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Impact of Cadmium-contaminated water and irrigation levels on microbiological properties of soils with different textures

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Abstract

Cadmium (Cd) contamination poses a significant threat to soil health and agricultural productivity, particularly under varying water availability and soil textures. This study examines the effects of water levels (25%, 50%, 75%, and 100% field capacity) and soil textures (sandy clay loam, silty loam, and clay) on key microbiological properties, including basal soil respiration (BSR), microbial biomass carbon (Cmic), dehydrogenase activity (DHA), and catalase activity (CA), in Cd-contaminated soils. An incubation experiment was conducted under controlled conditions at 20 ± 0.5°C for 10 days. Microbiological properties were assessed using standard methods: alkali absorption for BSR, substrate-induced respiration for Cmic, spectrophotometric assays for DHA, and volumetric determination for CA. Optimal microbial activity across all parameters was observed at 75% field capacity, highlighting the importance of balanced soil moisture. Clay soils consistently exhibited the highest activity due to their superior organic matter content and buffering capacity, while sandy clay loam soils showed the lowest activity due to limited water retention and nutrient availability. Excessive moisture at 100% field capacity reduced oxygen diffusion, suppressing microbial activity, while insufficient moisture at 25% field capacity constrained microbial metabolism. These findings provide critical insights into the interplay between soil texture, water availability, and Cd contamination, offering valuable guidance for sustainable soil and water management practices to mitigate heavy metal toxicity in agricultural systems.

Keywords: Cadmium contamination, soil microbiology, water levels, soil texture, enzymatic activity.

Introduction

Soil health is critically important for both agricultural sustainability and ecological balance. Soil microorganisms play a vital role in fundamental biochemical processes such as carbon and nitrogen cycling, directly influencing the biological, chemical, and physical properties of soils (Vig et al., 2003; Chen et al., 2014; Kandziora-Ciupa et al., 2016; Li et al., 2018; Bayraklı and Dengiz, 2019). These microorganisms are essential for processes like organic matter decomposition, carbon sequestration, and the provision of bioavailable nitrogen to plants (Naidu et al., 2000; Effron et al., 2004).

Heavy metal contamination is one of the most significant threats to soil health. Cadmium (Cd) is a toxic heavy metal introduced into soils through anthropogenic activities such as industrial waste and mining, severely disrupting soil biochemical cycles by damaging microorganisms and enzymes (Moreno et al., 2001; Kızılkaya and Aşkın, 2002; Tan et al., 2014; Liu et al., 2021). Cadmium's characteristics of bioaccumulation and non-degradability make its environmental impacts severe and long-lasting (Chen et al., 2014; Liu et al., 2024).

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Microbiological parameters such as microbial biomass carbon (C_{mic}), basal soil respiration (BSR), dehydrogenase activity (DHA), and catalase activity (CA) are highly sensitive to environmental stressors, including cadmium contamination and water stress (Kızılkaya et al., 2004; Kızılkaya and Bayraklı, 2005; Li et al., 2018; Yeboah et al., 2021; Chebyshev et al., 2024; Zhang et al., 2024). These parameters are considered critical indicators for understanding how cadmium's toxic effects translate to disruptions in soil functions (Vig et al., 2003; Karaca et al., 2011; Kandziora-Ciupa et al., 2016).

However, there is limited knowledge about the interactions between cadmium contamination and varying water conditions on soil enzymatic activities. Specifically, the impacts of cadmium on microbial communities in soils with different textures remain underexplored (Naidu et al., 2000; Effron et al., 2004; Chen et al., 2014; Mandzhieva et al., 2014; Liu et al., 2024). This knowledge gap highlights the need for a better understanding of the complex interactions among soil texture, water levels, and heavy metal contamination.

The aim of this study is to comprehensively evaluate the effects of cadmium contamination and different water levels on microbiological properties and enzyme activities in soils with varying textures. This study seeks to provide novel insights into how optimal water management can mitigate the harmful effects of cadmium and improve soil health. Additionally, it aims to address existing gaps in the literature by elucidating the role of soil texture in cadmium bioavailability.

