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Trace Elements Behavior in Salt-Affected Soils: A Review

Muhammad Zaib[*], Muhammad Zubair[**], Sana Mumtaz[*], Chanda Shaheen[***], Hamza[**], Areeba Muqaddas[**], Rabia Sarwar[**], Muhammad Noman[****], Muhammad Irfan[**], Zulaikha Aman[**], Abdul Hanan[**], Swaid Sajid[**]

[*]Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, Punjab, Pakistan
Email: zaibch767@gmail.com

[**]Institute of Soil and Environmental Sciences, Faculty of Agriculture, University of Agriculture Faisalabad, Punjab, Pakistan
Email: muhammadzubair68852@gmail.com

[*]Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, Punjab, Pakistan
Email: s.malik.m488@gmail.com

[***]Department of Botany, University of Agriculture Faisalabad, Punjab, Pakistan
Email: chandashaheen786@gmail.com

[****]Department of Economics, University of Agriculture Faisalabad, Punjab, Pakistan
Email: ch5856976@gmail.com

[****]Institute Of Education, Agriculture Extension & Rural Development, University of Agriculture Faisalabad, Punjab, Pakistan
Email: muhammednouman89@gmail.com

[**]Institute of Soil and Environmental Sciences, Faculty of Agriculture, University of Agriculture Faisalabad, Punjab, Pakistan
Email: mirfangill693@gmail.com

[**]Institute of Soil and Environmental Sciences, Faculty of Agriculture, University of Agriculture Faisalabad, Punjab, Pakistan
Email: amanullah.zulaikha@gmail.com

[**]Institute of Soil and Environmental Sciences, Faculty of Agriculture, University of Agriculture Faisalabad, Punjab, Pakistan
Email: abdulhanana003@gmail.com

[**]Institute of Soil and Environmental Sciences, Faculty of Agriculture, University of Agriculture Faisalabad, Punjab, Pakistan
Email: malikswaid22@gmail.com

Corresponding Author:
Muhammad Zaib
zaibch767@gmail.com
Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, Punjab, Pakistan

Abstract

Salt-affected soils pose significant challenges to agricultural productivity and environmental sustainability. These soils contain elevated levels of soluble salts and often exhibit adverse conditions for plant growth, including high salinity, sodicity, and limited nutrient availability. Additionally, the behavior of trace elements in salt-affected soils can exacerbate soil quality issues and impact plant health. This review aims to provide a comprehensive analysis of the behavior of trace elements in salt-affected soils, focusing on their mobility, availability, and potential impacts on agricultural systems and ecosystems. The review highlights key factors influencing trace element behavior, such as soil properties, redox conditions, and the presence of competing ions. Furthermore, the role of management practices in mitigating trace element-related issues in salt-affected soils is discussed. The review concludes with recommendations for future research directions and sustainable soil management strategies to address trace element dynamics in salt-affected soils, ensuring improved agricultural productivity and environmental stewardship.

Keywords: **Trace elements, salt affected soils, soil properties, agriculture, environment, salinity, sodic soils**

