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Remote Sensing and GIS-Based Approaches for Soil Salinization Assessment: A Comprehensive Review

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Abstract

Soil salinization, a critical environmental challenge, significantly impacts land productivity, agricultural yields, and contributes to desertification, particularly in arid and semi-arid regions. Early detection and effective management of soil salinity are essential for sustainable agriculture and land management. Remote sensing (RS) and geographic information systems (GIS) have emerged as indispensable tools for mapping, monitoring, and analyzing soil salinity over vast areas. RS provides multi-temporal and multi-spectral data that helps identify salinity-affected regions, while GIS enables the integration and spatial analysis of this data to detect patterns and trends. This comprehensive review discusses the latest advancements in RS- and GIS-based techniques for soil salinization assessment, highlighting key spectral indices, mapping approaches, and spatial modeling techniques. Additionally, the paper explores the challenges in integrating RS and GIS, such as data limitations and the need for ground validation, while also suggesting future directions, including the use of machine learning and unmanned aerial vehicles for more precise salinity monitoring.

Keywords: Soil salinization, degradation, normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), remote sensing (RS), geographic information system (GIS)

INTRODUCTION

Soil salinization is a widespread environmental issue that poses significant threats to agricultural productivity, land sustainability, and ecosystem health. This process, characterized by the accumulation of soluble salts in the soil, affects plant growth, soil structure, and water quality. It is particularly prevalent in arid and semi-arid regions, where the combination of high evaporation rates and inadequate irrigation practices exacerbates salt deposition in the soil profile. Globally, over 20% of irrigated lands are estimated to be affected by salinity, translating into substantial economic losses, with some reports suggesting an annual loss of up to 12 billion in agricultural revenue [1]. In addition to impacting crop yields, salinization can lead to reduced soil fertility, the destruction of biodiversity, and the acceleration of desertification processes, further complicating efforts to achieve food security and sustainable land management.

The drivers of soil salinization can be both natural and anthropogenic. Natural processes, such as the rise of saline groundwater tables in low-lying areas, and the deposition of salts by wind or water erosion, contribute to soil salinization. However, human activities, particularly improper irrigation methods, the overuse of chemical fertilizers, deforestation, and poor drainage systems, have significantly accelerated the rate of salinization in many regions. Addressing soil salinity through effective monitoring, early detection, and appropriate management strategies is therefore crucial to mitigate its impacts and ensure long-term land productivity.

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Remote sensing (RS) and geographic information systems (GIS) have emerged as invaluable tools in the field of soil salinization assessment and management. These technologies offer a range of advantages over traditional ground-based salinity monitoring methods, such as field sampling and laboratory analysis, which are often labor-intensive, time-consuming, and spatially limited. RS, by utilizing data from satellite, aerial, and ground-based sensors, enables the collection of large-scale, multi-temporal, and multi-spectral data across diverse landscapes. It provides an efficient means of detecting salinity-related soil characteristics, such as changes in vegetation cover, soil moisture, and surface reflectance, thereby allowing for the timely identification of affected areas [2].

GIS, on the other hand, offers powerful tools for spatial analysis and data integration, enabling researchers and land managers to combine RS data with other spatial and temporal information, such as topography, climate, and land-use patterns. This facilitates the development of comprehensive maps and models that not only highlight the current extent of soil salinization but also allow for the prediction of future trends and the identification of salinization hotspots. Together, RS and GIS provide an integrated approach that can inform decision-making processes for sustainable land management and the implementation of targeted salinity control measures.

Numerous studies have demonstrated the potential of RS and GIS techniques in soil salinization assessment. For instance, multi-spectral sensors such as Landsat and Sentinel have been widely used to monitor salinity-induced changes in soil and vegetation over time. Salt affected soils are shown in Figure 1(a). Spectral indices, such as the normalized difference vegetation index (NDVI) and the salinity index (SI), have proven effective in detecting salinity stress in plants and soils, even in remote or inaccessible regions [3]. Additionally, GIS-based spatial modeling techniques, such as interpolation and regression analysis, enable the estimation of salinity levels in areas where ground data is limited, providing a more comprehensive view of salinity distribution across large landscapes.

