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Remote Sensing and GIS Applications in Soil Salinity Analysis: A Comprehensive Review

K. M. Gojiya [a++*], H. D. Rank [b#], P. M. Chauhan [a†], D. V. Patel [c#], R. M. Satasiya [d‡] and G. V. Prajapati [e^]

[a] College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh, India.
[b] Department of SWCE, College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh, India.
[c] Department of Agriculture Statistics, College of Agriculture, Junagadh Agricultural University, Junagadh, India.
[d] Polytechnic in Agricultural Engineerinqqg, Junagadh Agricultural University, Targhadiya, Rajkot, India.
[e] Department of REE, College of Agril. Engg. & Tech., Junagadh Agricultural University, Junagadh, India.

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[++] Ph.D. Scholar;
[#] Professor & Head;
[†] Principal & Dean;
[‡] Principal;
[^] Research Engineer;
**Corresponding author: E-mail: kashyapgojiya@gmail.com;*

ABSTRACT

Soil salinity is a pressing global issue with far-reaching implications for agricultural productivity and environmental sustainability, particularly in arid and semi-arid regions. The expansion of cultivated lands and the need for food production have intensified the challenges associated with soil salinization. This paper reviews the significance of monitoring and assessing soil salinity, especially in regions where traditional irrigation practices and inadequate drainage systems exacerbate the problem. The paper highlights the importance of satellite-based technologies for spatial and temporal mapping of soil salinity, providing cost-effective, rapid, and efficient sources of qualitative and quantitative spatial information. Multispectral remote sensing data have significantly improved the monitoring of soil salinity. The spectral characteristics of salt-affected soil, visible and near-infrared bands, enable the detection of salinity in both barren and vegetated areas. Various salinity and vegetation indices have been developed, with their effectiveness depending on the context and the extent of vegetation cover. Proper timing of fieldwork and measurement is essential for accurate results. The paper presents a comprehensive review of the remote sensing and GIS based methods of soil salinity estimation including salinity indices, vegetation indices, regression methos, neural network methods plus, sensing approaches, and satellite data utilized in soil salinity mapping. The majority of recent studies favour remote sensing technology over traditional methods due to its cost-effectiveness and efficiency. The choice of mapping approach is context-dependent, and there is no universally superior method. This review underscores the critical role of remote sensing in addressing the challenges posed by soil salinity, offering a promising avenue for monitoring and managing this imperative global concern.

Keywords: Soil salinity; remote sensing; multispectral data; spectral indices; mapping methods.

1. INTRODUCTION

Soil acts as a pivotal role in addressing global environmental concerns, encompassing the impacts of climate change, food and water security, land degradation, and habitat loss for various species [1,2]. Consequently, the evaluation of soil properties, such as soil salinity, is of paramount importance for the sustainability of land on local and regional scales [3]. Particularly in arid and semi-arid regions worldwide, soil salinization stands out as a significant and alarming phenomenon due to its detrimental effects on land productivity and plant growth.

1.1 The Prevalence of Soil Salinity

Soil salinity stands as a prevalent soil attribute that significantly impacts agricultural productivity and gives rise to considerable environmental challenges on a global scale, particularly in arid and semi-arid regions. In these areas, the scant precipitation falls short in facilitating natural water percolation through the soil profile, leading to the accumulation of soluble salts, thus negatively affecting soil structure [4]. The issue of soil salinization is not restricted to any one continent; it's a challenge faced worldwide. However, arid regions, characterized by low precipitation and high evaporation rates, suffer more profoundly due to the limited leaching of soluble salts through the soil profile [5].

