Libyan Journal of Ecological & Environmental Sciences and Technology
(LJEEST)
LJEEST
ISSN: 2710-5237
www.srcest.org.ly/jou

DOI: https://doi.org/10.63359/62xmzr32

Soil-Pollutant Interactions Under Climate Change: A Comprehensive Review

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ARTICLE INFO

Vol. 7 No. 2 Agustus, 2025
Pages (57- 68)

Article history:
Revised form 11 April 2025
Accepted 31 May 2025

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Keywords:
Climate change, Heavy metals, Organic contaminants, Soil processes

ABSTRACT

Heavy metal (loid) and organic pollution of soil is a serious environmental issue. The fate of such pollutants, their speciation, and the properties of the soils themselves control the manner in which they will migrate and cause ecological hazards. some factors that affect the toxicity and mobility of these pollutants are temperature, moisture levels, organic content, mineral composition, and microbiological activity. These parameters are quite sensitive to the effects of climate change, including an increase in the frequency of extreme precipitation events, extended periods of droughts, elevated erosion of soils, and higher sea levels. In this review, we synthesize evidence linking climate-driven changes in soil processes to changes in the mobility, transport, and sequestration of pollutants. Our findings suggest that alterations in soil organic carbon turnover, surface runoff regimes, redox status, and microbial populations under changing climate conditions can amplify human exposure to such contaminants. There are, however, uncertainties related to the exact interactions and long-term implications of these processes.

تفاعلات التربة والملوثات في ظل تغير المناخ: مراجعة شاملة

خليفة الصديق الاطرش

يُعَدُّ تلوث التربة بالمعادن الثقيلة (وأشباه الفلزات) والملوثات العضوية قضية بيئية خطيرة. إن مصير هذه الملوثات، وأنواعها الكيميائية(speciation) ، وخصائص التربة ذاتها، هي التي تتحكم في الطريقة التي ستنتقل بها وتسبب المخاطر البيئية. ومن العوامل التي تؤثر في سُمِّية هذه الملوثات وقابليتها للحركة: درجة الحرارة، ومستويات الرطوبة، والمحتوى العضوي، والتركيب المعدني، والنشاط الميكروبيولوجي. وتتسم هذه المعايير بحساسيتها الشديدة لتأثيرات تغير المناخ، بما في ذلك الزيادة في تواتر حوادث الهطول الشديدة، وفترات الجفاف الممتدة، وتزايد تآكل التربة، وارتفاع مستويات سطح البحر. في هذه المراجعة، نقوم بتجميع الأدلة التي تربط بين التغيرات المدفوعة بالمناخ في عمليات التربة والتغيرات في قابلية الملوثات للحركة والنقل والاحتجاز. وتشير نتائجنا إلى أن التغيرات في دورة تجدد كربون التربة العضوي، ونُظُم الجريان السطحي، وحالة الأكسدة والاختزال، والمجموعات الميكروبية في ظل الظروف المناخية المتغيرة يمكن أن تزيد من تعرض الإنسان لهذه الملوثات. ومع ذلك، هناك أوجه عدم يقين تتعلق بالتفاعلات الدقيقة والآثار طويلة الأمد لهذه العمليات.