However, despite the advancements in RS and GIS technologies, several challenges remain. Water erosion rate in India is shown in Figure 1(b). The accuracy of RS-based salinity detection can be influenced by factors such as soil moisture, atmospheric conditions, and vegetation cover, necessitating the use of ground-based validation techniques. Furthermore, high-resolution RS data can be costly, particularly for small-scale studies, and the integration of RS and GIS data requires technical expertise and computational resources.

This review aims to provide an in-depth examination of the current state of RS- and GIS-based approaches to soil salinization assessment. It will highlight key techniques, methodologies, and their applications, as well as discuss the limitations and future prospects of using these tools in salinity management. By synthesizing recent advancements in the field, this review seeks to contribute to the ongoing efforts to develop effective, scalable, and sustainable solutions for addressing soil salinization globally.

REMOTE SENSING IN SOIL SALINIZATION ASSESSMENT

RS has emerged as an essential tool in the field of environmental monitoring and land management, providing valuable data for assessing soil salinization. RS enables the collection of data across vast geographical areas, offering temporal consistency and high spatial resolution, which are crucial for tracking changes in soil properties and identifying areas affected by salinity. The following sections explore the major aspects of RS technology as applied to soil salinization, including the platforms used, key spectral indices for salinity detection, and the role of thermal infrared (TIR) sensors.

Overview of Remote Sensing Technologies

Remote sensing is the process of acquiring information about the Earth's surface without direct contact, typically using satellite or airborne sensors. These sensors capture data across multiple wavelengths of the electromagnetic spectrum, ranging from visible to infrared and thermal bands.

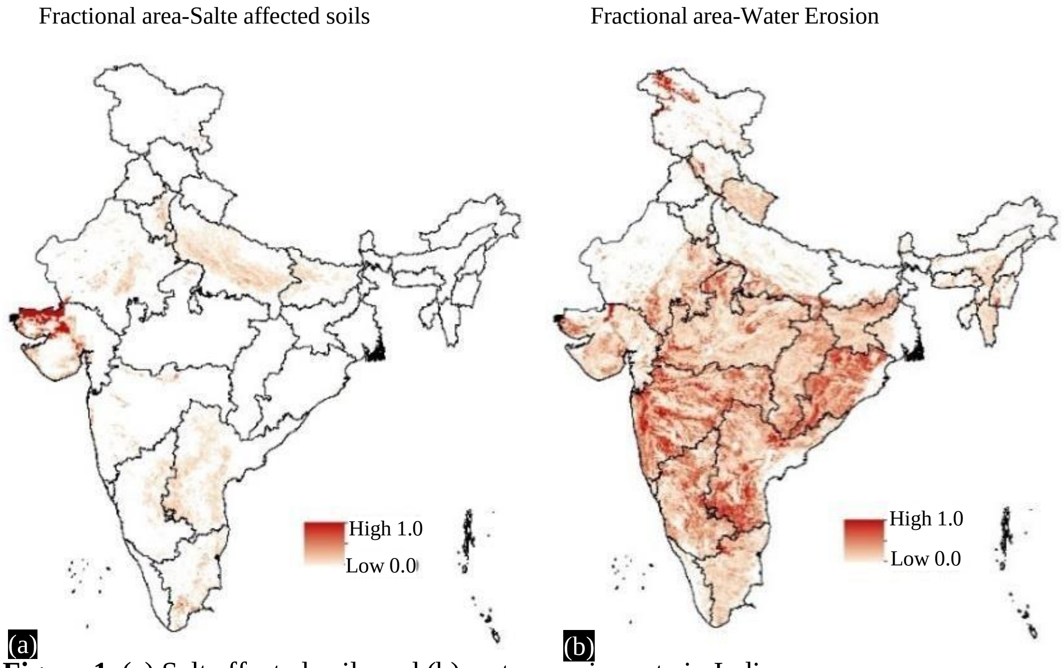

Figure 1. (a) Salt affected soils and (b) water erosion rate in India.
Source: https://www.nrsc.gov.in/

The reflected or emitted radiation from the Earth's surface is analyzed to derive critical information about soil characteristics, such as moisture content, texture, and the presence of salts. The use of RS in soil salinization assessment offers several advantages. It allows for multi-temporal monitoring, meaning that salinity trends can be observed over time, and it provides spatial coverage of large, inaccessible, or hazardous areas. Additionally, RS is cost-effective compared to extensive field-based data collection, especially when the study area spans hundreds or thousands of square kilometers [3].