1.2 Primary and Secondary Salinization

As the global population continues to expand rapidly, the demand for food production is on the rise. Yet, a considerable portion of cultivated land lies abandoned because of both primary and secondary soil salinization. Primary salinization, the expansion of salt in the soil resulting from natural processes like physical and chemical weathering, as well as the movement of salts from parent materials, geological deposits, or groundwater, is well-documented. Conversely, secondary salinization is predominantly a consequence of human activities [6,7], with traditional irrigation methods and inadequate drainage systems being the two main culprits, causing adverse effects on nearly 20 per cent of irrigated land globally, as observed by Mayak *et al*. [8]. Metternicht and Zinck [9] have drawn attention to the fact that approximately 77 Mha are affected by secondary salinization. A simplified flowchart illustrating primary and secondary soil salinization is presented in Fig. 1. Primary and secondary salinization in Devbhumi Dwarka region of Gujarat, India in photographs is given in Fig. 2.

1.3 Impact of Soil Salinity on Agriculture

Traditional irrigation practices, as highlighted by Matinfar *et al*. [10], play a significant role in exacerbating soil salinization and the degradation of soil quality. This, in turn, has adverse consequences on seed germination and restricts plant growth. As the world experiences rapid population growth, there is an escalating demand for food production. This will inevitably lead to the conversion of more dry lands into agricultural areas, resulting in an extension of the salinization hazard, mainly driven by irrigation. Hence, the continuous monitoring and assessment of saline soil hold paramount significance in mitigating its detrimental effects, such as land degradation and diminishing crop yields [11].

1.4 The Role of Remote Sensing and Geographic Information Systems (GIS)

The integration of remote sensing and GIS has found widespread utility across various domains within the agricultural sector, including but not limited to applications involving the assessment of basin characteristics, the evaluation of soil moisture content, the analysis of soil salinity levels, predictive modelling of drought events, the estimation of crop coefficients, and numerous other agricultural functions [12-16]. Conventional methods for assessing soil salinity in the field present limitations in terms of their ability to facilitate continuous and comprehensive monitoring due to their spatial and temporal constraints. These methods offer only localized, point-based data. The need for spatial and temporal mapping of soil salinity is paramount to guide decision-making processes aimed at mitigating the adverse effects of soil salinization. In this context, satellite-based technologies have emerged as cost-effective, rapid, and efficient sources of both qualitative and quantitative spatial information on saline soils [17,18].

The utilization of multispectral RS data has substantially enhanced the monitoring of soil salinity. An understanding of how salinity affects the spectral reflectance of both soil and vegetation is a crucial element in the effective use of multispectral imagery for mapping saline regions. Airborne remote sensing offers the potential for pixel-by-pixel detection of spatial variations in soil salinity, with particular significance in remote and distant areas, where it can provide vital information on environmental changes [19].

