

RESEARCH ARTICLE

Impact of earthquakes on soil chemical properties: A Review of mechanisms, changes, and implications for environmental and structural resilience

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ABSTRACT

The response of soil chemical properties to seismic events has gained significant attention in recent years due to its potential impact on both the environment and infrastructure. Earthquakes can alter the chemical composition of soils, leading to changes in their mechanical properties, which may subsequently affect the stability of embankments, retaining walls, and other civil infrastructure. This review presents a comprehensive analysis of the chemical changes in soils following earthquake events, with a particular focus on the factors influencing these changes and their implications for engineering applications. The paper examines the underlying mechanisms that govern soil behavior during and after seismic events, including liquefaction, soil consolidation, and contamination from hazardous materials. Furthermore, it highlights the importance of post-earthquake soil chemical analysis in assessing potential hazards, such as the release of harmful substances, and offers recommendations for improving soil management strategies in earthquake-prone regions. By reviewing both experimental studies and field observations, this research aims to provide a deeper understanding of the complex relationship between seismic activity and soil chemistry. The novelty of this review lies in its systematic approach to integrating chemical analysis and seismic impacts on soils, offering valuable insights for engineers, environmental scientists, and policymakers involved in disaster risk management and mitigation. Ultimately, this review serves as a foundational resource for enhancing earthquake-resilient infrastructure in geologically active areas.

Keywords: Earthquake; soil chemical properties; seismic impacts; liquefaction; soil compaction; nutrient cycling; earthquake-resistant infrastructure; Bangladesh; environmental resilience; post-disaster recovery

1. Introduction

Earthquakes are one of the most catastrophic natural disasters, causing significant damage to infrastructure, human life, and the environment. While the immediate physical destruction caused by earthquakes is well documented, their impact on soil chemical properties remains under-explored but is equally important for understanding post-earthquake recovery and resilience. Soil chemical alterations, such as changes in pH, nutrient availability, and the release of harmful substances, can have profound effects on

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ecosystems, agriculture, and the structural integrity of infrastructure. In many earthquake-prone regions, including Bangladesh, soil chemistry plays a crucial role in maintaining ecological balance and ensuring the stability of infrastructure. Soil health is particularly important in these regions, where agriculture is a significant economic sector, and groundwater sources are essential for human and agricultural needs^[1,2]

The effect of earthquakes on soil chemistry can be classified into immediate and long-term changes. On the one hand, the direct impact includes soil liquefaction, which alters soil texture and chemical composition, potentially releasing toxic chemicals into the environment^[3]. On the other hand, post-earthquake chemical changes such as acidification, nutrient leaching, and contamination from industrial sites can affect soil fertility and agricultural productivity, complicating recovery efforts^[4]. These changes are not only of concern for agricultural regions but also for cities and industrial zones where infrastructure and public health could be compromised due to contaminated soil and groundwater^[5].

Despite the growing recognition of the importance of soil chemistry in earthquake resilience, there remains a lack of comprehensive reviews that consolidate the existing knowledge on the subject. Most studies focus on either soil liquefaction or the physical impact of seismic events, without integrating the full spectrum of chemical changes that occur in the soil^[6,7]. This gap is particularly critical in regions like Bangladesh, where soil is heavily impacted by seismic activity, flooding, and industrial pollutants. Moreover, these chemical changes have the potential to exacerbate environmental degradation and affect the recovery of both soil and infrastructure after an earthquake^[6].

The objective of this review is to synthesize the latest research on the effects of earthquakes on soil chemical properties, focusing on the mechanisms of change, environmental consequences, and implications for post-disaster recovery and risk management. By gathering insights from both global and regional case studies, such as those from Bangladesh and Japan, this review aims to provide a comprehensive understanding of how seismic activity alters soil chemistry. It will also explore how these changes influence soil fertility, agricultural productivity, and the design of earthquake-resistant infrastructure.

