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Different effects of heavy metals in plant growth and soil degradation

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Abstract:

This article aims to identify the extent of the danger of heavy metals that spread in the environment. It is released into the soil in several ways, which leads to changes in some of its chemical, physical and biological properties in a way that makes it negatively affect all forms of life on its surface, such as humans, animals and plants. The danger lies in the fact that it remains in the soil for a long period of time without decomposition or any chemical change, and it enters into the natural cycle of the environment and is transferred between its various parts and contents. The article includes the methods of transferring elements from the soil solution contaminated with them through plant roots, their entry into the plant, and their transport by plant sap to the rest of the plant parts through the process of transpiration. There are other factors that control the movement of elements within the tissues of different plants, such as the degree of interaction, oxidation and reduction processes, ionic competition, hydrolysis, polymerization, and the formation of dissolved salts such as (oxalates and phosphates). It has inhibitory effects on plants by reducing and delaying growth due to its toxicity, which disrupts various metabolic activities in cells, such as photosynthesis, respiration, the formation of nucleic acids, the formation of proteins, as well as the activity and effectiveness of various enzymes and other vital processes that take place within plants, which ultimately leads to harm to their growth in all its stages and their productive capacity. Therefore, it poses a threat to life when used as food. The article also highlights the extent to which some plants growing in environments polluted with heavy metals can store them in their roots while controlling their transfer from the roots to the stems, leaves and fruits as a type of adaptation to resist the toxicity of these elements. The greater the amount of heavy metals in the soil, the greater the absorption process by the plant. Plants show resistance to toxicity to varying degrees by preventing its accumulation in the targeted sites or through the mechanism of tolerance to these elements when they enter the cytoplasm and when their level increases within plant tissues. The plant either collects or accumulates them in special locations in the roots, in the vegetative system, or in the fruits called vesicles, or converts them into other non-toxic forms inside the plant.

Keywords: ***heavy metals, plant growth, soil pollution.***

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التأثيرات المختلفة للعناصر الثقيلة على نمو النبات وتدهور التربة

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الخلاصة

هدفت هذه المقالة الى التعريف بمدى خطورت العناصر الثقيلة التي تنتشر في البيئة وتطرح في التربة بطرائق عده مما يؤدي بالتغيير في البعض من خصائصها الكيميائية والفيزيائية والحيوية بشكل يجعلها تؤثر سلباً بكافة اشكال الحياة فوق سطحها كالأنسان والحيوان والنبات والتي تكمن خطورتها في بقائها لمدة طويلة من الزمن في التربة من دون تتحلل او أي تغيير كيميائي وتدخل ضمن عناصر الدوره الطبيعية للبيئة وتنتقل بين اجزاءها ومحتوياتها المختلفة. وتتضمن المقالة طرائق انتقال تلك العناصر من محلول التربة الملوثه بها بواسطة جذور النباتات ودخولها داخل النبات وحملها بواسطة العصاره النباتية الى باقي أجزاء النبات بعملية النتح مع وجود عوامل أخرى تتحكم بحركة العناصر ضمن انسجة النباتات المختلفة كدرجة التفاعل وعمليات الاكسدة والاختزال والتنافس الايوني والتحلل المائي والبلمرة وتكون الاملاح الذائبة (كالاوكزالات والفوسفات) وما لها من تأثيرات تثبيطية في النبات من خلال أختزال النمو وتأخره بسبب سميتها والتي تضطرب بها مختلفة الفعاليات الأيضية في الخلايا مثل البناء الضوئي والتنفس وبناء الحوامض النووية وتكوين البروتينات وكذلك نشاط وفعالية الأنزيمات المختلفة وغيرها من العمليات الحيوية التي تجري داخل النباتات مما تؤدي بالنهاية الى الإضرار بنموها بكافة مراحله وطاقتها الإنتاجية وبالتالي تشكل خطوره على الحياة جراء استخدامها كغذاء. كما وتسلط المقالة الضوء على مدى إمكانية وقدرت بعض النباتات النامية في بيئات ملوثة بالعناصر الثقيلة على خزنها في جذورها مع التحكم في أنتقالاتها من الجذور إلى السيقان والأوراق والثمار كنوع من أنواع التكيف لمقاومة سمية تلك العناصر فكلما زادت كمية العنصر الثقيل في التربة زادت عملية إمتصاصه من قبل النبات , اذ تظهر النباتات مقاومة بدرجات متفاوته لسميتها من خلال منع تراكمها في المواقع المستهدفة أو من خلال ميكانيكية التحمل لهذه العناصر عند دخولها في السايتوبلازم وعند زيادة مستواها في داخل الأنسجة النباتية فأن النبات يقوم أما بتجميعها او مراكمتها في مواقع خاصة في الجذور او في المجموع الخضري او في الثمار تدعى بالحويصلات أو بتحويلها إلى أشكال أخرى غير سامة داخل النبات.