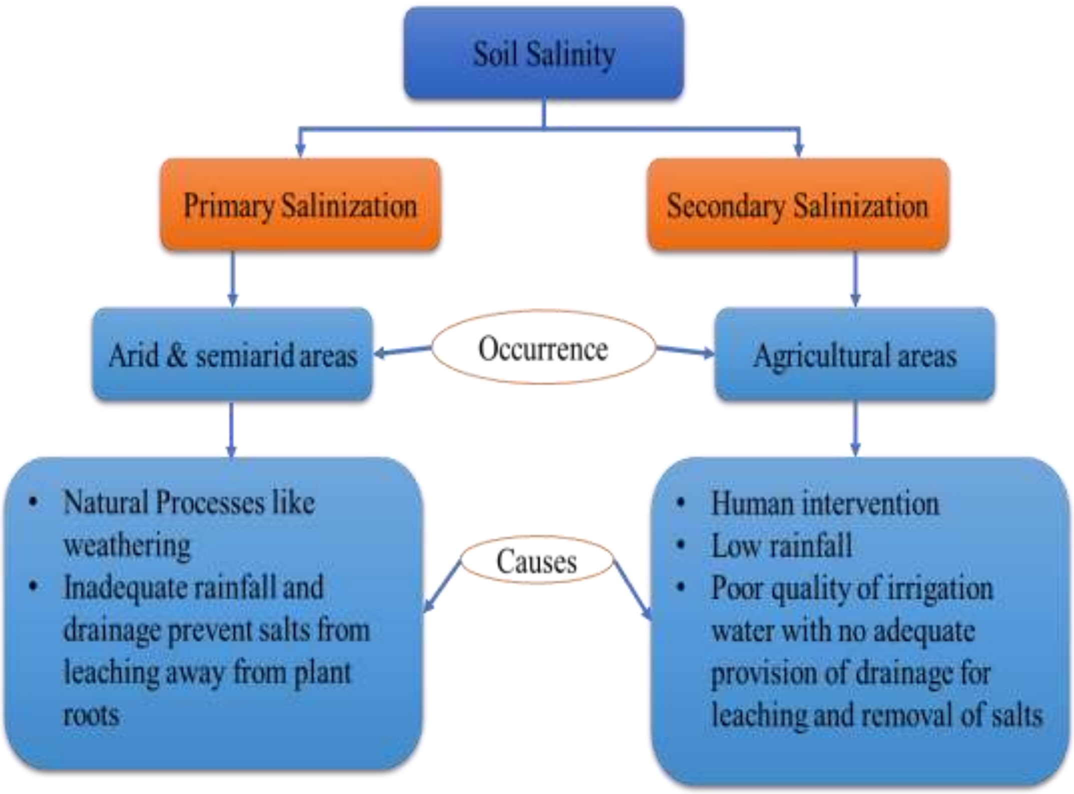

Fig. 1. Flowchart illustrating primary and secondary soil salinization

a. **Primary salinization**

b. **Secondary salinization**

Fig. 2 Soil salinity in Devbhumi Dwarka region of Gujarat, India

2. SOIL SALINITY MEASUREMENT AND ESTIMATION

2.1 Mapping and Monitoring Soil Salinity

To obtain accurate results in soil salinity mapping using RS and GIS, proper timing for fieldwork and measurement is essential. Acquiring RS data concurrently with field surveys is crucial for result validation. Moreover, considering the seasonality of salt accumulation in the soil, conducting soil salinity studies during the dry season is more suitable, as the rainy season may wash surface salts and reduce topsoil salinity levels [20]. Moreover, models for estimating soil salinity using remote sensing and GIS tools necessitate initial calibration specific to each area due to the varying nature of soil salinity responses in different environments. Therefore, these models should be developed regionally, tailored to the characteristics of the particular areas. There are several soil salinity measurement techniques, each with its advantages and limitations. Here are some common methods for measuring soil salinity:

1. **Electrical Conductivity (EC):**
   - **Direct Measurement**: In this method, a conductivity probe is inserted into the soil, and the electrical conductivity of the soil solution is measured. It provides a quick and relatively accurate measure of salinity.
   - **Soil Extract Method**: Soil samples are collected and mixed with deionized water. The electrical conductivity of the resulting solution is measured, providing an indirect estimate of soil salinity. Solution could be saturation extract (which is longer but more accurate process) or different soil water suspension ratios such 1:2.5 or 1:5 (which is faster and more widely used).
2. **Total Dissolved Solids (TDS):**
   - This method measures the concentration of all dissolved ions in the soil solution, including both cations and anions. TDS can be measured directly or estimated based on electrical conductivity.
3. **Sodium Adsorption Ratio (SAR):**
   - SAR measures the relative concentration of sodium ions to other cations in the soil solution. It is used to assess the sodicity of soil, which is related to soil salinity.
4. **Soluble Ions Analysis:**
   - Soil samples are collected and analyzed for the concentrations of specific ions, such as chloride (Cl^-), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), and others, which contribute to soil salinity.
5. **Exchangeable Sodium Percentage (ESP):**
   - ESP measures the percentage of sodium ions on the exchange sites of soil particles. It is often used to assess soil sodicity and salinity.

The choice of measurement technique depends on the specific research or monitoring objectives, the scale of the study, and the resources available. Each method has its strengths and limitations, and a combination of techniques may be used for a comprehensive assessment of soil salinity in a given area. Fig. 3 shows direct measurement of soil salinity in the field using salinity probe while Fig. 4 shows indirect measurement of soil salinity from 1:2.5 soil water suspension ratio.