Material and Methods

Soil sampling, preparation and analysis

Soil samples representing three distinct textural classes were collected from agricultural fields in Azerbaijan, specifically from a depth of 0–20 cm. To ensure accuracy in the experiment, the samples were carefully cleaned to remove surface stones and plant debris. The prepared soil samples were then transported to the laboratory for detailed analysis.

Under controlled laboratory conditions, the samples underwent several preparatory steps. Initially, they were air-dried in a shaded, cool environment to prevent any chemical alterations that could occur from excessive heat or sunlight exposure. Once dried, the soil samples were ground to remove residual moisture and achieve uniformity, followed by sieving through a 2 mm mesh to ensure consistent particle size. This process resulted in finely homogenized samples, ready for subsequent analyses.

Standard scientific methods were employed to determine various soil parameters. Textural analysis was conducted using the hydrometer method (Bouyoucos, 1962). Soil pH and Electrical Conductivity (EC) were measured in a 1:1 (w/v) soil-to-distilled water ratio using a pH meter and EC meter, respectively, following the methods outlined by Peech (1965) and Bower and Wilcox (1965). The organic matter content was assessed through the wet oxidation method using $K_2Cr_2O_7$, as described by Walkley and Black (1934). Calcium carbonate ($CaCO_3$) levels were evaluated volumetrically using a Scheibler calcimeter (Rowell, 2010). Water retention properties, including field capacity, wilting point, and available water content, were determined based on procedures detailed by Klute (1965) and Peters (1965).

For heavy metal analysis, available forms of metals such as Fe, Cu, Zn, Mn, Cd, Pb, and Ni were extracted using the DTPA method, while total heavy metals were quantified through aqua regia and HF digestion, followed by measurement with Atomic Absorption Spectrophotometry (Lindsay and Norvell, 1978; EN 13656, 2002).

Water sampling, preparation and analysis

Water samples, including those collected from the Sugovushan Reservoir (40.323985 N, 46.743843 E) in Azerbaijan, were analyzed to assess their properties. Upon collection, the samples were promptly transported to the laboratory for processing and filtered using Whatman No. 41 filter paper to remove particulates.

The pH and electrical conductivity (EC) of the water samples were measured using a pH meter and an EC meter, respectively. Anion concentrations, including Cl^-, HCO_3^-, SO_4^{2-}, NO_2^-, NO_3^-, and PO_4^{3-}, as well as cations such as Ca^{2+}, Mg^{2+}, Na^++K^+, and NH_4^+, were determined following standardized procedures described by the US Salinity Laboratory Staff (1954). Heavy metal concentrations, including Fe, Cu, Zn, Mn, Cd, Pb, and Ni, were quantified using an Atomic Absorption Spectrophotometer to ensure precise measurements.

Soil incubation experiment

The experiment was carried out in a constant temperature incubator set at 20±0.5°C for 10 days. Soil water properties, including field capacity, wilting point, and available water content, were assessed following the methodologies described by Klute (1965) and Peters (1965). A randomized complete block design was employed, incorporating four water levels (%100, %75, %50, and %25 of field capacity) with three replications for each treatment.

Fifty grams of each soil sample were weighed and placed into 100 mL plastic beakers. Plant-available water sourced from the Cd-enriched Sugovushan Reservoir was applied to the soil at the designated water levels. After thorough mixing to ensure uniform distribution, the beakers were sealed with perforated parafilm, allowing adequate air exchange while minimizing water loss through evaporation.

The samples were maintained in the dark under controlled temperature conditions for the entire incubation period. On the 10th day, soil samples were retrieved, and selected microbiological properties were analyzed.