الكلمات المفتاحية: ***العناصر الثقيلة , نمو النبات , تلوث التربة.***

Introduction

The environment is the medium in which living organisms exist, derive their means of sustenance, and interact with it while being influenced by it. Pollution, on the other hand, is any quantitative or qualitative undesirable change in the environment and its elements, caused by alterations in the energy levels of some of its components. This depends on the concentration and nature of the pollutant itself, Pollutants, in general, are considered among the most dangerous substances released into the environment. They primarily originate from various human activities and their undesirable effects can persist for decades, Soil pollution is defined as the disruption or imbalance affecting its system, which can be chemical, physical, or biological in nature. This disruption harms the natural equilibrium for which the soil was created, often due to excessive natural or human activities whether intentional or unintentional. Such activities lead to direct or indirect damage to the health of the soil, humans, and the environment as a whole, including all its components such as living organisms, natural resources, and economic assets. Since soil is an integral part of the ecosystem, any disturbance to the ecosystem will eventually affect the soil (Al-Mamari et al.,2022). Environmental pollution with heavy metals has become a global issue that transcends borders and distances. This type of pollution has been spreading due to increased industrial activity and widespread urbanization, posing a significant threat to ecosystems, including soil, water, and air. This extends to a direct impact on global food security sustainability and human health (Lorestani et al.,2012 . Ahmed et al., 2020. Kamal et al.,2025). The group of heavy elements is often referred to as "trace elements" because they naturally exist in the environment in minute quantities, measured in parts per million (ppm). They are also

sometimes called "toxic elements." However, both terms are considered chemically inaccurate. Therefore, the term "heavy metals" or "heavy elements" is the most widely accepted and comprehensive designation. It is commonly used to describe a broad range of elements with a specific density greater than 5 g/cm³ that negatively affect the environment and its components, particularly humans, animals, and plants, when used excessively (Al-Rubaie et al.,2022). However, not all heavy elements fall under the category of metals. Some are metalloids, such as arsenic, boron, and antimony, while others are non-metal elements like selenium. Therefore, the term "heavy metals" does not universally apply to all heavy elements. Similarly, the term "toxic elements" is also unsuitable for all of them, as some trace elements may not be toxic to living organisms in their natural states unless specific conditions lead to their concentration exceeding internationally permissible limits (Al Masmouri and Al Shamary.,2024). Thus, referring to them as "potentially toxic trace elements under certain conditions" is a term that may be the most comprehensive, appropriate, and widely accepted compared to other designations. This has been highlighted and clarified in relevant studies and discussions (Abdul Moneim and Al-Turki, 2012 and Alsaadoon et al.,2023). Soils are considered the most critical environmental medium for the survival of living organisms. Being an open ecological system, they are highly susceptible to various types of pollution, particularly toxic heavy elements, due to diverse human activities stemming from urban and industrial development. Contaminated soils with heavy metals are a direct source of health risks to humans, animals, and plants. The total content of heavy elements in soils originates from the minerals derived from their geological parent materials, as well as from high-level inputs through various pollution sources driven by continuous and intensive human activities. These include atmospheric deposition of particles carrying these elements, with diameters of less than 30 micrometers, and rain droplets falling on soils carrying heavy elements in particulate or gaseous forms. Additionally, the direct and scientifically unregulated addition of agricultural fertilizers both mineral and organic along with heavy wastewater, urban waste, sewage, drainage waters, and industrial by-products such as ash, mining residues, dyes, and wartime remnants, are significant contributors. These sources collectively represent key drivers of heavy element contamination in soils. Thus, soils serve as the ultimate repository for these toxic wastes released into the environment through diverse and unregulated human activities. Being one of the essential components of the ecosystem, this accumulation disrupts the balance of the system, leading to adverse environmental and ecological consequences (Alloway,2013 and Ahmed et al.,2022). Plants exhibit varied responses to heavy elements in the soil, leading to differences in their effects based on plant species, age, growth stage, root exudates, and the plant's sensitivity to heavy metal levels. Additionally, the physicochemical properties of the soil, total concentrations of heavy elements, their type, solubility, bioavailability, absorption rate, translocation, and chemical activity all contribute to the variability in their toxicity to plants. These factors collectively determine the extent of toxicity, as has been demonstrated in various studies and observations (Al-Hayani,2022). The bioavailability of heavy elements in different soils and their uptake by plants depend on the readily available fraction of these elements. This is influenced by the interaction of various soil and plant factors, such as the dominant clay mineral type, the quantity and quality of organic matter, soil pH, and the type, age, and variety of the cultivated plant. Its degree of tolerance to the toxicity of these elements and the speed of their transfer between its parts, such as the roots, stems, or leaves, as these elements are transferred from the soil to the inside of the plant according to specific mechanisms, and then

they are transferred inside the plant itself with the plant sap from the bottom (the roots) towards the top (the stems, leaves, and fruits). (Hassoun et al.,2019).