The utilization of remote sensing technology offers several advantages, which encompass time-saving, expansive coverage (especially vital when data is needed over large areas or regions), swifter data acquisition compared to ground-based methods, and support for long-term monitoring efforts. Remote sensing techniques provide multispectral images with resolutions that range from medium to high, as well as hyperspectral images. Over the years, these remotely sensed data have been effectively harnessed for monitoring and mapping soil salinity, albeit with varying degrees of success. Numerous researchers have employed diverse techniques using remote sensing data to monitor and map soil salinity, as elaborated below.

Fig. 3. Direct measurement of soil salinity using salinity probe

Fig. 4. Indirect measurement of soil salinity using EC meter

2.2 Multispectral Satellite Data for Soil Salinity Estimation

Over the past thirty years, considerable research efforts have been directed toward the utilization of satellite imagery for the mapping and monitoring of soil salinity. Primarily, this research has focused on multispectral sensors, including but not limited to the Landsat Thematic Mapper (TM), Landsat Multispectral Scanner System (MSS), Landsat Enhanced Thematic Mapper Plus (ETM+), Landsat (Operational Land Imager) OLI, Sentinel, SPOT, Advanced Spaceborne Thermal Emission and Reflection Radiometer (Terra-ASTER), Linear imaging self-scanning sensor (LISS-III), and IKONOS [9,21,22].

Numerous researchers, such as Katawatin and Kotrapat [23], Mehrjardi *et al*. [24] and Yu *et al*. [25] have explored the applicability and effectiveness of Landsat-7 Enhanced Thematic Mapper Plus (ETM+) data in the context of soil salinity mapping and monitoring. For instance, in Thailand, Katawatin and Kotrapat [23] conducted a study that involved the utilization of Landsat-7 ETM+ data in conjunction with three different sets of ancillary data sources (topography, geology, and underground water quality) for soil salinity mapping. They applied a maximum likelihood classification method in their research. The outcomes of their investigation demonstrated that the most precise soil salinity map was achieved when Landsat ETM+ data bands 4, 5, and 7 were combined with all three categories of ancillary data, resulting in an overall accuracy of 83.6 %. The application of multispectral sensors in soil salinity research has been a subject of investigation by Goossens *et al*. [26]. In their study, they conducted an analysis to assess and contrast the precision of Landsat Thematic Mapper (TM), Multispectral Scanner System (MSS), and SPOT XS imagery for soil salinity mapping. Their findings indicated that Landsat TM stood out as the most suitable choice for soil salinity mapping. Abbas *et al.* [27] mentioned that spectral response of the salt-affected soils higher than those of normal soils. Salty soils reflected more incident light energy in visible spectrum and this response extremely useful in the segregation of saline soils.

2.3 Application of Spectral Indices in Soil Salinity Studies

Likewise, various spectral indices tailored for the detection and mapping of salt minerals have been developed. Douaoui *et al*. [28] introduced three salinity indices (Table 1) derived from SPOT XS imagery to identify and map soil salinity hazards within a semi-arid region in Algeria. While these indices exhibited strong correlations with measured values, they notably underestimated salinity in areas with elevated surface salt content. Additionally, Khan *et al*. [29] proposed three spectral salinity indices: the Brightness index (BI), Normalized Difference Salinity Index (NDSI), and Salinity Index (SI) (Table 1) based on the LISS-II sensor of the IRS-1B satellite for assessing hydro-salinized land degradation in Pakistan. Among these indices, NDSI produced the most satisfactory results in distinguishing various salt classes.