INTRODUCTION

The growth of human civilization has long been prompted by the formation of novel compounds and chemical alteration of existing natural substances. Since the inception of environmental toxicology in the twentieth century, the struggle between the elimination of chemical contaminants and the rapid evolution of society has become more apparent (Pat et al., 2022). The increasing demand for products is anticipated to induce deep global economic growth, with calculations indicating that demand can potentially double to four-fold the current levels observed in 2010 by 2050 (Hanson & Nicholls., 2020). The manufacture and utilization of chemicals, especially solvents, have serious environmental impacts. Wagare et al. (2021) estimated that approximately 80% of the chemicals employed in synthesis, corresponding to approximately 20 million tons of solvents per year, are discharged into the environment. The Earth's critical zone (CZ) is an intricate interplay between rock, soil, water, air, and living organisms that governs essential resources and habitats from tree canopies to groundwater. They drive substrate transformation (Zaharescu et al., 2019) and sustain biogeochemical cycling. However, soil is the core interface between above- and below-ground ecosystems (Liu et al., 2020), which influences water and nutrient flow, carbon sequestration, and plant growth. In the Anthropocene, human-induced environmental alterations profoundly transformed soil properties. Excessive atmospheric greenhouse gases, primarily CO_2 and CH_4, trigger global warming, induce precipitation pattern changes, increase drought and rainfall events, boost storm frequency, and cause gradual soil degradation (Pu et al., 2024). Studies conducted in various geochemical environments recognize climate change as one of the ten Earth planetary boundaries that needs to be maintained for environmental sustainability (Dao et al., 2018; Tobian et al., 2024; (Diamond & Wang, 2024). Additionally, the emission of greenhouse gases, mostly caused by agricultural activities and burning of fossil fuels, also disrupts precipitation and storm frequency, which further influences soil characteristics and their functionality (Bhatti et al., 2023; Van Den Bergh et al., 2024). The presence of environmental pathogens and pollutants poses a serious public health risk (Balta et al. 2024). Climate change influences the bioaccumulation and distribution of persistent organic pollutants in the food chain (Alava et al., 2017; Thompson et al., 2023). Conversely, soil systems regulate many processes that are central to ecosystem function. Research by Fuchslueger et al. (2023) and Possinger et al. (2021) supports that climate change impacts humic substances, and they can potentially enhance their biodegradation, initiating the re-immobilization and desorption of soil pollutants. In addition, interactions within the soil ecosystem play an important role in determining the ecotoxicological impacts of pollutants (Liu et al., 2024). This review ultimately examines the complex interplay between climatic variables and soil processes in determining the fate of chemical pollutants, with an emphasis on the need for holistic strategies to counter mounting environmental problems. This review also provides recommendations for efficient and sustainable soil management strategies in the face of rapidly progressing climate change.

Chemical Pollutant Interactions, Soil Properties, and Processes

Pollutants that threaten ecological balance and human health include heavy metals and metalloids such as arsenic, mercury, lead, cadmium, and hexavalent chromium, as well as organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and persistent organic pollutants (POPs). In the vicinity of industrial and mining operations, the concentrations of these elements tend to surpass the natural background concentrations, thereby constituting serious ecological and health-related concerns (Xu et al., 2024). Their bioavailable fractions pose toxicological risks to soil organisms and humans (Li et al., 2024; Wang et al., 2024). The adsorption and desorption processes in the soil are affected by the pH, redox potential, and occurrence of different chemical species. Inorganic ions (e.g., HPO_4^{2-}, NO_3^-, Cl^-, SO_4^2−) and organic ligands (e.g., citrate, oxalate, fulvic materials, dissolved organic carbon) are a determining factor in pollutant behavior (Shaaban & Nunez-Delgado, 2024; Han et al., 2020; Zhang et al., 2024). In particular, competing anions like phosphates (PO_4^{3-}) enhance the soil's negative charge and promote cation sorption via electrostatic attraction (Han et al., 2020). whereas complexation by sulfates (SO_4^{2-}) and chlorides (Cl^-) may inhibit metal(loid) adsorption (Zhou & Cao, 2024). Organic matter (SOM), commonly measured as soil organic carbon (SOC) (Grant et al., 2024), plays a critical role in the adsorption of pollutants. Humic substances in SOM possess a strong affinity for metal cations because of their negative charge, extremely small particle size, and high density of oxygen-containing functional groups (e.g., –OH, –COOH, –SH, and–C=O) (Wang et al., 2024). In addition, microbial processes influence the degradation and destiny of soil pollutants, with microbial biodegradation being a natural process for degrading petroleum hydrocarbons (Li et al., 2024). Phytoremediation, which employs plants in a microbially active rhizosphere, is an effective strategy for the cleanup of heavy metals and metalloids (Xu et al., 2024).

Soil Properties, Dynamics, and Global Climate Variability

Temperature variations, extreme changes in precipitation patterns, soil erosion, and greenhouse gas emissions (Pu et al., 2024; Teng et al., 2024; Sun et al., 2024) affect many fundamental properties of soil and its dynamic processes. Temperature, hydrological cycles, soil moisture, salinity, redox conditions, and carbon distribution (Liu et al., 2024; Zhang et al., 2024; Jha et al., 2023; Zhang et al., 2022). Over the past 60 years, burning fossil fuels, industrial activities, and agricultural practices have increased CO_2, CH_3, and N_2O emissions. In 2018, the industrial sector accounted for 6.5% of the global greenhouse gas emissions. It has been a major source in this case, releasing approximately 2040 gigatons of CO_2 equivalent every year and showing similar patterns of emissions for both CH_4 and N_2O, proving its effect (Isella & Manca, 2022). Table 1 illustrates this input and identifies sectors comprising oil refining and ammonia synthesis, a part of which is taken up by terrestrial ecosystems.