Soil Pollution with Heavy Metals:

Heavy metals are among the most dangerous toxic substances that spread in the environment and are released into the soil in several ways. The continued emission of these substances from various sources leads to an increase in their concentrations in the soil. Their danger lies in their persistence for long periods without decomposing or undergoing any chemical change. These metals become part of the natural environmental cycle, moving between its components, both living and non-living. They are classified as transitional elements, distinguished by their ability to form stable complexes with a wide range of organic and inorganic compounds found within the bodies of living organisms (Ayangbenro et al.,2019). As a result of their presence in agricultural soils, heavy metals not only affect the growth of plants but also lead to the contamination of grains, fruits, and vegetables consumed by humans (Alloway,2013 and Al-daini et al., 2020). Hasanin et al (2007) defined agricultural soil contamination as the degradation that affects agricultural soils, causing changes in some of their chemical, physical, or biological properties. Such changes negatively impact the living organisms' humans, animals, and plants that inhabit the surface of the soil, either directly or indirectly. The negative effects on biological systems include the risk of developing a range of serious diseases such as cancers, heart diseases, kidney disorders, brain ailments, and neuropathies. The extent of agricultural soil contamination depends on both the type and degree of pollution. The chemical and physical properties of soils, prevailing climatic conditions, and natural working factors all play a role, as soil is considered the main reservoir for all types of pollutants, including heavy metals, due to its high capacity to bind various chemical substances. The sources of contamination in agricultural soils can be summarized as follows:

1-Atmospheric air and the gases and vapor it carries.
2-Reusing wastewater in agriculture without applying the necessary treatment.
3- Excessive, continuous, and unregulated use of chemical substances in agriculture and industry, including pesticides and fertilizers.
4- Burying solid and liquid waste in the soil.

Sources of soil pollution by heavy metals:

Heavy metals are transferred to the environment from various sources and enter the atmosphere as a mixture of industrial gases and vapors. These then settle on the soil surface and penetrate into the entire soil profile, causing soil contamination. They also reach groundwater, leading to water pollution, and accumulate on the bottoms of oceans and bays. Over time, they may be carried back to the surface. The sources of heavy metals in soil vary, but they can be mainly classified into two primary sources that cause increased concentrations in the soil:

1-Natural sources: Their primary origin is the weathering of parent rocks that contain certain amounts of these elements, erosion, and the deposition of particles carried by wind, volcanic eruptions, forest fires, as well as biological sources.

2-Human sources: These involve direct human activities that add heavy metals to the soil, including atmospheric deposition from fossil fuel combustion, mining, manufacturing processes, metal smelting, power plants, waste burning, cement production, phosphate fertilizers, and soil amendments. They also include untreated sewage waste, wastewater, agricultural pesticides, organic and animal fertilizers, organic waste, and food industry residues (Hassoun and Ahmed et al.,2022).

Heavy Metals Movement in Soil

Fadel and Hussein (2022) explained that continuous geochemical dynamic processes occur in soils, as they are open ecological systems that regulate the movement and transfer of elements, including heavy metals. This system acts as a reservoir containing all elements, including heavy metals. Numerous researchers in this field have studied the possible mechanisms through which heavy metal ions are retained in the soil. In natural conditions, these elements are in immobile or relatively low mobility forms located within the crystal structures of primary and secondary minerals. As a result of the various and continuous weathering processes to which rocks containing minerals carrying the ions of these elements are exposed, a portion of them will gradually transform over time into mobile forms if certain conditions are met. To become accessible to living organisms or may be associated with other soil components depending on the geochemical conditions affecting the soil profile. Or through the prevalence of pollution in its various degrees, which leads to changes in its chemical forms or images, and then its distribution, movement, and toxicity in the soil sector. (Abdul-Jabbar et al., 2017 and Odthar,2022). Soils can retain these elements through a set of reactions such as adsorption, precipitation and complexation, depending on a set of their chemical and physical properties such as the degree of reaction and their content of organic matter, clay particles and calcium carbonate. The process of restricting and restraining the movement of heavy metals through complexation and adsorption processes and isolating them from the soil solution plays a major role in controlling the environmental pollution process. Heavy metals are adsorbed on the surfaces of organic materials and clay particles. If the soil reacts more and its calcium carbonate content increases, this will inevitably lead to an increase in the accumulation of these elements.