Another study conducted by Vidal *et al*. [30] and Vincent *et al*. [31] examined salinity by distinguishing vegetated from non-vegetated areas using the Normalized Difference Vegetation Index (NDVI). Subsequently, the Brightness index (BI) was computed to identify moisture and salinity conditions in fallow land and deserted fields. Furthermore, Bannari *et al*. [32] introduced three distinct salinity indices, SI-1, SI-2, and SI-3 (Table 1), based on the EO-1 ALI spectral bands to discriminate between slight and moderate soil salinity and sodicity in Morocco. Although the results showed that SI-3 exhibited the highest correlation (46.9%), its outcome was insufficient for providing precise information. Therefore, they devised two additional Soil Salinity and Sodicity Indices (SSSI) (Table 1). Their results indicated that these SSSI indices were likely to enhance accuracy in identifying areas with low and moderate salinity, as they displayed the most significant correlation (52.9%) with ground electrical conductivity measurements.

In Pakistan, Abbas and Khan [37] proposed an integrated approach based on spatial analysis of both ground and satellite data to assess soil salinity. They developed remotely sensed data-based salinity indices and utilized Principal Components Analysis (PCA) for salinity detection. Among the six salinity indices (Table 1) considered, S3 yielded the most promising results compared to ground measurements. Additionally, they concluded that PCA and salinity indices hold promise for soil salinity prediction based on satellite images. Asfaw *et al.* [38] presented a regression model to map soil salinity using remote sensing and geographic information systems. Different spectral indices were calculated from original bands of Landsat images. They calculated total of six indices including salinity index (SI), brightness index (BI), Normalized difference salinity index (NDSI) and three vegetation indices. Statistical correlation between field measurements of electrical conductivity (EC) and remote sensing spectral indices showed that salinity index (SI) had the highest correlation with EC. Combining these remotely sensed and EC variables into one model yielded the best fit with $R^2 = 0.78$. Out of the total area, 19% and 23% were identified as moderately and slightly saline, respectively. The study showed that remote sensing data can be effectively used to model and map spatial variations of soil salinity.

Upon reviewing the existing literature on vegetation and soil salinity indices, several noteworthy findings emerge. The utility of vegetation indices in assessing and mapping soil salinity, particularly in regions with dense vegetation cover, holds significant promise. However, in the case of bare soils, the identification of salt using vegetation indices proves to be ineffective. In such scenarios, the application of soil salinity indices emerges as the more suitable approach, especially for bare soils or those with minimal scattered vegetation cover, resulting in highly favorable outcomes. These observations align with the findings of Bouaziz *et al*. [39] and Fan *et al*. [40]. Bouaziz *et al*. [39] discovered that vegetation indices like SAVI, NDVI, and EVI exhibited a low correlation with electrical conductivity (EC) due to inadequate vegetation cover, whereas soil salinity indices demonstrated stronger correlations with EC. Similarly, Fan *et al*. [40] identified a significant negative relationship between NDVI values and soil salinity in vegetated soils, whereas this relationship remained unclear in the case of bare soil.

A comprehensive workflow for the estimation of soil salinity using Remote Sensing (RS) and Geographic Information Systems (GIS) typically comprises several key stages. These stages encompass soil sampling, the collection of satellite data, data pre-processing, the generation of spectral indices, including salinity and vegetation indices, the formulation of salinity prediction models, model validation using independent testing datasets of measured soil samples, performance assessment of the developed models, and the eventual prediction or estimation of soil salinity. A visual representation of this standard workflow is depicted in Fig. 5.

3. APPLICATIONS AND CASE STUDIES

The increasing volume of research dedicated to the detection and monitoring of soil salinity underscores a shared commitment to preserving soil fertility and mitigating the adverse consequences of salinization. Table 2 provides a concise summary of specific findings from various case studies, including shared and novel mapping techniques, sensing approaches, satellite data utilization, and the accuracies in each study. This review underscores that the majority of recent investigations have demonstrated a preference for Remote Sensing (RS) technology over other tools when it comes to soil salinity monitoring. RS technology offers compelling advantages in terms of cost-effectiveness, time efficiency, and reduced manpower requirements, surpassing the traditional methods in these regards. Additionally, it's worth noting that studies relying on RS technology typically require minimal field surveys and sampling, as there is a need to corroborate RS data with ground truth measurements.