Table (1): Global greenhouse gas emissions in 2018 by sector of production (source: Isella & Manca, 2022).

Sector	GHG Emissions [Mt-CO2,eq/y]	Mass Share [-]
Electricity and Heat[1]	15,875	32.20%
Transportation	8418	17.10%
Manufacturing and Construction[2]	6223	12.60%
Agriculture[3]	5803	11.80%
Fugitive Emissions[4]	3354	6.80%
Buildings[5]	3106	6.30%
Industrial Processes	2967	6.00%
Waste[6]	1607	3.30%
Land-Use Change and Forestry	1388	2.80%
Other Fuel Combustion[7]	627	1.30%
Total	49,368	100%

[1] Electricity and heat plants, other Energy Industries. [2] Emissions due to direct fuel combustion in manufacturing and construction sites. [3] Including livestock and manure. [4] Intentional or unintentional releases of gases from human activities (mainly due to fossil fuels extraction, processing, and transmission). [5] Both residential and commercial. [6] Waste management activities (e.g., landfills and wastewater). [7] Emissions related to other unstated sectors, from stationary and mobile sources.

These activities increase soil organic carbon (SOC) concentration and enable nitrogen uptake in vegetation (Shakoor et al., 2020). Consequently, soils operate as both carbon sinks and sources, thereby establishing a robust linkage with climatic dynamics. Throughout the past century, global surface temperatures have experienced a marked increase of approximately 0.3–0.6°C, consequently elevating soil temperature levels notably (Ma et al., 2022; Bhatti et al., 2023; Van Den Bergh et al., 2024). According to Li et al. (2024), temperature is a key factor in controlling the dynamics of soil organic carbon (SOC). It has a wide range of different effects that depend on the reaction of microbes and the environment at the time. For instance, Li et al. (2024) estimated that a rise of 1°C in soil surface temperature would result in an approximate loss of carbon from approximately 30 ± 30 to 203 ± 161 petagrams in the uppermost 0–15 cm depth. Teng et al. (2024) also predicted that higher temperatures in forest ecosystems might cause a small increase in SOC, while reducing dissolved organic carbon (DOC). However, both SOC and DOC are expected to decrease significantly in heavily farmed land. Wang et al. (2024) documented a widespread SOC decline in the forests of northeastern China, with estimated losses of approximately 122 Tg by the 2050s and greater decreases by the 2090s under elevated CO_2 and temperature conditions. Han et al. (2024) argued that hydrological mechanisms and OC substance composition drive the responsiveness of SOC decomposition. They pointed out that precipitation exerts a huge impact on soil carbon flow, noting that dissolved OC is highly sensitive compared with soil organic carbon (Sun et al., 2024). However, topsoil erosion causes the loss of DOC, and particulate organic carbon occurs more rapidly. Soil pH changes transpire more slowly than those in aquatic systems. Adding sulfuric and nitric acids from humans along with CO_2 from the air is what mostly makes water more acidic (Ferdush et al., 2023), but minerals (such as calcium, magnesium, and sodium) balance out the pH of the soil by exchanging hydrogen ions for basic cations. However, excessive rainfall can leach these vital cations, thereby making the soil progressively more acidic (Luo et al. 2015). Additionally, atmospheric nitrogen deposition combined with acidifying agents (e.g., SO_3^{2-}, NO_3^-) further significantly promotes acidification. According to Chen et al. (2023), over a forty-year span, acid deposition diminished soil respiration by 0.23%, whereas nitrogen deposition reduced it by 1.54%, culminating in an average soil pH decline of 0.16 units. Zhang et al. (2024) and Liu et al. (2024) illustrated that numerous soil properties, such as its classification, organic matter content, moisture, and microbial populations, share a strong and statistically significant correlation with soil contamination caused by emerging contaminants (ECs), potential-toxic elements (PTEs), and heavy metals.

As discussed in Sections 2 and 3, soil contamination by pollutants, including emerging contaminants (ECs), potentially toxic elements (PTEs), and heavy metals, is influenced by soil properties (Figure 1).