1. Introduction

Salt-affected soils are soils that have accumulated high concentrations of soluble salts, leading to adverse effects on plant growth and agricultural productivity. These salts primarily include sodium chloride (NaCl), calcium sulfate ($CaSO_4$), and magnesium sulfate ($MgSO_4$). The excessive presence of salts can create challenging conditions for plant roots to uptake water and essential nutrients, resulting in poor crop growth and reduced yields. The term "salt-affected soils" is often used interchangeably with "saline soils" or "sodic soils," depending on the specific dominant salt type and the overall soil characteristics. Salt-affected soils are a significant concern in many agricultural regions worldwide, and their management requires appropriate soil reclamation and irrigation strategies to improve crop productivity and preserve soil health[1].Salt-affected soils are widespread globally and are found in various regions with different climatic and geographical conditions. The prevalence and distribution of salt-affected soils are influenced by factors such as natural soil-forming processes, climate, irrigation practices, and anthropogenic activities.Salt-affected soils cover a substantial portion of the Earth's land area. It is estimated that approximately 6% of the world's total land area is affected by salinity, sodicity, or both[2].Salt-affected soils are particularly prevalent in arid and semi-arid regions, where the combination of low rainfall and high evaporation rates contributes to salt accumulation in the soil[3].Irrigation practices can lead to the accumulation of salts in the soil due to the use of water containing dissolved salts. Over-irrigation or poor drainage in irrigated areas exacerbates the problem[4].Salt-affected soils are prevalent in coastal regions due to saline water intrusion from the sea. Coastal agriculture faces challenges in managing soil salinity and its impact on crops[5].Sodic soils, characterized by high pH and exchangeable sodium, are prevalent in alkaline areas. These soils pose challenges to plant growth due to poor soil structure[6].Salt-affected soils are found in dryland regions, where limited rainfall and high evaporation rates result in the accumulation of salts in the soil[7].Human activities, such as improper irrigation practices, land degradation, and deforestation, can contribute to soil salinization and sodification in various regions[8].The prevalence and distribution of salt-affected soils are a global concern, affecting agricultural productivity and ecosystem health. Proper soil management practices, including irrigation management, soil drainage, and appropriate crop selection, are essential to mitigate the impacts of salt-affected soils and ensure sustainable land use.

Salt-affected soils, also known as saline or sodic soils, present significant challenges in both agricultural productivity and environmental sustainability. These soils are characterized by elevated levels of soluble salts and adverse physicochemical properties, which can negatively impact plant growth and ecosystem health.Salt-affected soils often have high levels of salinity, which can lead to osmotic stress and ion toxicity in plants, impairing their growth and yield[9].Saline soils have low water-holding capacity, as high salt concentrations reduce water availability for plant uptake, exacerbating water stress in crops[10].Saline and sodic soils often exhibit nutrient imbalances, with reduced availability of essential nutrients such as nitrogen, phosphorus, and potassium, leading to nutrient deficiencies in plants[11].High salt concentrations can cause soil particles to disperse, leading to soil structure degradation, reduced water infiltration, and increased soil erosion.Saline soils are often associated with the use of saline water for irrigation, which can lead to the accumulation of salts in the soil, further exacerbating soil salinity[12].Excessive use of saline irrigation water can lead to the leaching of salts from the soil, which can contaminate groundwater resources.Saline soils can create inhospitable conditions for many plant species, leading to reduced biodiversity and negative impacts on terrestrial and aquatic ecosystems[13].

Addressing the challenges posed by salt-affected soils requires sustainable soil management practices, including soil reclamation, proper irrigation management, and the use of salt-tolerant crops. Integrated approaches that consider both agricultural and environmental aspects are essential for mitigating the adverse effects of salt-affected soils and ensuring long-term agricultural productivity and ecological balance.

2. Trace Elements in Salt-Affected Soils

Trace elements in salt-affected soils refer to the presence of various essential micronutrients and potentially toxic elements in soils with elevated levels of soluble salts. These elements play a crucial role in plant nutrition and overall soil health but can also pose challenges to agricultural productivity and environmental sustainability when their concentrations become excessive.

Trace elements found in salt-affected soils include both essential micronutrients, such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B), as well as potentially toxic elements, like cadmium (Cd), lead (Pb), and arsenic (As). These elements are naturally present in soil minerals, organic matter, and parent materials.The sources of trace elements in salt-affected soils can vary and may include natural weathering of rocks, volcanic activity, anthropogenic activities such as industrial emissions, agricultural practices, and the use of chemical fertilizers and pesticides.The mobility and speciation of trace elements in salt-affected soils depend on several factors, including soil pH, redox conditions, organic matter content, and the presence of specific minerals that can bind or release these elements. Redox conditions, especially in waterlogged or anaerobic soils, can influence the availability and mobility of certain trace elements.The availability of trace elements to plants is influenced by soil properties, pH, and interactions with other ions. Soil pH plays a crucial role in determining the solubility and uptake of trace elements by plants.Trace elements are essential for plant growth and play crucial roles in various metabolic processes. However, excessive concentrations of certain trace elements can be toxic to plants, leading to reduced yields and overall crop health.Elevated levels of trace elements in salt-affected soils can have significant implications for soil microbial communities, soil health, and terrestrial and aquatic ecosystems. Certain trace elements, such as cadmium and lead, can be particularly detrimental to ecosystem health[14].