Table 1. Spectral indices used for soil salinity estimation in different studies

Sr. No.	Indices	Equation	References
1	Normalized Differential Vegetation Index	$NDVI = (NIR - R)/(NIR + R)$	[33]
2	Enhanced Vegetation Index	$EVI = 2.5(NIR - R)/(NIR + 6R - 7.5Blue + 1)$	[34]
3	Soil Adjusted Vegetation Index	$SAVI = (NIR - R)/(NIR + R + L) \times (1 + L)$	[35]
4	Ratio Vegetation Index	$RVI = NIR/R$	[36]
5	Normalized Differential Salinity Index	$NDSI = (R - NIR)/(R + NIR)$	
6	Brightness Index	$BI = \sqrt{(R^2 + NIR^2)}$	[29]
7	Salinity Index	$SI = \sqrt{Blue \times R}$	
8	Salinity Index	$SI1 = \sqrt{G \times R}$	
9	Salinity Index	$SI2 = \sqrt{G^2 + R^2 + NIR^2}$	[28]
10	Salinity Index	$SI3 = \sqrt{G^2 + R^2}$	
11	Salinity Index	$SI\text{-}1 = ALI9/ALI10$	
12	Salinity Index	$SI\text{-}2 = (ALI6 - ALI9)/(ALI6 + ALI9)$	
13	Salinity Index	$SI\text{-}3 = (ALI9 - ALI10)/(ALI9 + ALI10)$	[32]
14	Soil Salinity and Sodicity Indices	$SSSI\text{-}1 = (ALI9 - ALI10)$	
15	Soil Salinity and Sodicity Indices	$SSSI\text{-}2 = (ALI9 \times ALI10 - ALI10^2)/ALI9$	
16	Salinity Index	$S_1 = Blue/R$	
17	Salinity Index	$S_2 = (Blue - R)/(Blue + R)$	
19	Salinity Index	$S_3 = (G \times R)/Blue$	
20	Salinity Index	$S_4 = \sqrt{Blue \times R}$	[37]
21	Salinity Index	$S_5 = (Blue \times R)/G$	
22	Salinity Index	$S_6 = (R \times NIR)/G$	

