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[Review Article] Excessive Aluminum in Soil

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Abstract

This review paper explores the impact of excessive aluminum in soil on plant growth, environmental factors, and human health. It highlights the complex effects of aluminum on plants, emphasizing its role in inhibiting root growth. The study discusses sources of aluminum contamination, health risks associated with exposure, assessment methods, and remediation strategies. Recent advances include phytoremediation, genetic engineering, and nanotechnology. The paper concludes with strategies for preventing aluminum overload in agricultural lands through proper soil management and sustainable farming practices.

Keywords: Soil pH, Aluminum toxicity, Soil fertility, Metal pollution

Effects of Aluminum Accumulation in Soil

Aluminum (Al) is the third most abundant element in the earth's crust (Silva, S., 2012) and can have profound effects on soil properties and plant growth when it accumulates. The accumulation of Al in soil primarily occurs due to the weathering of Al-containing minerals, such as feldspars and micas, and the subsequent release of Al ions into the soil solution.

The impact of Al accumulation on soil properties is multifaceted. At a chemical level, Al can react with water to form Al hydroxides, which can lead to soil acidification. This acidification can further increase the solubility of Al, leading to a self-reinforcing cycle of Al accumulation and soil acidification (Bojórquez-Quintal, E. et al., 2017). Moreover, Al can form complexes with organic matter and phosphates, reducing the availability of these essential nutrients for plant uptake.

From a physical perspective, Al accumulation can alter soil structure. Excess aluminum in soil can alter its structure and negatively impact plant growth. In acidic soils, aluminum can exist in mobile forms, leading to its absorption and assimilation by plants. This can disrupt the mineral nutrition of plants, affecting processes such as water regulation, nitrogen metabolism, mineral uptake, and photosynthesis. The presence of excessive aluminum ions can also stimulate various anatomical and morphological changes in plants, leading to phytotoxicity (Horst, J, W., Wang, Y. and Eticha, D., 2010).