3. Mobility and Speciation of Trace Elements

3.1.Mobility of trace elements

The mobility of trace elements in soils refers to their ability to move within the soil profile or transfer to other environmental compartments, such as groundwater or surface water. The mobility of trace elements is influenced by various factors, including soil properties, redox conditions, pH, and the presence of competing ions. Understanding the mobility of trace elements is crucial for assessing their potential impacts on the environment and human health.

The mobility of trace elements is influenced by soil properties, such as soil texture, organic matter content, and clay minerals. Soil texture and organic matter can adsorb and retain trace elements, reducing their mobility, while clay minerals may enhance their mobility through ion exchange processes.Redox conditions in the soil, specifically the presence of reducing or oxidizing environments, can significantly influence the mobility of trace elements. In reduced conditions, such as waterlogged soils, certain trace elements like arsenic may become more mobile and prone to leaching.Soil pH plays a crucial role in determining the mobility of trace elements. pH influences the solubility and speciation of trace elements, with some becoming more mobile under acidic conditions (low pH) and others under alkaline conditions (high pH).The presence of competing ions in the soil can affect the mobility of trace elements. For instance, the uptake of essential elements like zinc and copper by plants may be influenced by the presence of other cations, such as calcium and magnesium.Leaching is a common process by which trace elements are transported downward through the soil profile, potentially reaching groundwater. The mobility of trace elements in the soil greatly impacts their leaching potential[15]. Understanding the mobility of trace elements in soils is critical for sustainable land management, environmental protection, and human health. It helps in designing appropriate soil management practices to minimize the environmental impact of trace elements and safeguard soil and water quality. Researchers and policymakers continually work to improve our understanding of trace element mobility to develop effective strategies for managing their distribution and minimizing their potential risks.

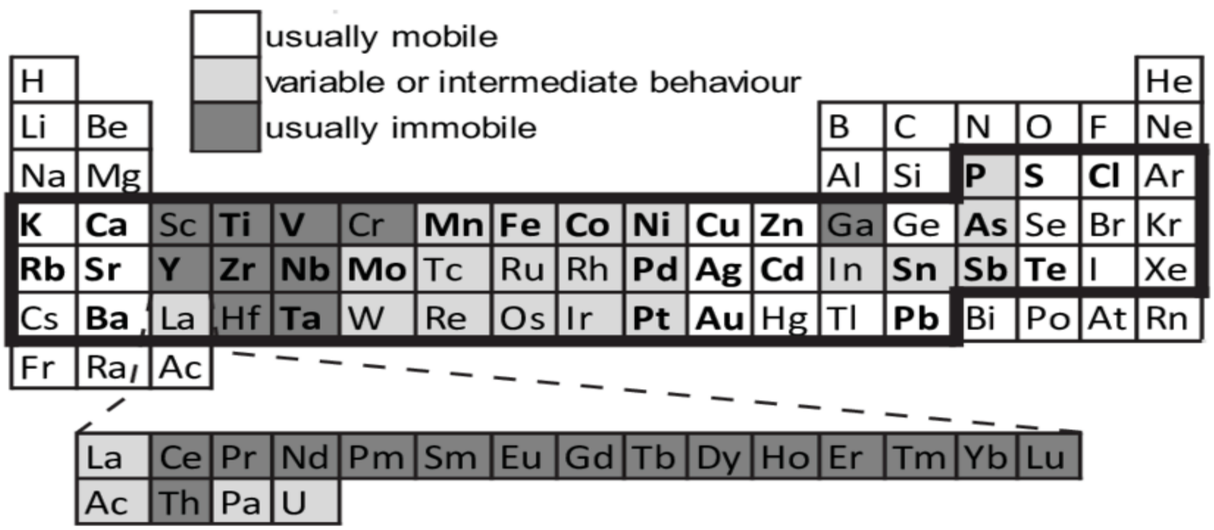

Figure 1. Periodic table with elements coded according to mobility during alteration.