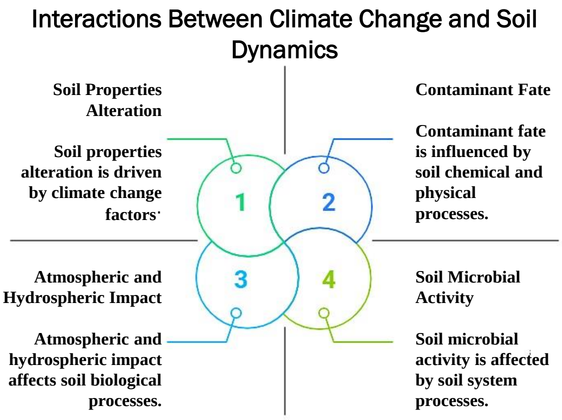

Fig. (1): Climate change influences chemical pollution and soil dynamics.

Quadrant 1 shows how soil property changes in structure and nutritional value brought on by climate change, so influencing fertility and water-holding capacity, quadrant 2 investigates how chemical processes and soil affect concentration, movement, and degradation of pollutants, quadrant 3 stresses how soil biological and chemical processes are affected by atmospheric and hydrospheric conditions including temperature and precipitation. Lastly, quadrant 4 looked at how environmental stresses affect the adaptation of microbial populations to control of soil functioning and microbial activity.

Theoretical frameworks and empirical data are used in the following sections to explore the links between climatic factors, soil processes, and chemical pollutant emissions.

CLIMATE SHIFTS IN SOIL PROCESSES AND POLLUTANT EXPOSURE

Numerous studies have demonstrated that climate change directly influences contaminant transfer among the atmosphere, aquatic systems, soils, sediments, and biota through the interplay of physical, chemical, and biological processes (Alava et al., 2017; Thompson et al., 2023). These processes govern the dilution, accumulation, and partitioning of pollutants (Liu et al., 2024) (González-Prieto & Romero-Estonllo, 2022) (Burke et al., 2023). Moreover, climate-driven alterations in soil conditions modify processes such as surface runoff, air–soil exchange, deposition, and rain-induced dissolution, which in turn affect contaminant transformations via photolysis, microbial degradation, and atmospheric oxidation ((Liu et al., 2024; Zhang et al., 2022; Hung et al., 2022).

. *The Role of Water, Erosion, and Soil Temperature*

Recent studies have documented shifts in contaminant transport mechanisms, including volatilization, precipitation, runoff, degradation, and transformation, in response to climate-induced soil warming (Liu et al., 2024; González-Prieto & Romero-Estonllo, 2022) (Burke et al., 2023) (Figure 2).

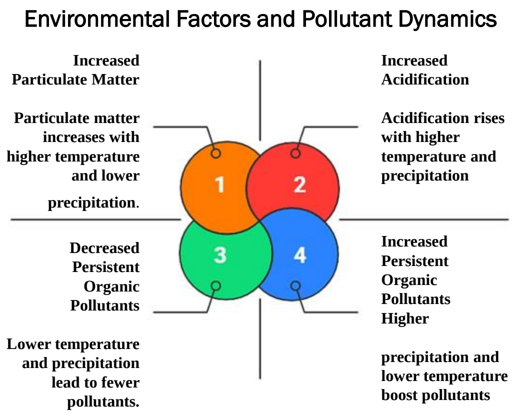

Fig. (2): illustrates how temperature and precipitation shifts influence pollutant dynamics.

The first quadrant (orange) shows particulate matter increasing with higher temperature and lower precipitation, while the second (red) shows acidification rising under higher temperature and precipitation. The third quadrant (green) suggests persistent organic pollutants decrease with lower temperature and precipitation, whereas the fourth (blue) indicates their increase under higher precipitation and lower temperature. These relationships underscore the complex interactions between environmental variables and pollutant behaviors.