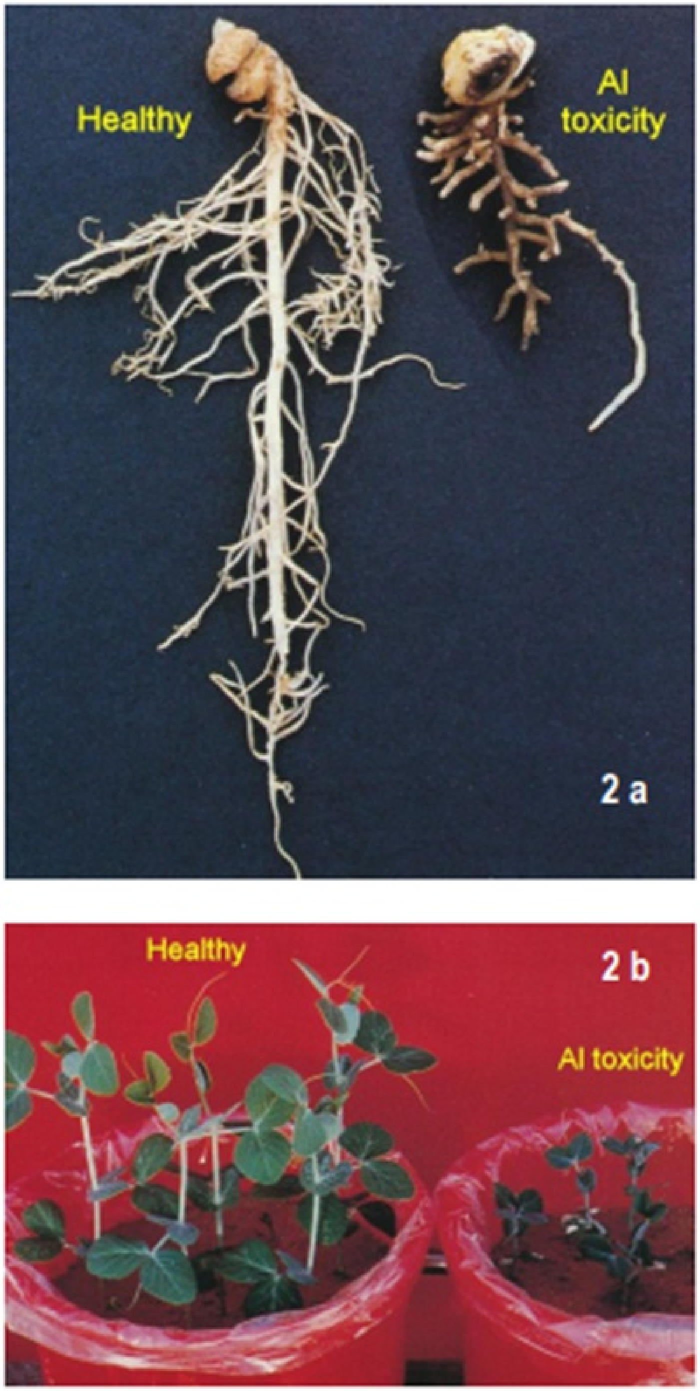

Figure 1. *Aluminum toxicity symptoms in field pea (a) Plant roots (b) Foliage.*

The biological effects of Al accumulation are also significant. High Al concentrations can be toxic to many plant species, inhibiting root growth and function. This can lead to nutrient deficiencies, as the plant's ability to take up nutrients from the soil is compromised. Furthermore, Al toxicity can induce oxidative stress in plants, damaging cellular structures and impairing plant health (Syndrome of aluminum toxicity and diversity of aluminum resistance in higher plants., 2007).

However, it's important to note that not all effects of Al accumulation are negative. Some plant species have evolved mechanisms to tolerate high Al concentrations, and Al can play a role in certain soil microbial processes (Foy, D, C., 1988). Studies have shown that silicon can reduce aluminum accumulation and mitigate its toxic effects in plants, and that aquatic plants have the potential for aluminum phytoremediation.

Additionally, in tea plants, a moderate supply of aluminum has been found to promote root growth, with the role of indole acetic acid (IAA) in facilitating these beneficial effects being studied. It was found that aluminum induces short-term IAA synthesis in the root tip and enhances IAA transport in other parts of the root over the longer term, thus promoting root growth in tea plants by limiting IAA accumulation (Zhou, P. et al., 2014).

Nevertheless, in many agricultural and natural ecosystems, Al accumulation in soil is a major concern that requires careful management to maintain soil health and productivity.

High soil aluminum levels can have significant environmental impacts as well, particularly in industrialized areas. Studies have shown that the use of materials such as steel slags in construction and aluminum smelting activities can lead to the accumulation of aluminum in soil and groundwater, resulting in high concern due to its potential hazard (Bojórquez-Quintal, E. et al., 2017). The strong alkaline nature of industrial materials can lead to contaminant leaching processes and affect metal mobility, posing risks to the environment and human health. Elevated aluminum concentrations in groundwater can lead to poor soil-plant relationships and cause important environmental problems.

Sources of Aluminum Contamination in Soil

There are several sources of aluminum contamination in soil but in this article we will only discuss three major ones.

One of the primary sources is acid deposition, which includes acid rain and acidic atmospheric pollutants. These sources contribute to the acidification of soil, leading to the dissolution of aluminum-containing minerals and the subsequent release of aluminum ions (Cronan, S, C. and Schofield, L, C., 1979).