Microbiological properties

Basal soil respiration (BSR)

Basal soil respiration (BSR) at field capacity, measured as CO_2 production at 22°C without glucose addition, was determined following the method outlined by Anderson (1982). CO_2 released during a 24-hour incubation period was absorbed using a solution of $Ba(OH)_2 \cdot 8H_2O$ and $BaCl_2$, and the residual OH^- was titrated with standardized hydrochloric acid, with phenolphthalein as an indicator. Each sample was tested in triplicate, and results were expressed as µg CO_2-C per gram of dry soil.

Microbial biomass carbon (C_{mic})

Microbial biomass carbon (C_{mic}) was assessed using the substrate-induced respiration (SIR) method described by Anderson and Domsch (1978). A moist soil sample equivalent to 100 g of oven-dry soil was mixed with 400 mg of glucose powder. The CO_2 evolution rate was recorded hourly for 4 hours, following the method of Anderson (1982). The maximum initial respiratory response was used to calculate C_{mic} as 40.04 mg CO_2 g^{-1} soil + 3.75. Each sample was analyzed in triplicate, with data expressed as mg CO_2-C per 100 g of dry soil per hour.

Dehydrogenase activity (DHA)

Dehydrogenase activity (DHA) was determined using the procedure described by Pepper et al. (1995). A mixture of 6 g of soil, 30 mg of glucose, 1 mL of 3% 2,3,5-triphenyltetrazolium chloride (TTC), and 2.5 mL of distilled water was prepared. The samples were incubated at 37°C for 24 hours. The formation of 1,3,5-triphenylformazan (TPF) was quantified spectrophotometrically at 485 nm. Results were expressed as µg TPF per gram of dry soil.

Catalase activity (CA)

Catalase activity (CA) was measured following the method of Beck (1971). Five grams of soil were combined with 10 mL of phosphate buffer (pH 7) and 5 mL of a 3% H_2O_2 substrate solution. The volume of oxygen released over 3 minutes at 20°C was recorded. Controls included the addition of 2 mL of 6.5% (w/v) NaN_3 to inhibit catalase activity. Each sample was tested in triplicate, and results were expressed as mL O_2 per gram of dry soil.

All determinations of Microbiological properties were performed in triplicate, and all values reported are averages of the three determinations expressed on an oven-dried soil basis (105 ^{0}C).

Results and Discussion

Soil Physico-chemical Properties

The characteristics of the soils used in the incubation experiment are summarized in Table 1. The results indicate significant differences in soil texture among the three samples analyzed. One soil is classified as 'Sandy Clay Loam' (SaCL), another as 'Silty Loam' (SiL), and the third as 'Clay' (C). All soils exhibit an alkaline pH and are calcareous in nature. While the SaCL soil is non-saline, the SiL and C soils are classified as saline. Additionally, the organic matter content across all samples is low, reflecting the typical characteristics of the sampled agricultural regions.

According to Kloke's (1980) classification, no heavy metal contamination was detected in the soils, as the heavy metal concentrations remained within the buffering capacity of the soils. Despite this, the total cadmium (Cd) content varied among the soils, with values of 1.75, 2.12, and 2.66 mg/kg for SaCL, SiL, and C soils, respectively. These differences align with findings by Holmgren et al. (1993), which suggest that Cd concentrations tend to increase with higher clay and organic matter content.

The threshold for Cd contamination in soils is generally considered to be 3 mg/kg or higher (Akbar et al., 2006). The Cd levels in the soils used for this study were below this threshold, indicating they are not significantly contaminated. Gradients in Cd concentration are commonly associated with proximity to industrial facilities, roadways, or urban areas (Page et al., 1987; Joimel et al., 2016). The absence of significant Cd contamination in these soils can be attributed to their origin from agricultural fields in Azerbaijan. These fields are typically fertilized with phosphorus-based chemical fertilizers to boost rice production (Islamzade et al., 2024), which could explain the moderate Cd levels. Although the Cd content is slightly elevated, it remains below the critical threshold of 3 mg/kg, indicating a non-contaminated status suitable for agricultural use.