Several satellite platforms are commonly used in soil salinization studies. Landsat, with its long history of data collection dating back to 1972, offers a balance between spatial and temporal resolution, making it a popular choice for monitoring long-term trends in soil salinity. Its sensors (e.g., TM, ETM+, and OLI) cover a wide range of spectral bands, including visible, near-infrared, and thermal, enabling detailed analysis of surface features [4]. Sentinel-2, launched by the European Space Agency, provides higher spatial resolution (up to 10 m) and a revisit frequency of 5 days, making it ideal for more frequent monitoring of salinity changes. Other widely used sensors include MODIS (Moderate Resolution Imaging Spectroradiometer), known for its global coverage and high temporal resolution, and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), which provides detailed thermal and spectral data useful for assessing soil surface conditions.

Spectral Indices for Soil Salinity Detection

One of the primary methods for assessing soil salinity using RS data is the application of spectral indices. Spectral indices are mathematical combinations of reflectance values at different wavelengths, designed to highlight specific surface properties. Several indices have been developed to enhance salinity detection by targeting salinity-related soil and vegetation characteristics.

Normalized Difference Vegetation Index

NDVI is one of the most widely used indices in RS, primarily for assessing vegetation health. Saline soils often reduce vegetation cover due to the osmotic stress caused by high salt concentrations, leading to lower NDVI values. NDVI has been extensively used to indirectly estimate salinity levels by detecting areas of stressed or sparse vegetation [5]. NDVI is particularly useful in agricultural areas, where changes in crop health can signal salinity issues.

Salinity Index

SI is specifically designed for direct detection of soil salinity. It is based on the distinct reflectance characteristics of saline soils in the visible and near-infrared (NIR) regions of the electromagnetic spectrum. High salinity results in increased reflectance in the visible bands due to the white or light color of salt crusts on the soil surface, while NIR reflectance decreases [6]. SI is particularly effective in regions with low vegetation cover, where the spectral signature of the bare soil is more prominent.

Soil-Adjusted Vegetation Index

In areas with sparse or uneven vegetation cover, the standard NDVI may not be sufficient for salinity detection due to interference from soil background reflectance. SAVI was developed to mitigate this issue by incorporating a soil brightness correction factor, making it more suitable for semi-arid and arid regions where vegetation is sparse [7]. Studies have demonstrated the effectiveness of SAVI in identifying salinity stress in vegetation across various ecosystems.

Bare Soil Index

In addition to NDVI, SI, and SAVI, the bare soil index (BSI) has also been used to detect salinity. BSI combines visible and shortwave infrared reflectance to highlight bare soil areas, which are often more affected by salinity due to a lack of vegetation cover [7]. By focusing on bare soil, BSI is particularly useful in landscapes dominated by agricultural fallows or desert environments, where salinization is a critical issue.

Thermal Infrared for Salinity Monitoring

TIR sensors provide a unique perspective for assessing soil salinity by measuring the emitted long-wave radiation from the Earth's surface. Saline soils exhibit different thermal properties compared to non-saline soils, primarily due to their altered soil structure and higher moisture retention. TIR data can thus be used to infer soil salinity levels by analysing temperature variations across the soil surface [8].

Research has shown that saline soils tend to have lower temperatures during the day and higher temperatures at night compared to non-saline soils, a phenomenon attributed to differences in soil heat capacity and conductivity. These thermal anomalies, when detected by TIR sensors, provide valuable information for salinity assessment. The combination of TIR data with multispectral observations enhances the accuracy of salinity detection, particularly in heterogeneous landscapes where soil and vegetation types vary significantly [9].

TIR sensors are available on several satellite platforms, including Landsat-8's Thermal Infrared Sensor (TIRS) and ASTER. When combined with multispectral data, TIR data has proven effective in identifying areas with high salinity levels, especially in arid and semi-arid regions. The integration of TIR data with other RS-derived indices allows for more comprehensive monitoring of salinity dynamics, offering greater accuracy in distinguishing saline soils from non-saline soils.

GEOGRAPHIC INFORMATION SYSTEM APPLICATIONS IN SOIL SALINIZATION ASSESSMENT

GIS has become indispensable in environmental monitoring, offering powerful tools for spatial data analysis, mapping, and modeling. In soil salinization assessment, GIS is often used in conjunction with RS to analyze the spatial distribution and temporal dynamics of salinity, providing valuable insights into how salinity interacts with environmental factors such as topography, land use, and hydrology. This section delves into the major applications of GIS in soil salinization assessment, including the integration of RS data with GIS, spatial modeling, mapping, and temporal analysis.