While studies have addressed the physical effects of earthquakes on soil, this review stands out by providing a focused analysis of the chemical consequences of seismic events, an area that has not been comprehensively reviewed in the literature. The novelty of this review lies in its integration of diverse earthquake-induced soil chemical changes, including the role of liquefaction, soil compaction, leaching of toxic substances, and acidification. Additionally, this review provides an in-depth look at the post-earthquake recovery process, examining how soil chemistry influences ecosystem restoration and agricultural recovery. The review also highlights the significance of soil chemical monitoring in disaster management and the need for targeted interventions to mitigate soil degradation following seismic events. The **Figure 1** shows the Carbon Cycle.

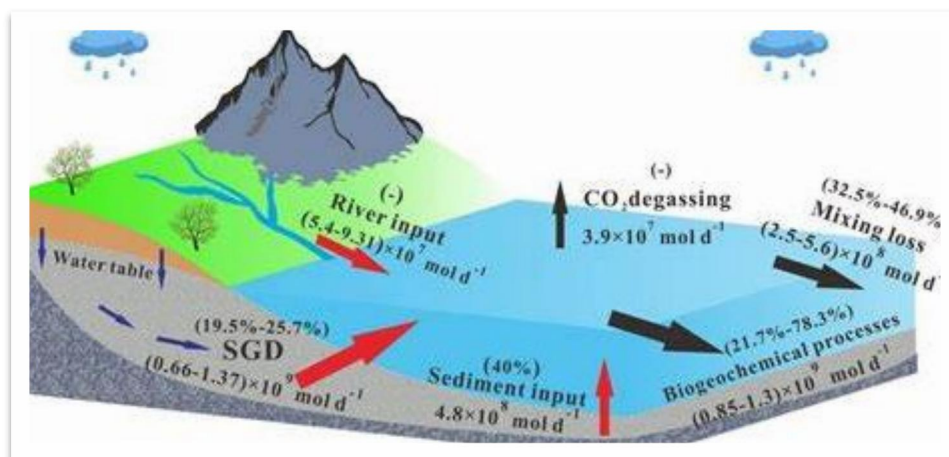


Figure 1. Carbon cycle.

This review offers several benefits to researchers, practitioners, and policymakers. For researchers, it provides a thorough compilation of existing studies, filling a gap in the understanding of earthquake-induced soil chemical changes. It also suggests future research directions, such as the development of more robust methodologies for monitoring soil chemistry in earthquake-prone regions. For practitioners and engineers, the review underscores the importance of soil chemical analysis in the design of earthquake-resistant structures and the development of sustainable land management practices. Lastly, policymakers can use the findings of this review to formulate disaster preparedness strategies that include soil chemical monitoring, thereby enhancing resilience to both the immediate and long-term effects of earthquakes on the environment and infrastructure.

By enhancing the understanding of the impact of earthquakes on soil chemical properties, this review aims to provide a foundation for more effective disaster response and recovery strategies. This knowledge is crucial for reducing the environmental and economic toll of seismic events and ensuring long-term sustainability in earthquake-prone regions.

2. Literature review

The relationship between earthquakes and soil chemical changes has been the subject of growing interest over the past few decades. Researchers have explored various aspects of this issue, from physical soil alterations like liquefaction to more subtle chemical changes that may affect soil quality over time. A thorough review of the literature on this topic is essential to understand the underlying mechanisms at play.

2.1. Soil pH and nutrient availability

Soil pH plays a crucial role in determining the availability of essential nutrients. Earthquakes often lead to the release of acidic substances, which can lower soil pH and disrupt nutrient cycles^[8]. This is particularly true in areas where the soil is prone to liquefaction. Studies have shown that the shaking of the ground can lead to a temporary reduction in pH due to the mobilization of sulfuric compounds^[4]. This acidification can affect the solubility of metals and other contaminants, further impacting soil fertility and the health of plants^[9].

2.2. Soil liquefaction and chemical reactions

Soil liquefaction is a phenomenon that occurs when saturated soils temporarily lose strength and behave like liquids due to seismic shaking. This can lead to a variety of chemical reactions, including the leaching of pollutants into the environment^[10]. Liquefaction can also cause the formation of cracks and fissures in the

soil, leading to the release of harmful substances such as petroleum products, heavy metals, and other contaminants. These chemical releases pose significant environmental risks, particularly in industrial areas where hazardous chemicals are used^[11, 12].