Table 1. Characteristics of the Soils Used in the Incubation Experiment

	SaCL	SiL	C
Sampling point	38.6322740 N 48.8646310 E	40.2559770 N 47.6289990 E	40.5438710 N 47.2880790 E
Texture			
Sand, %	50,69	11,55	6,76
Silt, %	15,91	78,58	7,69
Clay, %	33,41	9,87	85,55
Class	Sandy Clay Loam	Silty Loam	Clay
Soil water properties			
Field Capacity, % Vol	32,30	30,90	44,90
Wilting point, % Vol	21,60	10,40	35,00
Available Water, % Vol	10,70	20,50	9,90
Bulk density, g cm^{-3}	1,48	1,37	1,19
Chemical properties			
pH	7,70	8,17	7,86
EC, dSm^{-1}	0,51	7,62	4,77
$CaCO_3$, %	12,93	15,06	6,69
Organic matter, %	1,61	0,88	2,47
Available heavy metals			
Fe, mg kg^{-1}	65,50	6,21	35,71
Cu, mg kg^{-1}	7,54	1,80	7,74
Zn, mg kg^{-1}	0,58	0,31	0,43
Mn, mg kg^{-1}	23,01	3,76	7,34
Cd, mg kg^{-1}	0,20	0,16	0,15
Pb, mg kg^{-1}	2,48	3,58	3,25
Ni, mg kg^{-1}	3,68	2,15	3,59
Total heavy metals			
Fe, %	3,12	3,81	5,39
Cu, mg kg^{-1}	84,82	75,36	95,15
Zn, mg kg^{-1}	191,17	185,58	296,61
Mn, mg kg^{-1}	0,18	0,13	0,25
Cd, mg kg^{-1}	1,75	2,12	2,66
Pb, mg kg^{-1}	86,85	93,19	95,85
Ni, mg kg^{-1}	75,69	65,48	86,15

Chemical Properties of the Water

The chemical composition of the water used in the incubation experiment is detailed in Table 2. The Sugovushan Reservoir, a vital water body in Azerbaijan, is primarily fed by the Terter River. The Terter River, the largest river in the Karabakh region, has historically supported the agricultural and domestic needs of over 400,000 residents. However, between 1994 and 2020, the river was heavily polluted due to gold mining activities during the period of occupation by Armenian forces (Babayeva et al., 2024). The absence of effective environmental regulations during this time led to the direct discharge of mining waste into the river system, severely affecting the ecosystem and contaminating both the Terter River and the Sugovushan Reservoir, with cadmium (Cd) being the most concerning pollutant.

The water used in the experiment exhibited an alkaline pH of 8.0 and an electrical conductivity (EC) of 3.10 dS m^{-1}, indicating salinity. The heavy metal analysis revealed that while most heavy metal concentrations were within acceptable limits for agricultural use, the Cd concentration was significantly elevated at 1.64 mg L^{-1}. This exceeds the upper threshold for Cd in irrigation water, which is set at 0.01 mg L^{-1} by FAO (1985) standards. Other heavy metals, such as Fe, Mn, and Pb, were present but did not pose a similar level of risk to agricultural activities.

The historical contamination of the Sugovushan Reservoir underscores the environmental consequences of unregulated industrial practices. While the water's chemical properties make it unsuitable for agricultural use without remediation, the data highlight the critical need for environmental restoration and sustainable water management in the region.

Table 2. Chemical properties of the water used in the incubation experiment

pH	8,00	**Anions**		**Heavy metals**	
EC, dSm^{-1}	3,10	Cl^-, mg L^{-1}	20,40	Fe, mg L^{-1}	210,00
Cations		HCO_3^-, mg L^{-1}	114,60	Cu, mg L^{-1}	<0,01
Ca^{2+}, mg L^{-1}	38,1	SO_4^{2-}, mg L^{-1}	67,90	Zn, mg L^{-1}	<0,01
Mg^{2+}, mg L^{-1}	9,90	NO_2^-, mg L^{-1}	0,01	Mn, mg L^{-1}	4,17
Na^++K^+, mg L^{-1}	64,80	NO_3^-, mg L^{-1}	1,43	Cd, mg L^{-1}	1,64
NH_4^+, mg L^{-1}	0,15	PO_4^3, mg L^{-1}	0,10	Pb, mg L^{-1}	9,82
Total cations	112,95	Total anions	204,44	Ni, mg L^{-1}	<0,01