Speciation of trace elements

Trace elements, such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg), can exist in multiple chemical forms in soil, water, and biological systems. These forms include inorganic species, organic complexes, nanoparticles, and colloidal particles.Inorganic speciation of trace elements involves different oxidation states and complexation with inorganic ligands, such as sulfates, chlorides, carbonates, and hydroxides. These forms can vary in solubility and mobility, influencing their transport in the environment.Trace elements can form complexes with organic ligands, such as fulvic acids, humic acids, and amino acids, in soil and water environments. Organic complexes can affect the bioavailability and toxicity of trace elements to plants and organisms.Trace elements can also exist as nanoparticles or be associated with colloidal particles in natural waters and soils. Nanoparticles may have distinct reactivity and mobility compared to larger particles or dissolved forms.Redox conditions play a crucial role in the speciation of some trace elements. For example, arsenic can exist in both oxidized (As(V)) and reduced (As(III)) forms, with As(III) generally more toxic and mobile.The speciation of trace elements directly influences their bioavailability to plants and organisms. Certain forms may be more easily taken up by plants, leading to potential toxicity in the food chain[16].

4. Factors influencing the mobility of trace elements in salt-affected soils

Factors influencing the mobility of trace elements in salt-affected soils are multifaceted and involve various soil properties, redox conditions, and interactions with other elements.

Soil pH is a crucial factor that affects the mobility of trace elements. pH influences the speciation of trace elements, determining their solubility and availability for uptake by plants. In acidic soils, certain trace elements may become more mobile and leachable, while in alkaline soils, they may form less soluble compounds, reducing their mobility.The presence of organic matter in soil can influence the mobility of trace elements by forming complexes with the elements. Organic matter can enhance the retention of trace elements through adsorption and reduce their mobility by preventing leaching.Redox conditions in soil, particularly in waterlogged or flooded environments, can significantly impact trace element mobility. Reducing conditions can increase the solubility of certain trace elements, leading to enhanced leaching and potential contamination of groundwater.Soil CEC influences the adsorption and retention of trace elements. Soils with higher CEC tend to retain trace elements more effectively, reducing their mobility and potential for leaching. The presence of other ions, such as calcium, magnesium, and iron, can compete with trace elements for adsorption sites on soil particles. High concentrations of competing ions can reduce the retention of trace elements and increase their mobility.Soil texture influences the porosity and permeability of soils, which can affect the movement and retention of trace elements. Fine-textured soils, such as clays, tend to retain trace elements more effectively than sandy soils[17].

5. Redox conditions and their impact on trace element behavior

Redox conditions refer to the prevailing state of reduction (gain of electrons) and oxidation (loss of electrons) reactions in the soil environment. These conditions significantly influence the behavior of trace elements, affecting their mobility, availability, and potential toxicity.

Redox conditions in soils can vary from highly oxidizing to strongly reducing. Oxidizing conditions occur when oxygen is present in the soil, facilitating oxidation reactions. In contrast, reducing conditions occur in waterlogged or anaerobic soils, where oxygen is limited, promoting reduction reactions. Under oxidizing conditions, certain trace elements, such as manganese (Mn), iron (Fe), and arsenic (As), tend o form more soluble and mobile oxyanions. These oxyanions can leach into groundwater or be transported through soil water, potentially reaching surface water bodies. Redox conditions can influence the availability of trace elements for plant uptake. Under oxidizing conditions, the presence of iron and manganese oxides can adsorb trace elements, reducing their bioavailability to plants. In contrast, reducing conditions can lead to the dissolution of iron and manganese oxides, releasing adsorbed trace elements and increasing their availability. Certain trace elements, such as chromium (Cr) and selenium (Se), exhibit redox-sensitive behavior, forming different chemical species under oxidizing and reducing conditions. These species may have different toxicity levels and environmental implications. Redox conditions can affect the toxicity of trace elements to plants and soil organisms. For example, under reducing conditions, some trace elements like cadmium (Cd) and mercury (Hg) can be converted to more toxic forms, increasing their potential negative impacts on living organisms [18].