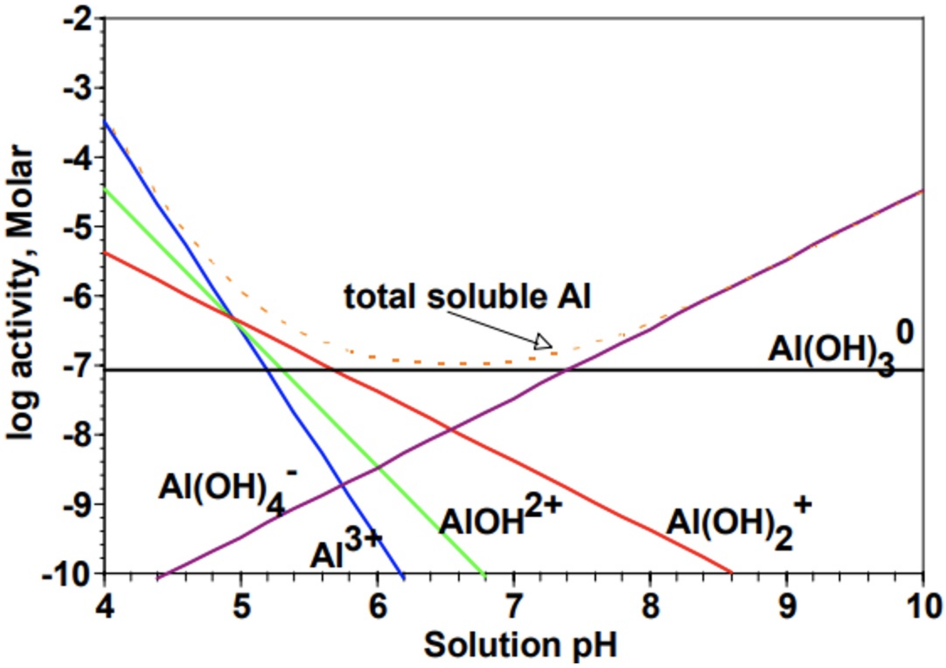

Figure 2. *Solubility diagram of the most significant species of Aluminum in an aqueous solution of Aluminum chloride at different pH. Source: McBride 1994*

Another source of aluminum contamination in soil include industrial activities, such as aluminum smelting can be a significant source of aluminum contamination in soil. A study conducted at an aluminum smelter plant in Nigeria found high concentrations of metals, including aluminum, in soils and plants, which can lead to serious environmental impacts and human health risks (Taboada-Castro, M., Rodríguez-Blanco, L, M. and Taboada-Castro, M., 2020)

Aluminum-based fertilizers can increase the concentration of aluminum in soil. Synthetic nitrogen fertilizers like, Ammonium Sulphate, Urea, Ammonium Nitrate, and Ammonium Sulphate Nitrate are commonly used in industrial agriculture, can exacerbate soil acidification, leading to increased accumulation of aluminum in the soil, by binding with the cations which can have detrimental effects on plant growth and soil quality. The use of aluminum-based fertilizers can also contribute to the accumulation of aluminum in soil, which can lead to serious environmental impacts and human health risks.

Assessment Methods for Soil Aluminum Concentration

Several assessment methods are used to measure soil aluminum concentration. These methods include the measurement of "labile" aluminum after short contact times with colorimetric reagents or cation-exchange resins, as well as the use of geostatistical tools to investigate the spatial distributions of aluminum in soil.

Labile aluminum refers to the fraction of aluminum in the soil that is readily available for chemical reactions and potential toxicity. It is often measured after short contact times with colorimetric reagents or cation-exchange resins. The estimation of toxic aluminum relies on the measurement of labile aluminum, which is the portion of aluminum that is not complexed with other ligands such as fluoride, sulfate, and oxalate.

This labile form of aluminum, particularly Al3+ and Al-hydroxy monomers, is related to aluminum toxicity in plants and can have adverse effects on soil and the rhizosphere bacterial community. However, it is important to note that shifts in equilibrium may result in non-toxic forms of aluminum reacting with the complexing agent or resin, so the assessment of labile aluminum requires careful consideration of the specific soil and environmental conditions.

The best techniques that can be used for measuring Aluminum concentration in soil are:

1. One commonly used method for assessing soil aluminum concentration is through soil sampling and analysis. This involves collecting soil samples from different locations within a field or area of interest and analyzing the samples in a laboratory. The collected samples can be extracted using various techniques, such as KCl or water extraction, to measure the concentration of soluble aluminum. (Singh, S. et al., 2017). Water extraction technique is a method used to measure aluminum contamination in soil. The technique involves adding water to soil samples and shaking them to extract the soluble aluminum. The extracted aluminum is then measured using colorimetric reagents or cation-exchange resins to determine the concentration of labile aluminum, which is the portion of aluminum that is not complexed with other ligands such as fluoride, sulfate, and oxalate. The measurement of labile aluminum in soil water extracts can provide information on the potential for aluminum toxicity in the soil. The distribution and phytotoxicity of soil labile aluminum fractions and aluminum species in soil water extracts have been analyzed in studies on tall fescue, which found that different forms of aluminum in soil can be toxic to plants and the bacterial community. Therefore, water extraction technique is a useful method for measuring aluminum contamination in soil and assessing the potential for aluminum toxicity (Zimmerman, J, A. and Weindorf, C, D., 2010).
2. Another method for assessing soil aluminum concentration is through the measurement of soil pH (Singh, S. et al., 2017). Soil pH is known to influence the solubility and availability of aluminum in the soil. In acidic soils, aluminum can become more soluble and available, potentially leading to aluminum toxicity in plants. Therefore, while soil pH measurement itself may not directly quantify soil aluminum concentration, it is an important factor to consider when assessing the potential for aluminum toxicity in the soil. The provided search results discuss the estimation of toxic aluminum through the measurement of "labile" aluminum after short contact times with colorimetric reagents or cation-exchange resins, as well as the influence of soil acidification on aluminum toxicity effects on plants.
3. One emerging technique is the use of advanced analytical instruments like X-ray fluorescence spectrometry. X-ray fluorescence (XRF) spectrometry is a powerful technique for measuring heavy metal concentrations in soil. It allows for the rapid and non-destructive analysis of a wide range of heavy metals, providing valuable information for combating soil pollution, repairing ecosystems, and guiding agricultural practices (Li, X. et al., 2019). Studies have utilized XRF spectrometry to identify heavy metal pollutants and their sources in farmland, assess heavy metal contamination in agricultural soils, and analyze soil heavy metal pollution along rivers. The technique has been employed to measure and quantify the concentrations of various heavy metals such as aluminum, chromium, copper, lead, mercury, nickel, zinc, thallium, vanadium, and cadmium in soil samples. XRF spectrometry offers a comprehensive and efficient approach to assessing heavy metal contamination in soil, providing essential data for environmental management strategies and regulatory decision-making.

The Deep Spectral Prediction Network (Chen, T. et al., 2009) is another advanced analytical method that utilizes deep learning techniques to quantitatively determine heavy metal elements in soil through X-ray fluorescence (XRF) analysis. This approach provides an accurate and effective means of measuring heavy metal concentrations, which is of great significance for combating soil pollution, rehabilitating ecosystems, and guiding agricultural practices. The method leverages deep learning algorithms to analyze the spectral data obtained from XRF analysis, allowing for the precise quantification of heavy metal elements in soil samples. By employing this innovative approach, researchers and environmental professionals can obtain rapid and reliable measurements of heavy metal concentrations in soil, facilitating informed decision-making and targeted remediation efforts. The Deep Spectral Prediction Network represents a cutting-edge application of deep learning in environmental analysis, offering a promising solution for addressing soil contamination and its associated impacts.

4. Reflectance spectroscopy, particularly visible-near infrared (Vis-NIR) spectroscopy, works by analyzing the interaction between soil and light to measure metal concentrations. This technique involves shining light on the soil and measuring the amount of light that is reflected. Different metals absorb and reflect light in unique ways, creating distinct "spectral signatures" that can be detected and analyzed. By comparing these signatures to known patterns, such as those obtained from soil samples with known metal concentrations, the technique can estimate the metal content of the soil (Wang, J. et al., 2014). Reflectance spectroscopy has been used to assess soil heavy metal concentrations determined by different analytical protocols, providing a rapid and non-destructive method for measuring metal concentrations in soil. It has also been employed to develop improved estimation models for retrieving soil heavy metal concentrations in mining areas, demonstrating its utility in environmental and agricultural applications.
5. Energy Dispersive X-Ray Fluorescence Spectrometry (EDXRF) is a technique that can help determine metal concentrations in soil by measuring the characteristic X-rays emitted by a sample when it is irradiated with high-energy X-rays. This method has been used in various studies to assess heavy metal contamination in agricultural soils and to analyze the existence of metal pollution in soil samples. For example, a study conducted in Bani-Alharith used EDXRF to analyze soil samples for heavy metals such as Al, V, Cr, Co, Ni, Cu, Zn, Pb, Sn, Mn, Ti, and Zr, revealing that the concentration levels of these heavy metals in all examined soil exceeded the recommended safety values (Mohsen, T, H., Zahran, N. and Helal, I, A., 2007). Similarly, another study used EDXRF to measure and quantify the concentrations of heavy metals such as Cr, Cu, Pb, Hg, Ni, Zn, Tl, V, and Cd in soil samples collected along the Subin River in Ghana. These findings demonstrate the utility of EDXRF in assessing and managing heavy metal contamination in soil, providing valuable information for environmental protection and agricultural practices (Embong, Z. et al., 2015).