Heavy Metal pollution of Plants

Plants growing in polluted environments vary in their response to heavy metal pollution intensity depending on the species, age, growth stage, and physicochemical properties of the soil. (Farhan, 2020 and Al-Janabi et al., 2024). Heavy metals move from contaminated soil according to specific mechanisms to the plants growing in it, and they accumulate and collect in different parts of the plants. It moves from the roots upwards to the stems, the vegetative group, and then the fruit. Its transfer within different parts of the plant is evaluated by a factor called the site transfer or bioaccumulation factor (BCF). The majority of heavy metals are absorbed from the soil solution by plant roots and then enter the plant and are carried by the plant sap to the rest of the plant parts. The process of its transfer over long distances within the different parts of the plant is partially related to the intensity of the transpiration process. In addition to other factors such as the degree of reaction, oxidation and reduction processes, ionic competition, hydrolysis, polymerization, and the formation of dissolved salts (such as oxalates and phosphates), all of these factors combined control the movement of heavy metals within the various plant tissues. (Ansari et al., 2018). Shammi et al. (2016) found, When evaluating the risk resulting from the reuse of liquid waste from a textile factory in Bangladesh (Dhaka) when used for irrigation of

leafy vegetable plants, the in situ transfer factor (TF) for heavy elements was Pb > Cu>Cd>Zn, while for both lead and copper it was recorded within the range (1-1.7), which indicates the possibility of their accumulation inside plants and the danger they pose to human life as a result of their use as food. Heavy metals also have inhibitory effects on plants by reducing and delaying growth. The basis of this effect may be due to the toxicity of heavy metals, which disrupt various metabolic activities in cells, such as photosynthesis, respiration, the formation of nucleic acids, and the formation of proteins, as well as the activity and effectiveness of various enzymes and other vital processes that take place within plants. Ultimately, these disruptions damage plant growth at all stages and reduce their productive capacity. Hasan (2022) demonstrated that the presence of cadmium in plants grown in contaminated soils reduces the expansion of plant cells due to the accumulation of hydrogen peroxide in the cell walls, leading to increased rigidity. This explains the weakened root growth observed. Furthermore, continuous exposure to high concentrations of this toxic element destroys most of the plant hormones responsible for growth, such as auxins and gibberellins, which function in transmitting cellular signals. Additionally, cadmium stimulates the accumulation of abscisic acid (ABA) and ethylene (ET) in the roots, which negatively affects root growth and the development of the plant's green parts during advanced growth stages.

Determinants of Heavy Metals in Soil and Plants:

International agencies, global organizations, and research institutions, as a result of ongoing studies and extensive experiments, have established standard toxicity limits for heavy metals in both soil and plants to determine the critical thresholds for these elements, such as (FAO, WHO,2007).

Table 1. shows the critical threshold values for the concentrations of heavy metals (lead, cadmium, zinc, and nickel) in plant, expressed in mg kg^{-1}.

Heavy Metals	Cd	Pb	Zn	Ni	Reference
Th permissible limit in plants by WHO	0.02	2	50	10	Nazir et al.,2015

Table 2. shows the critical threshold values for the concentrations of heavy metals (lead, cadmium, zinc, and nickel) in soil, expressed in mg kg^{-1}.

Heavy Metals	Cd	Pb	Zn	Ni	Reference
Th permissible limit in plants by WHO	3	100	250	50	Nazir et al.,2015

Methods by which plants mitigate the risk of heavy metal pollution:

The vegetative parts of leafy vegetable plants are characterized by their high capacity to capture and deposit heavy metals directly from polluted atmospheric air. This occurs through stomata or absorption via roots extending into contaminated soil, as heavy metals bind to plant cell walls. Additionally, excessive and hyperactive cellular responses aim to mitigate the harmful effects of heavy metals by secreting resistance enzymes within plant cells or isolating and aggregating heavy metals into specific locations such as vacuoles or vesicles within the cells. Heavy metals can also be chelated by organic or inorganic ligands or converted into less soluble compounds within the plant cells (Meneh ,1997and Abdul,2020). In a study conducted by Ubaid (2010) to investigate the behavior of three carrot varieties under specific treatments with four heavy metals

using a single type of soil contaminated with these metals, it was concluded that, in general, the relationship between heavy metals and plants is governed by the physiological characteristics of the plant species as well as the concentration and properties of the heavy metal itself in the soil. Additionally, both Saeed (2014) and Muhammad et al. (2022) highlighted that the accumulation of heavy and toxic metal concentrations in plant tissues beyond internationally permissible limits can expose plants to stress, weakened growth, toxicity, and disruptions in various physiological processes.