6. Availability of Trace Elements to Plants

The availability of trace elements to plants refers to the extent to which these essential micronutrients are present in forms that plants can take up and utilize for their growth and development. Several factors influence the availability of trace elements in the soil and their uptake by plants.

6.1.Soil Properties and pH

Soil pH plays a crucial role in determining trace element availability. Some trace elements, such as iron (Fe) and manganese (Mn), become more available to plants in acidic soils, while others, like molybdenum (Mo) and boron (B), are more available in alkaline soils[18].

6.2.Redox Conditions:

As discussed in the previous response, redox conditions in the soil influence the availability of certain trace elements. Under reducing conditions, trace elements such as iron and manganese may become more soluble and available to plants[19].

6.3.Clay and Organic Matter Content:

Clay minerals and organic matter in the soil can adsorb trace elements, reducing their availability for plant uptake. However, organic matter can also chelate trace elements, enhancing their mobility and uptake by plants[20].

6.4.Competing Ions:

The presence of other cations in the soil, such as calcium (Ca), magnesium (Mg), and potassium (K), can compete with trace elements for binding sites on soil particles. High concentrations of competing ions may reduce trace element availability to plants[21].

6.5.Soil Fertility and Nutrient Interactions:

Adequate levels of essential macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), can influence the availability of trace elements to plants. Proper nutrient balance and interactions can enhance trace element uptake[22].

6.6.Plant Species and Genetics:

Different plant species and cultivars have varying abilities to uptake and utilize trace elements. Some plants have specific mechanisms, such as metal transporters, to enhance trace element uptake[22].

7. Influence of soil properties on trace element availability

In salt-affected soils, soil properties play a significant role in influencing the availability of trace elements to plants. The presence of high levels of soluble salts and specific soil conditions in these soils can impact trace element mobility, retention, and uptake by plants.

7.1.Salinity Effects on Trace Element Availability:

Salinity, characterized by high levels of soluble salts in the soil, can influence trace element availability in several ways:

7.1.1. Ion Competition:

High concentrations of sodium (Na) and chloride (Cl) ions in saline soils can compete with trace elements for adsorption sites on soil particles. This competition can reduce the adsorption of trace elements, making them more susceptible to leaching and reducing their availability to plants[23].

7.1.2. Leaching:

High salinity levels in the soil can increase the leaching of trace elements, especially under irrigation or rainfall. The increased leaching can lead to the loss of essential micronutrients from the root zone, reducing their availability to plants[24].

7.2.pH Effects on Trace Element Availability:

pH plays a vital role in determining the availability and speciation of trace elements in the soil. The influence of pH on trace element availability can vary depending on the specific trace element and its chemical behavior:

7.2.1. Redox Reactions:

Soil pH affects redox conditions, which, in turn, influence the transformation and speciation of trace elements. Under different pH levels, certain trace elements may be converted into more soluble or less available forms[25].

7.2.2. Trace Element Retention:

Soil pH can influence the adsorption of trace elements to soil particles. Some trace elements may be more adsorbed or retained by the soil at specific pH levels, affecting their availability for plant uptake[25].

7.2.3. pH-Dependent Speciation

The speciation of trace elements in the soil is strongly influenced by pH. For example, under acidic conditions (low pH), aluminum (Al) and manganese (Mn) can become more soluble and available to plants, while at higher pH levels, they tend to form less soluble compounds[23].