Microbiological Properties of Soils

Basal Soil Respiration (BSR)

Basal Soil Respiration (BSR) serves as a crucial indicator of soil microbial metabolic activity, reflecting the processes of organic matter decomposition and the carbon cycle. In this study, BSR values showed significant variation across different irrigation levels and soil textures, emphasizing the interplay between moisture availability and soil composition (Table 3). The highest BSR values were observed at 75% field capacity in all soil textures, indicating that this moisture level provides an optimal environment for microbial activity by balancing oxygen diffusion and substrate availability.

Among the soil types, sandy clay loam soils exhibited the lowest BSR values, which can be attributed to their limited capacity to retain water and nutrients. In contrast, clay soils displayed the highest BSR values, likely due to their higher organic matter content and enhanced buffering capacity. Specifically, at 75% field capacity, clay soils recorded BSR values that were approximately 25% higher than those of sandy clay loam soils, demonstrating their superior ability to support microbial respiration under optimal moisture conditions.

At 25% field capacity, all soil textures experienced a notable decline in BSR values, reflecting the limitations imposed by insufficient water availability, which restricts microbial activity. Conversely, at 100% field capacity, excessive water inhibited oxygen diffusion, resulting in a suppression of BSR across all textures. These findings underscore the critical role of maintaining moderate moisture levels to optimize microbial activity and soil health.

Table 3. Basal soil respiration (BSR) (μg CO_2-C g^{-1} soil) across soil textures and water levels

Water Level (% Field Capacity)	Sandy Clay Loam	Silty Loam	Clay
25%	2.10 ± 0.25	2.80 ± 0.32	3.50 ± 0.41
50%	3.20 ± 0.30	3.90 ± 0.35	4.70 ± 0.48
75%	3.80 ± 0.45	4.60 ± 0.40	5.40 ± 0.52
100%	3.00 ± 0.20	3.60 ± 0.28	4.20 ± 0.30

Cadmium contamination has been shown to significantly suppress BSR due to its inhibitory effects on microbial communities. Chen et al. (2014) reported that increasing Cd concentrations reduced BSR values, although elevated CO2 levels partially mitigated these effects. Similarly, Vig et al. (2003) emphasized that the bioavailability of cadmium, rather than its total concentration, correlates more strongly with toxicity. The observed variations in BSR across soil textures align with this notion, as the clay soils' higher organic matter content and buffering capacity likely reduced cadmium bioavailability and mitigated its toxic effects. Additionally, the observed lower BSR in sandy soils highlights their susceptibility to cadmium due to reduced sorption capacity and nutrient availability (Vig et al., 2003; Naidu et al., 1997).

Microbial biomass carbon (C_{mic})

Microbial Biomass Carbon (Cmic) is a vital parameter that represents the active microbial community in soil, playing a key role in nutrient cycling and organic matter decomposition. In this study, Cmic values varied significantly across irrigation levels and soil textures, with the highest values observed at 75% field capacity across all soil types (Table 4). This suggests that moderate moisture conditions create an optimal environment for microbial growth and carbon sequestration.

Clay soils exhibited the highest Cmic values, attributed to their superior water retention capabilities and higher organic matter content, which together provide a stable and nutrient-rich environment for microbial communities. Specifically, at 75% field capacity, clay soils recorded Cmic values that were approximately 30% higher than those of sandy clay loam soils, highlighting their enhanced buffering capacity against cadmium toxicity. Silty loam soils followed, with moderately high Cmic values that reflect their balanced physical and chemical properties. Conversely, sandy clay loam soils consistently showed the lowest Cmic values, likely due to their limited organic matter content and poor capacity to retain water and nutrients.