2.3. The role of organic matter

The organic matter in soil is another important factor that influences soil chemistry during and after an earthquake. Earthquakes can cause the breakdown of organic matter, releasing various organic acids and compounds that affect soil chemistry^[12]. Additionally, changes in moisture content due to seismic shaking can alter the decomposition rates of organic materials, leading to further chemical changes. Organic compounds released during these processes can impact plant growth and soil fertility in the post-earthquake recovery period^[4].

2.4. Chemical contaminants from industrial sites

In earthquake-prone areas, industrial facilities may be at risk of releasing hazardous chemicals due to seismic activity. Earthquakes can cause tanks, pipes, and other infrastructure to rupture, leading to the spillage of toxic substances into the surrounding environment^[13]. These chemicals can permeate the soil, altering its chemical properties and creating long-term ecological risks. Several studies have examined the effects of such releases, highlighting the need for effective mitigation strategies to reduce the environmental impact of industrial accidents during earthquakes^[14, 15].

3. Soil chemical properties before and after earthquakes

Understanding the soil conditions before and after an earthquake is crucial for assessing the extent of seismic impacts on soil chemistry. Soil properties such as organic matter content, nutrient availability, and pH are essential indicators of the vulnerability of soil to earthquake-induced chemical changes.

3.1. Pre-earthquake soil conditions

Pre-existing soil conditions play a significant role in determining how soils will respond to seismic events. Factors such as soil texture, moisture content, and organic matter levels influence the extent of chemical changes during and after an earthquake. Studies have shown that soils with high organic content are more resilient to the effects of seismic events, as organic matter can buffer changes in pH and nutrient availability^[16].

3.2. Post-earthquake soil changes

After an earthquake, soil can undergo significant chemical alterations, particularly in areas that experience liquefaction or soil compaction. For instance, the 2011 Tōhoku earthquake resulted in notable changes in soil pH, organic matter content, and nutrient cycling^[17]. The release of sulfuric and other acidic compounds during these events can further degrade soil health, while the redistribution of nutrients can lead to temporary soil infertility.

4. Chemical analysis of soil post-earthquake

After a seismic event, the chemical properties of soil undergo significant changes that can have long-term implications for both the environment and human health. Soil, as a dynamic natural resource, is influenced by a range of factors during and after an earthquake. These changes include alterations in pH, nutrient availability, heavy metal contamination, and shifts in organic matter composition^[7, 8]. The process of chemical analysis of soil post-earthquake is critical in understanding the extent of damage, mitigating risks associated with contamination, and formulating recovery strategies for agriculture, public health, and

infrastructure. This section explores the key chemical parameters that are commonly assessed in post-earthquake soil analysis, methodologies used in these assessments, and the implications of the findings for recovery efforts. **Figure 2** shows the ground and soil failure after earthquake at Ranau, Sabah.



Figure 2. Ground and soil failure after earthquake at Ranau, Sabah (Foong, 2016).

4.1. Key chemical parameters assessed in post-earthquake soil analysis

1. Soil pH

Soil pH is a crucial parameter that reflects the soil's acidity or alkalinity, which in turn influences nutrient availability and microbial activity. Earthquakes can trigger changes in pH due to soil liquefaction, which increases the mobility of acidic or alkaline contaminants^[7-9]. In areas prone to acid rain or industrial activity, soil acidification may be exacerbated post-earthquake, potentially leading to a reduction in soil fertility and an increase in the leaching of heavy metals. Conversely, alkaline conditions can disrupt nutrient uptake in plants, affecting agricultural recovery^[8]. Monitoring pH fluctuations in soils post-earthquake is therefore vital to assess potential hazards for agriculture and human health.

2. Nutrient leaching and availability

Earthquake-induced landslides, soil liquefaction, and flooding can lead to the mobilization and redistribution of nutrients, particularly nitrogen, phosphorus, and potassium, which are essential for plant growth. These changes can alter the fertility of the soil and impact agricultural productivity^[10]. For instance, an increase in surface runoff due to liquefaction and flooding can lead to nutrient leaching, reducing soil nutrient levels^[4]. Chemical analysis of nutrients, including micronutrients like zinc, copper, and manganese, is crucial for determining soil health post-earthquake and guiding fertilization strategies during recovery.