7.3.Interactions between trace elements and competing ions

Competing ions, such as calcium (Ca), magnesium (Mg), and potassium (K), can have a significant influence on the availability of trace elements in the soil. These competing cations compete with trace elements for binding sites on soil particles and exchange surfaces, affecting their adsorption and retention in the soil.Soil particles, particularly clay and organic matter, have negatively charged sites to which cations can bind. When competing cations like Ca, Mg, and K are present in high concentrations, they can occupy these binding sites, reducing the adsorption of trace elements. As a result, the availability of trace elements for plant uptake increases because fewer binding sites are occupied by competing cations.High concentrations of competing cations can lead to a reduction in the retention of trace elements in the soil. This reduced retention increases the mobility of trace elements, making them more susceptible to leaching, particularly in soils with poor adsorption capacity.With reduced adsorption and retention of trace elements due to competing cations, more trace elements are available in the soil solution. This increased availability enhances the uptake of essential micronutrients by plants, which is essential for their growth and development [26].

Balancing the presence of competing cations in the soil is essential for optimizing the availability of trace elements to plants. Adequate soil management practices, including proper fertilization and pH adjustments, can help maintain the right balance of cations, ensuring optimal nutrient availability for healthy plant growth.

8. Interactions between trace elements and competing ions

Trace elements may have a variety of effects on agricultural systems, including effects on crop growth, productivity, and quality. While trace elements are vital micronutrients for plants, it is important to carefully control their quantities to prevent toxicities or deficiency. An explanation of how trace elements affect agricultural systems is provided below:

Trace elements, such as iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), boron (B), molybdenum (Mo), and nickel (Ni), are essential for plant growth and development. They serve as cofactors in various enzymatic reactions and are crucial for processes such as photosynthesis, respiration, and nitrogen fixation.Inadequate trace element levels in the soil can lead to nutrient deficiencies in crops, affecting their overall health and productivity. For instance, iron deficiency can result in chlorosis, leading to reduced photosynthesis and yield losses[27].Elevated concentrations of trace elements in the soil can cause toxicity in plants. For example, excessive levels of heavy metals like cadmium (Cd), lead (Pb), and mercury (Hg) can impair plant growth, disrupt metabolic processes, and induce oxidative stress.Trace element concentrations can influence the nutritional quality of crops. For instance, high levels of zinc in cereals can enhance the nutritional value of the grains, improving human health when consumed.Controlled application of trace elements can be used as a biofortification strategy to enhance the micronutrient content of crops, ensuring improved nutrition in populations relying on staple food crops.Trace elements can interact with other nutrients, affecting their uptake and utilization in plants. For example, zinc influences phosphorus metabolism, while manganese affects iron utilization[28].

Managing trace elements in agricultural systems involves balancing their concentrations to avoid deficiencies and toxicities, employing biofortification strategies to enhance crop quality, and ensuring sustainable nutrient management practices to promote plant health and agricultural productivity.

Conclusion

It is evident that the behavior of trace elements in salt-affected soils is highly dynamic and influenced by various factors, including soil properties, salt concentration, pH, and the specific characteristics of the trace elements themselves. This dynamic behavior underscores the need for a holistic approach to studying and managing trace elements in such environments. The review highlights that elevated salinity levels can significantly impact soil health by altering the mobility, availability, and bioavailability of trace elements. This has implications for both plant growth and human health, as these elements can accumulate in crops grown in salt-affected soils. Various mitigation strategies have been explored in the literature to manage trace elements in salt-affected soils. These include soil amendments, phytoremediation, and the use of alternative crop species that are more tolerant to salt and trace element uptake. Understanding the effectiveness and feasibility of these strategies is crucial for sustainable soil management practices. Advances in analytical techniques have played a vital role in improving our understanding of trace element behavior in salt-affected soils. These techniques, such as spectroscopy and isotope analysis, have enabled researchers to characterize and quantify trace element interactions more accurately. The review identifies several gaps in the current understanding of trace element behavior in salt-affected soils. Future research should focus on elucidating the mechanisms underlying trace element mobility and bioavailability, developing innovative mitigation strategies, and assessing the long-term impacts of trace element accumulation on ecosystem health.

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