Natural Barriers That Limit the Uptake of Heavy Metals in Certain Plants:

There are several natural barriers that limit the uptake of toxic heavy metals into plants growing in contaminated soils, as highlighted by Louisville (2015). These include:

1. **Soil and Root Barrier:**

This is among the most significant natural barriers that limit the uptake of some heavy and toxic elements, such as lead. Lead has relatively low solubility in most soil types and cannot easily enter plant cells through the roots.

2. **Root Release Barrier:**

Most heavy metal elements tend to bind strongly with the roots, and their movement to other parts of the plant is relatively limited. This restriction helps reduce the impact of toxic metals on the rest of the plant.

3. **Barrier to Movement Toward Fruits:**

Studies and research in this field agree that most toxic elements are somewhat distant from affecting the fruiting parts of plants. Consequently, the impact of these elements is more concentrated on the vegetative parts of the plant.

Factors Facilitating the Mobility of Pollutants in Soil

The total concentration of heavy metals in the soil does not provide sufficient information about their mobility, availability, and accessibility to plants. The chemical and physical properties of soils control their appearance in the soil. Therefore, studying the relationship between the available concentration in the soil on the one hand and the levels of heavy metal in the plant on the other hand will give us scientific evidence of their availability. It also helps us know the extent of the danger of these elements in terms of their toxicity, movement and transfer in the soil. (Al-Faraj et al., 2010; Tasneem, 2023). Ahmed (2013) identified some factors that affect the availability of pollutants in the soil environment include:

1. Adsorption by organic and inorganic materials.
2. Forms of the Pollutant in Soil (Soluble or Insoluble).
3. Low Microbial Breakdown.
4. Leaching.

In 1984, Sposito demonstrated proven that there are multiple and diverse mechanisms to hold and restrict the movement of heavy metals in contaminated soils. Some of them depend on the ability of these polluting elements in the soil to be held by the surfaces of colloids, particles of organic materials, oxides such as iron and aluminum, or mineral carbonates. Heavy metals may be held together by ionic forces, electrostatic bonds, or covalent (van der Waals) bonds. Which limits its movement and spread depending on its concentration in the solution and the properties of the solid surface. The soil's ability to bind harmful elements and transform them into immobilized forms, making them unavailable for plant absorption, is part of the divine

miracles bestowed by God. This remarkable system grants plants the extraordinary capability to selectively absorb essential nutrients while excluding non-essential or harmful elements in the soil, ensuring their growth and survival (Mohammed, 2013 and Abdul and Akram, 2016).

Mechanisms of Heavy Metal Uptake by Plants

Most plants growing in contaminated environments develop an important characteristic: their ability to store heavy metals in their roots and control the transfer of certain amounts of these metals from the roots to the stems, leaves, and fruits. This adaptation helps them resist the toxicity of such elements. The higher the concentration of heavy metals in the soil, the greater the uptake by the plant, as demonstrated by Ali and Hamoudi (2008). Different plants vary in their ability and capacity to distribute heavy metals between their shoot and root systems. A study conducted by Senthilkumar et al., (2005) found that (Prosopis juliflora) tends to accumulate cadmium in its root system at concentrations significantly higher than in its shoot system. The study also revealed that the concentration of both copper and cadmium in the plant greatly exceeds their concentration in the soil solution.

Mechanisms of Plant Resistance to Heavy Metals

The term "plant resistance to toxicity" is defined as the ability of a living organism to confront the toxicity of heavy elements through various mechanisms as a form of adaptation, producing indirect responses to the types and forms of heavy elements. Plants exhibit varying degrees of resistance to the toxicity of heavy metals by either preventing the accumulation of these elements in targeted sites or through tolerance mechanisms when these elements enter the cytoplasm.When the level of heavy metals increases within plant tissues, the plant either accumulates or stores them in specific sites within the roots, foliage, or fruits known as vesicles or transforms them into other non-toxic forms within the plant (Memon et al., 2001and Al Shamary and Al-Joubory, 2024).

Conclusions:

Heavy metals are among the most dangerous toxic substances released into the environment, especially in the soil. Therefore, it must be disposed of in a safe and environmentally friendly manner. By planting plants with a high capacity to accumulate them in their various parts and distributing them in each of their vegetative, root, or fruit groups, and then getting rid of them in one of the safe ways. Therefore, we recommend expanding such studies by exploring new types of plants that accumulate these toxic and dangerous elements in their various tissues.

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