Remediation Strategies for Aluminum-Contaminated Soils

There are some effective techniques to control Aluminum and other metal contamination in soil and mitigate their adverse effects on plant growth and environment.

1. The immobilization technique can help in the remediation of aluminum-contaminated soils by reducing the bioavailability of aluminum, thereby minimizing its potential risks to the environment and living organisms. This technique works by using various soil amendments to manipulate the bioavailability of heavy metals, such as aluminum, under different soil conditions. By doing so, the immobilization technique aims to decrease the mobility of aluminum, thus reducing its uptake by plants, leaching into groundwater, and potential exposure to other living organisms (Li, X., Xing, Z. and Shi, Z., 2020). The use of soil amendments like red mud, biochar, and phosphate rock has been studied to demonstrate the effectiveness of the immobilization technique in reducing the bioavailability of heavy metals in contaminated soils. This approach is considered cost-effective and easily applicable to a large quantity of contaminants derived from various sources, making it a promising option for the remediation of aluminum-contaminated soils. Therefore, the immobilization technique works by altering the chemical form of aluminum in the soil, reducing its mobility and bioavailability, and ultimately minimizing its potential adverse effects on the environment and living organisms.
2. The soil washing technique can help in the remediation of aluminum-contaminated soil by enhancing the desorption and removal of heavy metals from the soil. It involves the use of washing agents, such as biosurfactants, humic acids, and low-molecular-weight organic acids, to solubilize and mobilize the contaminants, thereby facilitating their extraction from the soil. The washing agents can enhance the desorption of heavy metals, making it easier to remove them from the soil (Mao, X. et al., 2015). Additionally, the use of mixture washing and sequential washing has been adopted to improve the overall capacity of the washing agent for decontamination, thereby increasing washing efficiency. The soil washing technique works by utilizing agents that can solubilize and mobilize the heavy metals, making them more accessible for removal from the soil. This process can be further enhanced by the use of synergistic effects through mixture washing and the application of washing agents with high heavy metal removal rates in sequential washing. Therefore, soil washing offers a promising approach for the remediation of aluminum-contaminated soil by effectively enhancing the removal of heavy metals from the soil.
3. The soil phytoremediation technique can help in the remediation of aluminum-contaminated soil by utilizing plants to extract, stabilize, or degrade the contaminants. Phytoremediation is an effective method for the remediation of soil with metal pollutants, and the potential of different plant species for phytoremediation has been studied in various regions. The process of phytoremediation involves the uptake of contaminants by plant roots, translocation and accumulation within the plant, and subsequent removal of the contaminants through plant harvesting or fall of leaves (Sarwar, N. et al., 2017). This technique can be particularly useful for aluminum-contaminated soils, as certain plant species have the ability to accumulate and tolerate high levels of aluminum. Additionally, the use of biochar, a carbon-enriched residue, has been shown to promote the growth and phytoremediation competence of native or wild plants grown in metal-polluted soil, further enhancing the effectiveness of phytoremediation for aluminum-contaminated soils. Therefore, phytoremediation can be a sustainable and cost-effective approach for the remediation of aluminum-contaminated soils, utilizing the natural ability of plants to mitigate the environmental impact of the contaminants.
4. The bioremediation technique can help in the remediation of aluminum-contaminated soil by utilizing microorganisms to transform and detoxify the contaminants. This process can be achieved through biostimulation, which enhances the growth and activity of indigenous microorganisms, or bioaugmentation, which involves the introduction of specific