For example, simulations in Arctic landfills have shown that a 2 °C temperature rise significantly increases the mobility of BTEX compounds (benzene, toluene, ethylbenzene, and xylene) (Arif & Abdelaal, 2023). Elevated temperatures, combined with stronger wind speeds, enhance the volatilization and dispersion of both organic and inorganic pollutants (e.g., CH_4, NH_3, N_2O, S^{2-}, and Hg) (Zhang et al., 2022). Higher temperatures also accelerate the methylation of inorganic Hg in soils, water, and sediments, with oxygen-deprived conditions near +8 °C, leading to up to a tenfold increase in Hg methylation (Zhang et al., 2024; Alava et al., 2017). In the Qinghai–Tibet Plateau, temperature increases of 1–3.7 °C were linked to a 9.4–40% rise in elemental mercury (Hg^0) in surface soils, which raises concerns about the formation of bioavailable toxic mercury species (Arif & Abdelaal, 2023). Experimental comparisons under different air temperatures and drought conditions have also revealed that extreme scenarios result in significantly higher accumulation of Cd, Pb, and Zn in soil invertebrates (Mebane et al., 2020). In the Arctic regions, warming triggers the melting of ice and thawing of perennially frozen layers, which can release sequestered compounds, alter hydrological pathways, accelerate erosion, and enhance runoff (Burke et al. 2023). Such processes may increase pollutant influx into downstream waters, as evidenced by meltwater in Colorado's Rocky Mountains transporting substantial quantities of Zn, SO_4, and Mn from mining areas (Manning et al., 2024). Additionally, variations in annual precipitation impact pollution levels in urban soils, particularly in relation to PFOS mobilization during flood events. More rain increases leaching and runoff, thus remobilizing legacy pollutants (Richardson et al., 2022; Schwanen et al., 2023). Industrial and commercial zones show higher PFAS levels in cities, including Changchun and Ningbo (Zhao et al., 2024; Tang et al., 2020). Moreover, saline conditions during flooding can improve PFOS solubility and transport, thereby increasing the ecological risks (Liu et al., 2019).

Soil Organic Carbon

Climate change impacts SOC and DOC cycles, which affect the bioavailability and mobility of various contaminants. Microbial activity and SOM decomposition processes that are enhanced by elevated global temperatures aid coastal agricultural soils, and carbon reserves decrease due to SOC and DOC leaching (Zhou et al., 2023). In addition, climate change modifies SOC fractions and lowers MBC and EOC, while DOC concentrations increase (Zhou et al., 2023). In addition, higher surface runoff and POC transport were observed because of the enhanced unsaturated soil and anomalous precipitation erosion (Tiefenbacher et al., 2021). The degree of SOC degradation that is sensitive to temperature change is not uniform in soils, and low sensitivity due to the mineral protective effect is seen in highly weathered tropical soils, whereas higher vulnerability is found in freshly tilled temperate region soils (Kong et al., 2023; Reichenbach et al., 2022). Finally, SOC responses to warming are dependent on the pool of labile carbon in SOC, ecosystem type, and the form of SOC (Z. Zhang et al., 2023; J.-J. Wang et al., 2019).

. SOC and the Exposure of Organic Contaminants

Soil organic matter (SOM) acts as a buffer for pollutants by allowing their transport and diffusion within the organic matrix (Li et al., 2024). The classification of contaminant fractions into exchangeable, carbonate-bound, organic-bound, iron–manganese oxide-bound, and residual fractions shows the role of SOM and soil texture in contaminant mobility (Li et al., 2022). SOM has a role in both contaminant retention and mobilization, and clay retains long-chain hydrocarbons, with dissolved organic matter (DOM) influencing short-chain hydrocarbon behaviour (Shu et al., 2024). The mobility of contaminants and biological availability of heavy metals are further influenced by the different functional groups present in SOM, whereas microbial community composition and enzyme activity influence the contaminant biotransformation rate (Teslya et al., 2024). While increased temperatures enhance SOC decomposition and change microbial community structure, there is still the potential to increase stable mineral-associated organic carbon (MAOC) and iron-organic carbon (Fe-OC) pools as a warming response (Han et al., 2024; Liu et al., 2024; Boyle et al., 2024).

The metal(loid)s' presence in soil organic carbon and their release

Soil organic matter retention and release control the mobility of heavy metals, such as Cd, Pb, Cu, Ni, and Zn (Li et al., 2024; Kou et al., 2024).. Elevated temperatures and increased CO_2 concentrations have variable impacts on SOM across regions; warmer areas may see increases in SOM, while cooler zones may experience decreases (Han et al., 2024; Borah & Parmar, 2024; Song et al., 2024). Higher temperature-induced promotion of SOM degradation reduces the soil cation exchange capacity, and hence metal retention, and increases metal uptake by plants and organisms (Chitimus et al., 2023). Projections also indicate increased erosion rates through severe rain and storms, rising up to 12.06% to 36.90%, with the annual topsoil loss increasing up to 70–300 tons per hectare, from the current range of 60–80 tons per hectare. This increased erosion helps the SOC-bound pollutants to move more easily, and thus, their presence poses a threat to human health (Zhang et al., 2024; Qu et al., 2024). As a result, the suspended sediment possesses a greater capacity to bind metals than the original soil, which is further elaborated in Section 4.4.1.