At 25% field capacity, all soil textures displayed a marked reduction in Cmic values, indicative of water stress that restricts microbial activity. Meanwhile, at 100% field capacity, excessive moisture likely inhibited oxygen diffusion, reducing microbial biomass across all soil textures. These findings emphasize the critical role of maintaining adequate moisture levels to support microbial activity and enhance soil health.

Table 4. Microbial biomass carbon (C_{mic}) (mg C g^{-1} soil) across soil textures and water levels

Water Level (% Field Capacity)	Sandy Clay Loam	Silty Loam	Clay
25%	120.50 ± 6.50	140.20 ± 7.00	165.30 ± 7.50
50%	140.70 ± 7.20	160.50 ± 7.50	190.80 ± 8.00
75%	160.30 ± 8.00	185.40 ± 8.50	220.60 ± 9.00
100%	130.10 ± 6.80	150.30 ± 7.30	180.50 ± 7.80

Cadmium toxicity to microbial biomass is well-documented, with Chen et al. (2014), Vig et al. (2003), and Moreno et al. (2001) noting that soil properties such as organic matter content and pH play a critical role in modulating cadmium bioavailability. Higher organic matter and clay content in soils can reduce the free divalent cadmium ion, the most toxic species, thereby minimizing its adverse effects on microbial biomass (Naidu et al., 2000). Similarly, the findings of the study on water stress in rhizosphere soils suggest that microbial biomass is highly sensitive to changes in moisture availability, with significant reductions observed under both excessive and deficient water conditions (Zhang et al., 2024). These insights align with the observed trends in this study, where optimal moisture at 75% field capacity supported higher Cmic values, highlighting the importance of balanced water management.

Dehydrogenase activity (DHA)

Dehydrogenase activity (DHA) is a critical indicator of oxidative metabolism and overall microbial activity in soils. In this study, DHA values demonstrated significant variability across irrigation levels and soil textures, peaking at 75% field capacity for all soil types (Table 5). This peak reflects optimal conditions for microbial enzymatic functions, where oxygen diffusion and substrate availability are well-balanced.

Table 5. Dehydrogenase activity (DHA) (µg TPF g^{-1} soil $24h^{-1}$) across soil textures and water levels

Water Level (% Field Capacity)	Sandy Clay Loam	Silty Loam	Clay
25%	45.10 ± 2.50	52.40 ± 2.90	60.70 ± 3.10
50%	50.80 ± 2.70	58.60 ± 3.20	68.40 ± 3.60
75%	55.60 ± 2.90	65.10 ± 3.40	75.90 ± 3.80
100%	48.30 ± 2.60	55.20 ± 3.00	63.50 ± 3.40

Clay soils consistently exhibited the highest DHA values across all moisture levels, with a peak value of 75.90 µg TPF g^{-1} soil $24h^{-1}$ at 75% field capacity. This superior performance can be attributed to the higher organic matter content and buffering capacity of clay soils, which help mitigate the toxic effects of cadmium. Silty loam soils recorded intermediate DHA values, benefiting from their balanced texture and moderate organic matter content, while sandy clay loam soils consistently exhibited the lowest DHA values due to their limited organic matter and poor buffering capacity.

At 25% field capacity, the lowest DHA values were observed across all soil textures, reflecting the limitations of water stress on microbial metabolic activity. Conversely, excessive moisture at 100% field capacity likely restricted oxygen diffusion, leading to a significant reduction in DHA values. For instance, DHA values decreased by approximately 10% in clay soils and 14% in sandy clay loam soils compared to their respective peaks at 75% field capacity.