Integration of Remote Sensing and Geographic Information System

The integration of RS and GIS offers a comprehensive framework for assessing soil salinity across large areas. Remote sensing provides valuable spectral data related to soil salinity, while GIS allows for the spatial analysis of this data, combining it with other geospatial information such as soil types, topography, hydrological networks, and land use patterns. This combination enables researchers and land managers to visualize salinity levels in relation to environmental variables and to identify spatial patterns of salinization more effectively.

GIS-based platforms allow users to manipulate and analyze multiple layers of spatial data, offering insights that would be difficult to obtain from RS or field measurements alone. For example, salinity-related RS data can be overlaid with digital elevation models (DEMs) to understand the relationship between salinity and topographic features, such as drainage patterns or slope gradients. This integrated approach provides a more holistic understanding of how salinity propagates through the landscape, taking into account factors like surface water flow, soil permeability, and human activities such as irrigation and land clearing [10].

Furthermore, GIS provides the capability to build predictive models by integrating salinity data with environmental parameters. By identifying key drivers of salinization, such as proximity to irrigation canals or the presence of saline groundwater, GIS-based models can highlight areas at risk of future salinization. These models can serve as valuable decision-making tools for stakeholders in agriculture, water management, and land reclamation, helping them develop targeted strategies to mitigate salinization risks.

Spatial Modeling and Mapping of Soil Salinity

Spatial modeling is one of the core applications of GIS in soil salinization assessment. Various GIS-based spatial modeling techniques are employed to estimate salinity levels in areas where ground data is scarce or incomplete. One of the most common methods for mapping soil salinity is interpolation, which estimates values at unsampled locations based on known measurements from surrounding areas.

Several interpolation techniques are widely used in soil salinity studies, including kriging, inverse distance weighting (IDW), and spline interpolation. Kriging is a geostatistical method that not only estimates salinity levels based on spatial autocorrelation but also provides a measure of uncertainty for the predicted values. This makes kriging especially valuable in regions with complex salinity patterns or limited ground-based observations [11]. IDW, on the other hand, is a deterministic method that assumes values closer to a known data point are more similar than those farther away, making it simpler but less accurate in heterogeneous landscapes. These interpolation methods generate continuous salinity maps that help visualize salinity distribution across entire regions, allowing land managers to identify high-risk areas and devise appropriate management strategies.

In addition to interpolation, GIS platforms enable more advanced spatial modeling techniques, such as multivariate regression and machine learning-based models. These approaches incorporate multiple environmental variables—such as soil texture, groundwater levels, climate data, and land use—to predict soil salinity. For example, multiple linear regression (MLR) can be used to quantify the relationships between salinity and explanatory variables, enabling the prediction of salinity in areas where direct measurements are unavailable. More recently, machine learning algorithms such as random forests, support vector machines (SVM), and artificial neural networks (ANN) have been employed in GIS-based salinity assessments. These algorithms excel in handling complex, non-linear relationships between salinity and environmental factors, providing higher prediction accuracy than traditional statistical models [11].

GIS-based salinity maps generated from these models offer crucial insights for sustainable land management. They allow stakeholders to visualize salinity hotspots, assess soil suitability for agricultural production, and implement salinity control measures such as improving drainage or adopting salt-tolerant crop varieties. Moreover, these maps can help guide resource allocation, ensuring that salinity mitigation efforts are focused on the most affected or vulnerable areas.

Temporal Analysis of Salinity Trends

Another significant application of GIS in soil salinization assessment is the ability to perform temporal analysis, tracking salinity trends over time. This is particularly useful for monitoring the progression or regression of soil salinization, providing insights into the effectiveness of remediation efforts, irrigation management practices, or changes in land use.

Temporal analysis in GIS involves the integration of time-series RS data with historical records of salinity measurements, allowing researchers to identify changes in salinity levels across multiple time periods. For instance, RS data from satellites like Landsat and Sentinel-2, captured at regular intervals, can be processed in GIS to create a chronological series of salinity maps. These maps provide a visual representation of salinity dynamics, showing how salinity-affected areas expand, contract, or shift over time [12].