. Nitrogen and Phosphorus in Soil

Soil pollution affects the transformation of nitrogen and phosphorus through perturbation of microbial community structure and enzyme function due to the presence of chemical contaminants, especially heavy metals (Shi et al., 2023 Song et al., 2024). The reduction of lowered microbial biomass accompanied by modified enzyme function in polluted degraded soils may cause N limitation and slow nutrient cycling. The processes of nutrient runoff and the degradation of water sources due to pollution, also known as eutrophication, are exacerbated by climate change factors, such as increased temperatures, precipitation changes, and soil erosion (Shi et al., 2023). For example, Mediterranean ecosystems have demonstrated how slight increases in average temperature of 1-5 degrees Celsius can increase the concentration of nitrate (NO_3^-) while simultaneously decreasing the concentration of ammonium (NH_4^+), leading to a disturbance in nitrogen dynamics (Mu et al., 2024). Although the overall nitrogen balance remains ambiguous, drought conditions hinder vital enzyme activities such as urease and proteases (Asensio et al., 2023). Nitrogen oxides (NO_x) and nitrous oxide (N_2O) also affect soil processes through atmospheric deposition, which modifies leaching, acidification, the rate of organic matter mineralization, and nitrification (Nieland et al., 2024; Wu et al., 2024). Increased levels of nitrogenous compounds are thought to also increase eutrophic emissions of N_2O, decrease soil pH, and increase aluminum (Al^{3+}) concentration, which lowers biodiversity and deteriorates ecosystem balance (Chen et al., 2023; Cen et al., 2024). Moreover, higher amounts of nitrogen can lead to the increased dominance of certain species of grasses, which promotes the acidification of soil and the movement of heavy metals (Cen et al., 2024; Nieland et al., 2024). Eutrophication also worsens due to increased rainfall coupled with temperature variance, which increases phosphorus runoff and soil erosion. Due to these changes, phosphorus runoff is now 3.3 - 16.5 percent higher in the coastal-temperate northern areas, while the warming-induced acidification in the range of agricultural soils low in phosphorus makes the immobilization of heavy metals such as cadmium through iron plaque formation less effective (Lou et al., 2024; Yu et al., 2024; Liu et al., 2024). The fate of soil biological processes and contaminants is **discussed in Section 4.5.**

Chemical pollutant and soil mineral dynamics

Clay minerals, including illite, vermiculite, and kaolinite, are widespread in different types of soils and are considered regional geological histories and weathering agent pointers (Ouyang et al., 2021). Despite the lack of evidence on the effect of climate change on clay minerals, the interaction of clay with organic substances remains a significant factor in the mobility of pollutants. Higher temperatures destabilize organo-clay associations, leading to the transformation of heavy metals such as cadmium (Cd), lead (Pb), and chromium (Cr) to more bioavailable species (Zhang et al., 2024). Climatic fluctuations and enhanced erosion lead to an additional reduction in clay content in agricultural soils, thus impacting the pollutant transportation mechanism. The reduced protective function of clay also alters the quality of organic substances and restricts the immobilization of heavy metals (Zhang et al., 2024; Kou et al., 2024). Additionally, heavy precipitation has the potential to compromise soil structure through the leaching of soluble salts and dispersion of clay particles, thus affecting adsorption and microbial degradation mechanisms in aquatic systems (Azzouz et al., 2024; Liu et al., 2023). Although enhanced solar radiation accompanied by intensified photodegradation may enhance the degradation of organic pollutants, the lack thereof creates harmful intermediates (Wu et al., 2024).