Previous studies support these findings. Vig et al. (2003), Naidu et al. (2003), and Chen et al. (2014) reported that cadmium contamination suppresses enzymatic activity by disrupting enzyme-substrate interactions and microbial metabolic pathways. Zhang et al. (2024) emphasized that such suppression is exacerbated under fluctuating moisture conditions, highlighting the importance of stable soil management practices. Moreover, Moreno et al. (2001) underscored the role of organic carbon in mitigating cadmium toxicity, with higher organic carbon levels correlating with reduced enzymatic inhibition. These observations align with the trends observed in this study, particularly the superior performance of clay soils under optimal moisture conditions.

Catalase Activity (CA)

Catalase activity (CA) is a vital enzymatic indicator of oxidative stress responses in soils, reflecting the ability of microbial communities to detoxify reactive oxygen species. In this study, CA values exhibited significant variation across irrigation levels and soil textures, with the highest values recorded at 75% field capacity for all soil types (Table 6). This peak underscores the importance of balanced moisture conditions for optimal microbial activity and effective stress management.

Table 6. Catalase activity (CA) (ml O_2 g^{-1} soil 3 min^{-1}) across soil textures and water levels

Water Level (% Field Capacity)	Sandy Clay Loam	Silty Loam	Clay
25%	4.30 ± 0.30	5.60 ± 0.40	6.40 ± 0.50
50%	5.10 ± 0.30	6.30 ± 0.40	7.30 ± 0.50
75%	5.80 ± 0.30	7.10 ± 0.50	8.10 ± 0.60
100%	4.90 ± 0.30	6.00 ± 0.40	7.00 ± 0.50

Among the soil textures, clay soils consistently exhibited the highest CA values, with a peak of 8.10 ml O_2 g^{-1} soil 3 min^{-1} at 75% field capacity. This superior performance is attributed to their higher organic matter content and buffering capacity, which mitigate the adverse effects of cadmium toxicity and provide a more stable environment for microbial communities. Silty loam soils recorded intermediate CA values, reflecting their moderate buffering capacity and organic matter content, while sandy clay loam soils exhibited the lowest CA values, highlighting their limited resilience to both moisture stress and cadmium toxicity.

At 25% field capacity, all soil textures experienced significant reductions in CA values due to water stress limiting microbial enzymatic responses. Similarly, excessive moisture at 100% field capacity likely restricted oxygen availability and increased cadmium bioavailability, leading to a notable decline in CA. For instance, CA values in clay soils decreased by approximately 13% compared to their peak at 75% field capacity.

These findings align with previous studies. Naidu et al. (2000), Vig et al. (2003), and Zhang et al. (2024) demonstrated that cadmium contamination significantly suppresses catalase activity by interfering with microbial enzymatic systems. Furthermore, Zhang et al. (2024) emphasized the sensitivity of catalase activity to water stress, with severe reductions observed under drought conditions. This highlights the necessity of optimal water regulation, particularly in cadmium-contaminated soils. Moreno et al. (2001) emphasized the role of higher organic carbon levels in reducing cadmium bioavailability, thereby mitigating its inhibitory effects on CA. The trends observed in this study reinforce the critical role of soil organic matter and texture in modulating oxidative stress responses under environmental stress conditions.

Conclusion

This study demonstrated that cadmium contamination and water levels significantly influence microbial properties and enzyme activities in soils with varying textures. Moderate moisture levels (75% field capacity) were shown to provide optimal conditions for microbial activity, while extreme moisture conditions (25% and 100% field capacity) suppressed enzymatic responses and microbial biomass. Clay soils exhibited the highest resilience to cadmium toxicity due to their superior organic matter content and buffering capacity, whereas sandy clay loam soils were the most vulnerable, showing the lowest microbial and enzymatic activity. These findings emphasize the necessity of maintaining optimal water levels to enhance microbial health and mitigate the adverse effects of cadmium in contaminated soils. Future studies should explore the long-term effects of cadmium on soil microbial dynamics under diverse environmental conditions and investigate the role of organic amendments in enhancing soil resilience. This research underscores the critical role of integrated water and soil management in addressing heavy metal contamination and improving agricultural sustainability.

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