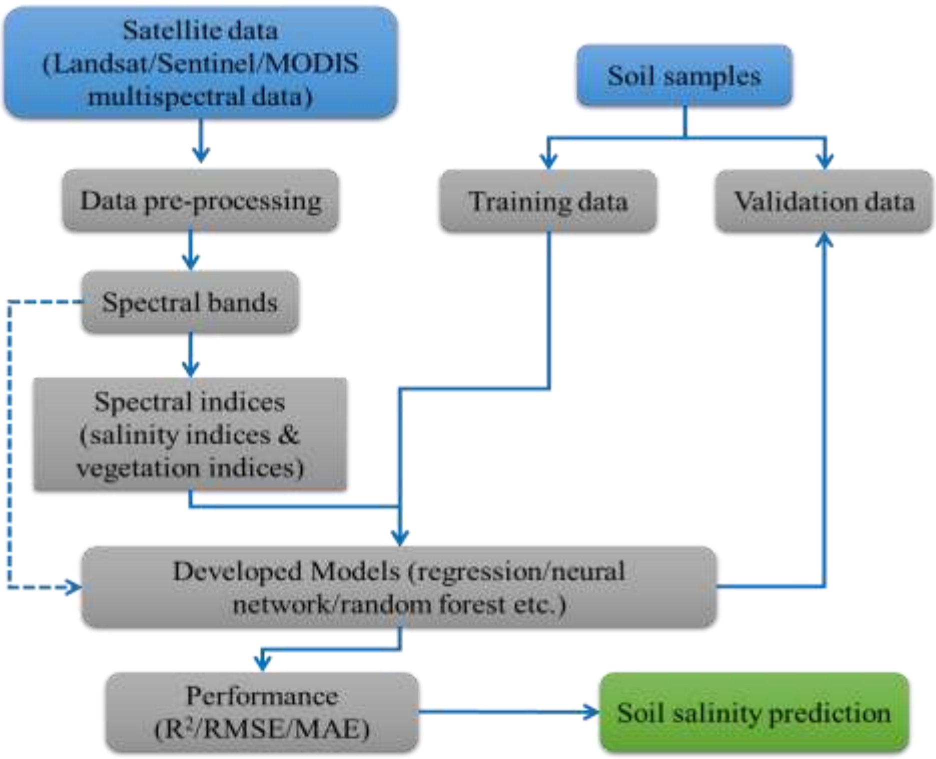

Fig. 5. Standard workflow for soil salinity estimation using remote sensing and GIS

Table 2. Recent case studies examining the detection and monitoring of soil salinity using Remote Sensing technology

Study Year	STUDY Area	Spatial Extent	Data & Methods	Accuracy	Reference
2022	Egypt	373,191 km^2	Landsat 8 (OLI)	R^2 up to 0.90	Aboelsoud *et al.* [41]
2021	Jilin, China	46,985 km^2	Landsat-5 TM and Landsat-8 OLI	R^2 = 0.57	Li *et al*. [42]
2019	China	6064 km^2	Sentinel-2 MSI, SVM, ANN	R^2 = 0.88, RMSE = 4.89 dS/m	Wang *et al.* [43]
1989-2018	Vietnam	2360 km^2	Landsat TM, ETM+ and OLI, regression	R^2 = 0.749	Tran *et al*., [44]
1987-2017	Kuwait	4,500 km^2	Landsat TM, ETM+, OLI	R^2 = 0.97, RMSE = 13 %	Bannari and Al-Ali [45]
2017	Vietnam	2341 km^2	Landsat 8 OLI	R^2 = 0.89, RMSE = 0.96 dS/m	Nguyen *et al.* [46]
2017	China	2671 km^2	Landsat-8 OLI, Sentinel-2 MSI, Cubist	R^2 = 0.912, NRMSE = 9.23 %	Wang *et al.* [47]
2017	Iran	local	MODIS	R^2 = 0.87, RMSE = 5.20	Taghadosi *et al.* [48]
2016	Iran	18 km^2	Landsat-8 OLI and Sentinel-2A, regression	R^2 up to 0.77	Gorji *et al.* [49]
2012-2016	Greece	50 km^2	Landsat 8, regression analysis	R^2 = 0.652	Alexakis *et al*., [50]
2016	Turkey	local	Sentinel-1A, MLR	R^2 = 0.84, RMSE = 2.46 %	Sekertekin *et al*., [51]
2016	China	2671 km^2	Landsat OLI, NN	R^2 = 0.91	Wang *et al*., [52]
2009-2016	Algeria	1878 km^2	Landsat 8 OLI, TIRS, regression fitting	R^2 = 0.82	Abdellatif, [53]
2016	Tunusia	300 km^2	Landsat 8, ASTERGDEM2, Ordinary kriging (OK), simple regression	R^2 = 0.52, RMSE = 0.66 dS/m	Triki Fourati *et al*., [54]
1984-2015	Algeria	5000 km^2	Landsat 5, Landsat 8, Decision tree classification	Accuracy 95 %	Afrasinei *et al*., [55]
1990-2015	Turkey	1500 km^2	Landsat 5 TM, Landsat 8, linear, exponential regression	R^2 = 0.93 and 0.83	Gorji *et al*., [56]
2015	India	430 km^2	Landsat ETM+ and OLI, linear regression	R^2 = 0.73	Periasamy and Shanmugam [57]
2007-2013	USA	local	Landsat 7, canopy response salinity index	R^2 = 0.728, MAE = 2.94 dS/m	Scudiero *et al*., [58]
2012	Ethiopia	65 km^2	Landsat TM, regression model	R^2 = 0.78, RMSE = 0.54 dS/m	Asfaw *et al.* [38]
2011	Thailand	400 km^2	Landsat ETM+, neural networks	R^2 = 0.92, RMSE = 9.59 %	Phonphan *et al*., [59]
2000-2010	India	808 km^2	Landsat TM and ETM+, Kringing	N/A	Das *et al*., [60]

