes in Turfloop, Limpopo Province, South Africa. Horticulturae, 10(4), 328.

Singh DV, Bhat RA, Upadhyay AK, Singh R, Singh D, 2021. Microalgae in aquatic environs: A sustainable approach for remediation of heavy metals and emerging contaminants. Environmental Technology & Innovation, 21, 101340.

Tabaglio V, Gavazzi C, Menta C, 2009. Physico-chemical indicators and microarthropod communities as influenced by no-till, conventional tillage and nitrogen fertilisation after four years of continuous maize. Soil and Tillage Research, 105(1), 135–142.

Tabatabai M, 1996. Soil organic matter testing: An overview. Soil Organic Matter: Analysis and Interpretation, 46, 1–9.

Ullah R, Abbas Z, Bilal M, Habib F, Iqbal J, Bashir F, Noor S, Qazi MA, Niaz A, Baig KS, 2022. Method development and validation for the determination of potassium (K_2O) in fertilizer samples by flame photometry technique. Journal of King Saud University–Science, 34, 102070.

Wang J, Zhang Y, Liu X, Song C, 2023. Community structure of nematodes in agricultural soils: Influence of edaphic factors and land management. Pedobiologia, 97, 150839.

Wu H, Liu Y, Zhang T, Xu M, Rao B, 2024. Impacts of soil properties on species diversity and structure in Alternanthera philoxeroides-invaded and native plant communities. Plants, 13(9), 1196.

Yang Y, Zhang S, Li Y, Wang Y, Zhang X, 2024. Response of soil nematode community structure and metabolic footprint in the alfalfa fields across varying levels of N supply in the semi-arid region. Scientific Reports, 14(1), 10189.

Yeates GW, 2003. Nematodes as soil indicators: Functional and biodiversity aspects. Biology and Fertility of Soils, 37(4), 199–210.

Young EH, Unc A, 2023. A review of nematodes as biological indicators of sustainable functioning for northern soils undergoing land-use conversion. Applied Soil Ecology, 83, 104762.

Zhao X, Zhou D, He W, 2021. Effects of land use changes on soil nematode communities and diversity in farmland ecosystems. Agriculture, Ecosystems & Environment, 312, 107310