This form of analysis is crucial in agricultural regions, where the success of salinity mitigation measures, such as improving irrigation practices or planting salt-tolerant crops, must be monitored over time. By analyzing salinity trends, land managers can assess the long-term sustainability of their interventions and make necessary adjustments. In addition, temporal analysis helps identify areas where salinization is worsening, providing early warnings that prompt preventive measures before irreversible damage occurs.

The ability of GIS to handle large, multi-temporal datasets makes it an ideal tool for evaluating long-term salinization trends. With the integration of climate models, soil moisture data, and hydrological records, GIS can also be used to predict future salinity trends under different climate change scenarios, helping policymakers plan for long-term challenges in land and water management.

CHALLENGES AND LIMITATIONS

While the integration of RS and GIS has significantly advanced the field of soil salinization assessment, several challenges and limitations persist, which affect the accuracy, cost, and applicability of these technologies.

One of the key challenges in RS-based salinity detection is the influence of environmental factors such as soil moisture, vegetation cover, and atmospheric conditions. High soil moisture can mask salinity by altering the spectral reflectance of the soil, making it difficult to distinguish between saline and non-saline areas. Similarly, dense vegetation cover can obscure soil characteristics, limiting the effectiveness of RS techniques, particularly those based on spectral indices like NDVI, which rely on vegetation health as a proxy for soil salinity [13]. Atmospheric conditions, including cloud cover and aerosols, can also interfere with satellite-based RS observations, reducing data quality and requiring correction algorithms that may not fully restore accuracy.

Another challenge arises from the variability in RS platforms. Different RS platforms, such as Landsat, Sentinel, MODIS, and ASTER, offer different spectral, spatial, and temporal resolutions, leading to potential discrepancies in salinity assessments. For instance, platforms with lower spatial resolution may miss small-scale salinity features, while those with higher resolution may capture more detail but require more complex processing and higher computational resources. As a result, data from multiple platforms often need to be validated and calibrated against ground-based measurements to ensure accuracy. Ground-truthing, however, is time-consuming and resource-intensive, making it difficult to apply on a large scale [14].

Data resolution is another critical limitation. While platforms like Landsat and Sentinel provide free and accessible RS data, their spatial resolution (30 and 10 m, respectively) may not be sufficient for detailed, local-scale salinity studies, especially in heterogeneous landscapes. For small-scale projects that require finer detail, high-resolution RS data (e.g., from commercial satellites such as World View or Geo Eye) can offer improved accuracy, but these datasets often come at a high cost, limiting their accessibility to researchers and practitioners with restricted budgets [15]. This cost barrier can be especially prohibitive for developing countries, where salinization is often a significant issue but financial and technical resources are limited.

Moreover, data processing and analysis in both RS and GIS require specialized technical skills and significant computational power, which may not be readily available in all research or management settings. Processing high-resolution RS data, integrating it into GIS platforms, and performing spatial modeling require expertise in geospatial analysis, limiting the widespread use of these tools in regions where technical capacity is low.

Lastly, temporal limitations in satellite revisit times may impede the continuous monitoring of soil salinity. Although platforms like Sentinel-2 have relatively short revisit times (about 5 days), they may still miss short-term fluctuations in salinity that occur due to irrigation cycles, rainfall, or other transient environmental factors. Long-term monitoring is essential for assessing salinization trends, but data gaps due to satellite coverage and processing delays can hinder timely decision-making.

In summary, while RS and GIS offer invaluable tools for assessing soil salinity, challenges related to environmental interference, data resolution, platform variability, cost, technical expertise, and temporal limitations remain. Addressing these challenges through the development of improved algorithms, better data integration techniques, and enhanced accessibility to high-resolution data will be crucial for advancing soil salinization assessments and enabling more effective land management practices in the future.

FUTURE DIRECTIONS AND RECOMMENDATIONS

As technology continues to evolve, the future of RS and GIS in soil salinization assessment holds significant promise. Emerging innovations such as hyperspectral imaging, unmanned aerial vehicles (UAVs), and artificial intelligence (AI) are expected to revolutionize salinity detection, offering higher precision, more comprehensive data, and greater accessibility for a range of applications.