Non-clay minerals, as well as other soil components, including feldspar, carbonates, micas, iron oxides, sulfides, and chlorites, play a central role in contaminant dynamics. Higher atmospheric levels of CO_2 and rising temperatures accelerate weathering and dissolution of minerals, thus altering their sorption properties and, in turn, affecting contaminant mobility (Shaaban & Nunez-Delgado, 2024; Bolan et al., 2023; Sarkar et al., 2021). Soil pH acts as an essential factor in governing contaminant action; the degradation of pyrite, arsenopyrite, and marcasite forms acidic conditions that improve the mobilization of mobilized heavy metal(loid)s, which are sequestered in the minerals (Qu et al., 2024; Zhang et al., 2024). On the other hand, minerals including calcite, dolomite, and limestone have the ability to raise soil pH, thus promoting the deposition of oxides and hydroxy sulfates that immobilize metals (Qu et al., 2024; Zhang et al., 2024). Climate change also affects non-clay minerals through mechanisms related to flooding and sea level rise, which alter hydrological regimes by lowering oxygen availability and redox potential. In aquatic systems, oxygen deficiency may cause the reductive dissolution of arsenic-containing hydro (oxides), leading to elevated arsenic levels in coastal waters (Lemonte et al., 2017). Moreover, flooding-drying cycles cause redox potential fluctuations, thus affecting the action of trace metals by altering soil pH, dissolved organic carbon (DOC), and minerals; although redox cycling temporarily stores inorganic contaminants, the follow-up phases of drying and oxidation might result in the acidification of the soil and the mobilization of metals that are complexed, and flooding events are closely related to a sudden increase in heavy metal contamination in the soil in agriculture, highlighting the need for more research (Mikutta et al., 2024).

soil life, enzymes, and plant responses interact

Organic matter decay, nutrient cycling, and pollution transformation depend on soil microbes and their enzymes (Jones et al., 2020; Shakoor et al., 2023). Their ecological roles are sensitive to changes in soil temperature and moisture caused by the climate. For example, a 4°C rise in temperate forests could increase soil respiration by 34–37% because long-stored carbon (Boyle et al., 2024; Li et al., 2024) breaks down. Promising directions for further knowledge of these processes will be presented in future studies on mineral-bound organic carbon using depth-gradient analyses (Underwood et al., 2024). By encouraging photosynthesis and root exudation, atmospheric CO_2 enrichment improves plant productivity and phytoremediation, thus increasing the availability of pollutants for microbial degradation (Zaman et al., 2024) (Wang et al., 2024). Lower contaminant concentrations in the rhizosphere enable phytoextraction and phytostabilisation (Deng et al., 2024). The composition of root exudates, including organic acids, amino acids, and sugars, significantly affects microbial biodegradation rates; studies have reported rates exceeding 90% in the rhizosphere compared to less than 50% in bulk soil (Eze & Amuji, 2024). Glycine and other exudates have been shown to synergistically accelerate the breakdown of petroleum hydrocarbons (He et al., 2022). Arbuscular mycorrhizal fungi (AMF), soil warming, and excessively high nitrogen inputs also affect rhizobial populations. Although nitrogen addition can lower hyphal density and change community composition, warming could increase AMF spore density and diversity, thus influencing nutrient cycling and plant–microbe interactions (Mei et al., 2024). Moreover, by altering pH and organic matter composition, CO_2-induced soil acidification may alter the adsorption of trace metals (Yang et al., 2021). This increases the bioavailability of pollutants and plant absorption. Rising temperatures in polar areas have been linked to increased fungal enzyme activity and organic matter breakdown, which may affect contaminant bioavailability (Khan and Ball, 2023).

.CONCLUSION

This review explains how climate change alters temperature, precipitation, and extreme weather events affecting soil properties and processes, thus influencing soil–pollutant relationships. Climate-induced changes in organic matter, minerals, and microbial populations affect the mobility, transformation, and bioavailability of pollutants through processes such as enhanced volatilization, modified sorption-desorption, and nutrient cycles. These complex feedback loops complicate remedial actions and risk assessments. This review stresses the need for multidisciplinary cooperation to increase our knowledge of soil-pollutant interactions in view of the fast-changing environment. Some of the main consequences are improved forecasting models, including biological activity, mineral weathering, erosion, and precipitation; adaptive policies supported by long-term, high-resolution monitoring data to control soil pollution; and the development of phyto- and bioremediation techniques adjusted to changing climate conditions. This work provides a foundation for future developments in integrated monitoring, experimental techniques, and predictive models. Filling in these gaps will enable us to better understand the dynamics between soil and pollutants and support effective environmental management in view of fast-growing climate change. Future studies should focus on combining multidisciplinary approaches to improve the predictive models and develop adaptive management strategies. This will help lower risks, guide policy decisions, and preserve ecosystem health in the face of ongoing climate change. These projects are expected to drive progress.

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