microorganisms to the contaminated site. The microorganisms, such as bacteria and fungi, can metabolize the aluminum and reduce its bioavailability, thereby mitigating its adverse effects on the environment (Jin, T. et al., 2021). The search results did not provide specific information on bioremediation of aluminum-contaminated soil. However, the general principles of bioremediation and its application to other contaminants suggest that it could be a potential strategy for aluminum remediation. Further research specifically addressing bioremediation of aluminum-contaminated soil may be necessary to determine the effectiveness and specific mechanisms of this technique.

Future Outlook: Preventing Aluminum Overload in Agricultural Lands

In order to prevent aluminum overload in agricultural lands, several key strategies can be implemented. These strategies include proper soil management practices, such as liming to raise the pH of acidic soils and reduce aluminum availability. Furthermore, regular soil testing can help identify areas with excessive aluminum levels and enable targeted remediation efforts.

1. Breeding aluminum-resistant crops is a potential solution for managing excessive aluminum in soil. A study from 1997 reported that Mexican researchers were able to make tobacco and papaya plants aluminum-tolerant by providing them with a bacterial gene that causes them to pump citric acid into the soil, which ties up aluminum ions and prevents them from entering and damaging the plants' roots (Fuente, I, d, M, J. et al., 1997). This genetic engineering approach offers a promising solution for developing crops that can tolerate aluminum-contaminated soil. Additionally, a review article on heavy metals stress, mechanism, and remediation techniques in rice discusses the selection and development of rice varieties (Rasheed, A. et al., 2020) resistant to heavy metal stress and bioaccumulation as a reasonable approach to alleviate heavy metal toxicity in rice. This approach could also be applied to other crops to develop aluminum-resistant varieties. The latest advancements in the field of breeding aluminum-resistant crops offer promising prospects for addressing excessive aluminum in soil and ensuring sustainable agricultural practices.
2. Recent advancements in bioremediation techniques have shown promise in the remediation of aluminum-contaminated soil. Bioremediation involves the use of microorganisms to transform and detoxify contaminants. Recent research has shown that genetic engineering can make plants aluminum-tolerant by providing them with a bacterial gene that causes them to pump citric acid into the soil, thereby preventing aluminum from damaging the plants' roots (Emenike, U, C. et al., 2018). Additionally, a study on the remediation of petroleum-contaminated soils using bioremediation technology found that the bacterial community structure and physicochemical characteristics of the soil treated using different bioremediation regimens were analyzed. The study found that biostimulation and bioaugmentation significantly increased the removal efficiency of petroleum hydrocarbons (PHs) from the soil, and combined biostimulation with bioaugmentation had the highest PHs removal efficiency (Agnello, C, A. et al., 2016). These findings suggest that bioremediation techniques, including genetic engineering and biostimulation/bioaugmentation, may be effective in the remediation of aluminum-contaminated soil. Further research is necessary to determine the most effective bioremediation strategies for aluminum-contaminated soil.
3. Soil amendments are materials added to soil to improve its physical, chemical, and biological properties. Recent

advancements in the field of soil amendments include the use of red mud, biochar, and phosphate rock for immobilization of heavy metals in contaminated soils, including aluminum (Zhou, Y. et al., 2016). The immobilization technique involves the manipulation of the bioavailability of heavy metals using a range of soil amendment conditions, which can efficiently alleviate the risk of groundwater contamination, plant uptake, and exposure to other living organisms (Xia, H. and Yan, Z., 2010). The use of biosurfactants has also been studied to enhance soil washing for the remediation of co-contaminated soils by heavy metals and polycyclic aromatic hydrocarbons (PAHs) (Xia, H. and Yan, Z., 2010). These advancements offer promising prospects for addressing excessive aluminum in soil and ensuring sustainable agricultural practices. The immobilization technique, which is inexpensive and easily applicable to large quantities of contaminants derived from various sources, holds promise as a remediation strategy for managing excessive aluminum in soil.

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