One of the most promising advancements is hyperspectral imaging. Unlike traditional multispectral sensors that capture data in a few broad bands, hyperspectral sensors acquire data in hundreds of narrow spectral bands. This capability allows for the detection of subtle soil properties that are indicative of salinity, such as mineral composition, moisture content, and salt crust formations. Hyperspectral imaging can differentiate between various types of salts and can improve the accuracy of salinity detection, particularly in heterogeneous or mixed-use landscapes [16]. Although currently limited by high costs and processing complexity, future advancements in hyperspectral technology, coupled with improved algorithms for data analysis, are likely to make this a more viable option for large-scale applications.

The use of UAVs (drones) for soil salinity assessment is another area of rapid growth. UAVs equipped with multispectral, hyperspectral, and thermal sensors provide highly detailed, site-specific data at a relatively low cost. They offer flexibility in terms of timing and coverage, allowing for the collection of high-resolution imagery in areas where satellite data may be unavailable or insufficient due to spatial or temporal limitations. UAVs are particularly valuable in small, heterogeneous areas where soil conditions vary significantly over short distances, enabling more targeted and efficient management practices [17]. The proliferation of commercial drone platforms and improved sensor technology is expected to increase the adoption of UAVs in both research and practical applications of soil salinity management.

AI and machine learning are also set to play a crucial role in advancing soil salinization assessment. The integration of AI with RS and GIS allows for the automated analysis of large datasets, improving both the speed and accuracy of salinity assessments. Machine learning algorithms can detect complex patterns in RS data that may be missed through traditional analysis methods, enabling more accurate predictions of soil salinity levels. Moreover, AI-driven models can be trained to recognize subtle changes in spectral signatures associated with early stages of salinization, facilitating proactive management [18–20]. As AI and machine learning technologies continue to evolve, their incorporation into salinity monitoring systems is likely to result in more efficient and scalable solutions, particularly in regions where salinization is a growing concern.

Cloud computing is another emerging trend that will further enhance the accessibility and scalability of RS- and GIS-based salinization assessments. Cloud platforms enable researchers to process vast amounts of satellite and UAV data without the need for local high-performance computing infrastructure. For example, platforms like Google Earth Engine provide access to large archives of satellite imagery and powerful computational tools, allowing users to perform complex analyses directly in the cloud [21–23]. This development reduces the barriers to entry for smaller institutions and developing countries, where financial and technical resources may be limited. Finally, the integration of multidisciplinary approaches will be key to advancing soil salinity assessment. Future research should aim to combine RS, GIS, hydrological models, and ground-based data collection to develop more comprehensive and accurate salinity monitoring systems. Collaboration between soil scientists, hydrologists, agronomists, and remote sensing specialists can lead to the development of robust, predictive models that account for the complex interactions between soil, water, and climatic factors in salinity dynamics [24, 25].

CONCLUSION

Soil salinization is a significant global issue, particularly in arid and semi-arid regions where it threatens agricultural productivity, food security, and environmental sustainability. Addressing this challenge requires timely and accurate assessment methods, which can be greatly enhanced through the integration of RS and GIS. As demonstrated throughout this review, RS technologies offer powerful tools for detecting and monitoring salinity by capturing multi-spectral, multi-temporal data over large areas, while GIS enables sophisticated spatial analysis, modeling, and mapping of salinity dynamics. Advancements in spectral indices such as NDVI, SI, and SAVI have improved the accuracy of soil salinity detection, particularly when combined with TIR data. Additionally, the integration of RS with GIS has allowed for the development of predictive models and the visualization of spatial and temporal trends, offering more comprehensive insights into salinity progression and risk areas. However, challenges such as environmental interference, data resolution variability, and the high cost of high-resolution RS platforms persist, highlighting the need for continued innovation in this field.

Looking forward, emerging technologies like hyperspectral imaging, UAVs, AI, and machine learning are set to further enhance the capabilities of RS and GIS for soil salinity assessment. Hyperspectral sensors can detect more nuanced salinity-related soil properties, while UAVs provide high-resolution, flexible, and cost-effective data collection. AI and machine learning hold great potential for automating and improving data analysis, making salinity monitoring faster and more accurate. Cloud computing platforms such as Google Earth Engine also provide an accessible means to process large datasets, enabling broader participation in salinity research and management.

Despite current challenges, the integration of RS and GIS has already proven invaluable in managing soil salinity. As new technologies are developed and multidisciplinary approaches are increasingly adopted, the potential for even more effective and scalable solutions will continue to grow. Future research should focus on refining these tools, improving data accessibility, and expanding collaborations across disciplines to better understand and mitigate the impacts of soil salinization worldwide.

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