3. Heavy metals and toxic contaminants

Earthquakes may trigger the release of toxic chemicals and heavy metals from industrial sites, hazardous waste storage areas, or mining operations. These substances can contaminate nearby soils, creating serious environmental and public health risks. Chemicals such as lead, arsenic, cadmium, and mercury can be mobilized into the soil following a seismic event^[14]. In regions with industrial activity, post-earthquake soil chemical analysis often focuses on detecting and quantifying these pollutants to mitigate their impact on local ecosystems and populations^[5]. The introduction of these

toxic substances into the soil not only affects plant life but also contaminates groundwater, which can have cascading effects on public health.

4. Organic matter degradation

Organic matter in the soil, including decomposed plant and animal material, plays a vital role in maintaining soil structure, water retention, and nutrient cycling. Earthquakes can disrupt soil structure, leading to a loss of organic matter or changes in its composition^[14]. The physical displacement of soil particles can expose organic material to oxygen, accelerating its decomposition. Conversely, in areas where soil becomes waterlogged due to liquefaction, anaerobic conditions may prevail, leading to the production of harmful gases such as methane and hydrogen sulfide. Chemical analysis of organic matter helps to assess changes in soil fertility and identify strategies for restoring soil health after an earthquake.

4.2. Methodologies for soil chemical analysis post-earthquake

Post-earthquake soil chemical analysis typically involves several stages: sample collection, preparation, chemical analysis, and data interpretation. The choice of methodology depends on the specific goals of the analysis, the type of contamination, and the resources available. Common methodologies include:

1. Soil sampling

Systematic soil sampling is crucial for capturing the spatial variability of soil chemical properties across earthquake-affected areas. Samples are usually collected from different depths and locations, especially from areas prone to liquefaction, landslides, or flooding^[7]. Sampling should be conducted immediately after the earthquake and periodically during the recovery process to track changes over time.

2. Spectroscopic techniques

Spectroscopic methods, including atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), are commonly used for detecting heavy metals and other toxic substances in soil^[10]. These methods offer high sensitivity and precision, enabling the identification and quantification of trace elements that may pose environmental and health risks.

3. Chromatographic techniques

Gas chromatography (GC) and high-performance liquid chromatography (HPLC) are widely used to analyze organic compounds and pollutants in soil samples. These techniques are particularly useful for identifying petroleum hydrocarbons, pesticides, and other organic pollutants that may be released during an earthquake due to infrastructure damage^[17].

4. Soil pH and nutrient analysis

Soil pH is typically measured using a potentiometer, and nutrient levels are assessed using methods such as the Mehlich-3 extraction technique for macronutrients and micronutrients. These analyses provide valuable insights into changes in soil fertility and nutrient availability after an earthquake.

4.3. Implications of soil chemical analysis for post-earthquake recovery

The results of post-earthquake soil chemical analysis are integral to several aspects of recovery, including agricultural restoration, public health management, and infrastructure resilience.

- **Agricultural Recovery:** Soil chemistry plays a key role in determining the fertility of agricultural land post-earthquake. The analysis provides information on nutrient depletion, contamination, and

soil degradation, helping to guide appropriate soil management practices such as fertilization, remediation, and crop selection.

- **Environmental Risk Assessment:** By identifying the presence of hazardous chemicals or heavy metals in soil, chemical analysis helps assess the environmental risks posed by contaminated land. These findings are critical for devising policies to mitigate the long-term impacts of soil contamination on ecosystems and communities.
- **Public Health Monitoring:** Chemical analysis also helps identify potential threats to public health from contaminated soil and groundwater. For example, high levels of heavy metals or toxic chemicals may require immediate intervention to prevent exposure through direct contact or ingestion^[16].

In conclusion, soil chemical analysis following an earthquake is a crucial tool for assessing the environmental and health impacts of seismic events. By providing data on changes in soil pH, nutrient availability, heavy metal contamination, and organic matter, chemical analysis supports effective recovery efforts and helps mitigate future risks. Understanding these chemical changes enables more informed decisions regarding land use, agriculture, and public health in earthquake-prone areas.

5. Discussion

The chemical properties of soil are profoundly impacted by earthquakes, with potential long-term consequences for the environment, public health, and economic recovery, particularly in agriculture and infrastructure. The comprehensive review of post-earthquake soil chemical analysis in this study highlights several key findings and offers a nuanced understanding of the mechanisms and effects of soil changes. This section discusses these findings in the context of previous research, the implications for post-earthquake recovery, and the challenges associated with soil chemical analysis in disaster-affected regions.

5.1. Implications for agricultural recovery

Agriculture is often one of the most severely impacted sectors following a major seismic event, and soil chemical changes play a central role in the long-term restoration of agricultural productivity. The leaching of essential nutrients, such as nitrogen and potassium, as well as contamination from heavy metals and toxic chemicals, can drastically reduce soil fertility and hinder the ability of crops to thrive^[10-14]. For example, soil pH changes post-earthquake can disrupt nutrient uptake, especially in crops sensitive to soil acidity or alkalinity^[1]. The findings from Hossain's research^[8] emphasize that the most significant challenge in agricultural recovery is the loss of soil fertility due to nutrient leaching and contamination from industrial activities, which may be exacerbated by liquefaction and flooding.

Chemical analysis, therefore, provides the crucial data needed for informed decision-making regarding agricultural practices. The identification of nutrient deficiencies allows for the targeted application of fertilizers, while detecting heavy metal contamination helps to prevent the cultivation of crops that could accumulate toxic substances. For instance, the high levels of arsenic and cadmium observed in soils following the 1999 Turkey earthquake underscored the need for comprehensive soil remediation strategies, such as phytoremediation or soil amendments, to restore the soil's health.

However, as highlighted by Hossain et al.^[8], the recovery of agricultural lands may be slow and require continued monitoring. Long-term chemical changes to soil require not only short-term interventions but also strategies for sustainable land management to rebuild soil health over the decades following a disaster.

Furthermore, the interplay between soil chemistry and physical soil properties such as texture and structure must be considered, as it impacts water retention and root growth, which are essential for crop recovery^[7].

5.2. Environmental and health implications

In addition to the direct effects on agriculture, soil contamination following earthquakes poses serious environmental and public health risks. Industrial spills, the release of hazardous chemicals from damaged infrastructure, and the mobilization of toxic elements due to liquefaction can lead to the contamination of both soil and groundwater^[3]. The review highlights several instances where heavy metals like lead, mercury, and cadmium have been found in high concentrations in soil after earthquakes, such as during the 2004 Indian Ocean tsunami and the 1999 Turkish earthquake. These contaminants are persistent and pose long-term risks to human health, especially for communities that rely on groundwater for drinking and irrigation^[11].

The chemical analysis of soil after earthquakes thus serves as an essential tool for assessing environmental risks and informing health safety measures. Early detection of contaminants enables the rapid implementation of remediation measures, such as the isolation of contaminated areas, the introduction of phytoremediation plants, and the treatment of polluted groundwater^[8]. Furthermore, soil testing can help public health authorities determine the extent of exposure to hazardous materials and implement protective measures for communities in the affected areas.

The Fukushima accident^[9] and similar events have demonstrated the importance of immediate soil chemical analysis for identifying and addressing contamination. The movement of toxic substances through soils can be rapid, requiring timely intervention to prevent long-term health problems, including cancer, neurological disorders, and developmental issues in children^[10]. Therefore, post-earthquake soil chemical analysis not only helps in immediate disaster response but also in planning for long-term recovery and health monitoring.

5.3. Challenges in post-earthquake soil chemical analysis

Despite the critical role that soil chemical analysis plays in post-earthquake recovery, several challenges complicate the effectiveness of such assessments. One of the primary challenges is the variability in soil properties and the impact of different types of seismic events on soil chemistry. Earthquake-induced changes can be highly localized and vary depending on factors such as soil type, the intensity of shaking, and the proximity to industrial or contamination sources. This spatial variability requires careful sampling strategies and sophisticated analytical techniques to ensure comprehensive coverage and accurate results.

Additionally, the presence of multiple contaminants in soils, such as heavy metals, petroleum hydrocarbons, and agricultural chemicals, often complicates the analysis. Many of these substances can interact with one another, leading to complex chemical reactions that can alter their mobility and toxicity^[7]. Furthermore, the lack of baseline data on soil chemistry in many earthquake-prone regions makes it difficult to determine the extent of changes caused by seismic activity^[8]. Therefore, establishing baseline soil data and enhancing soil monitoring networks in these regions are crucial for effective post-disaster recovery.

The technical and financial constraints of conducting thorough soil chemical analyses in disaster zones also present significant barriers. Soil testing, particularly for trace elements and organic contaminants, requires specialized equipment and trained personnel, both of which may be in limited supply in post-earthquake scenarios. International cooperation, capacity building, and investment in infrastructure are necessary to overcome these challenges and ensure timely and effective soil chemical analysis in the aftermath of earthquakes.

5.4. Future research directions

As the frequency of earthquakes increases due to climate change and urbanization, further research is needed to better understand the long-term effects of seismic events on soil chemistry and the environment. Future studies should focus on developing standardized methodologies for post-earthquake soil chemical analysis, incorporating a broader range of contaminants, and expanding research into soil remediation techniques that are both effective and sustainable^[9]. Furthermore, interdisciplinary research that combines soil science, environmental health, and engineering can provide more holistic solutions to address the challenges posed by earthquake-induced soil changes.

Innovations in remote sensing and soil analysis technologies also hold promise for improving the speed and accuracy of post-earthquake soil assessments. The integration of drone technology, geographic information systems (GIS), and soil sensors could provide real-time data on soil conditions, facilitating rapid decision-making and more efficient resource allocation during the recovery phase.

6. Conclusion

The chemical analysis of soil following earthquakes plays a pivotal role in understanding the immediate and long-term environmental, agricultural, and public health consequences of seismic events. This review has highlighted the profound changes that occur in soil properties as a result of earthquake-induced processes such as liquefaction, erosion, and contamination from industrial accidents. Through the systematic examination of soil pH, nutrient content, and the presence of heavy metals and organic contaminants, soil chemical analysis provides invaluable insights that guide post-earthquake recovery efforts.

Key findings from this review underscore the importance of timely and comprehensive soil testing in regions affected by earthquakes. Soil fertility is often significantly reduced due to nutrient leaching, while soil contamination from hazardous chemicals can have far-reaching consequences for both the environment and human health. The agricultural sector, in particular, faces significant challenges in restoring soil health, with disruptions to crop growth caused by changes in soil chemical properties. As such, early detection of these changes is critical for implementing effective recovery strategies, including the targeted application of fertilizers, soil amendments, and remediation techniques. The findings also stress the importance of considering the broader environmental and public health impacts of post-earthquake soil contamination. The release of toxic substances, including heavy metals and chemicals from damaged industrial facilities, can persist in the soil for extended periods, posing long-term risks to communities and ecosystems. Soil chemical analysis thus serves as a fundamental tool for assessing these risks, implementing mitigation measures, and ensuring safe living conditions for affected populations.

However, the review also highlights several challenges associated with post-earthquake soil chemical analysis. These include the spatial variability of soil changes, the complexity of contaminant interactions, and the limitations of technical resources in disaster-prone areas. The lack of baseline data in many regions further complicates the assessment of earthquake-induced soil changes. Addressing these challenges requires concerted efforts to improve soil monitoring infrastructure, establish baseline soil data, and enhance technical capacity in affected regions.

Looking ahead, future research should focus on improving methodologies for post-earthquake soil chemical analysis, exploring new remediation techniques, and developing advanced technologies, such as remote sensing and soil sensors, to expedite data collection and decision-making. Interdisciplinary research that integrates soil science, environmental health, and engineering will be essential in developing holistic solutions that address the multifaceted challenges posed by earthquake-induced soil changes.

In conclusion, soil chemical analysis is an indispensable tool for post-earthquake recovery. By providing critical information on soil health, contamination levels, and the potential for agricultural restoration, it informs decisions that can mitigate the long-term impacts of earthquakes on communities, the environment, and economies. Continued advancements in research, technology, and collaboration are essential to enhancing the effectiveness of soil chemical analysis and ensuring that communities are better equipped to recover from future seismic events.

Conflict of interest

The authors declare no conflict of interest.

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