Furthermore, this comprehensive review outlines the use of satellite data and Remote Sensing (RS) mapping algorithms for monitoring soil salinity trends over the years in various case studies. The sensing approaches employed are categorized based on the methods and tools utilized to gather information on saline soil, encompassing satellite images, field measurements, and laboratory analyses. A matrix, as depicted in Table 2, has been established, with columns representing the year of each selected article, the study area, spatial extent, satellite data, mapping techniques, sensing approaches, and the accuracies in each study. The information for each case study is presented in rows, arranged in reverse chronological order of study years.

Several conventional approaches, such as the utilization of common salinity and vegetation indices, correlation and regression analysis, principal component analysis (PCA), decision tree classification (DTC), partial least square regression (PLSR), and maximum likelihood classification, have enjoyed widespread application in the past and continue to be favoured in recent studies. Furthermore, recent years have witnessed the widespread adoption of various models and classification techniques, including neural network models (NNs), support vector machines, random forest regression models, and other newly developed models. This overview underscores the notion that the selection of an appropriate soil salinity mapping approach for each case study is contingent on the availability of data and the specific conditions of the study area. Importantly, it is evident that there is no universally superior method applicable across all contexts.

Furthermore, the developed matrix highlights a common practice observed in most of the studies, where field measurements are typically conducted to establish correlations between actual measured electrical conductivity (EC) values and those estimated through RS mapping approaches. Additionally, some studies have incorporated laboratory analyses to enhance the reliability of the data. Regarding the data sources utilized in these research endeavours, this review reveals that multispectral sensors, including Landsat series, Sentinel series, MODIS, IRS, ASTER and more have been employed for the investigation of soil salinity. These sensors are instrumental in the detection, monitoring, and mapping of saline soils. It is worth noting that Landsat series data has garnered extensive usage in comparison to other multispectral data sources, primarily due to its global availability and the extensive time span it covers, ranging from 1972 to the present day. Considering the exceptionally high spatial resolution (1m or even better) offered by satellites like IKONOS, Quickbird, and Worldview-2, this category of Remote Sensing (RS) data finds its primary application in the analysis of relatively small, localized areas, delivering intricate spatial details. Meanwhile, the MODIS satellite, despite its commendable temporal resolution for providing frequent observations of soil salinity, presents a limitation due to its moderate spatial resolution (100m or coarser). This constraint restricts the level of spatial detail that can be derived from MODIS data. Nevertheless, MODIS proves exceptionally suitable for the monitoring of larger geographic regions, particularly at the regional scale, with the availability of repeated images.

The comprehensive review illustrates that most case studies were situated in arid and semi-arid regions across the globe, encompassing countries in the Middle East, India, China, the United States, and several European nations. In these regions, safeguarding lands against the perils of soil salinization and erosion has emerged as a prominent concern, significantly impacting agricultural productivity. Indeed, the challenge of preserving agricultural lands and ensuring an adequate food supply for the rapidly expanding population in these areas has become increasingly daunting.

4. CHALLENGES AND LIMITATIONS

Estimating soil salinity using remote sensing and Geographic Information Systems (GIS) offers numerous advantages, but it also comes with several challenges and limitations. Here are some of the key challenges and limitations in soil salinity estimation using these technologies:

1. **Limited Soil Profiling:** Remote sensing primarily captures surface information, making it challenging to estimate soil salinity throughout the entire soil profile. Salinity can vary significantly with depth, and remote sensing data may not provide information on subsurface salinity, especially in deeper soil layers.
2. **Influence of Vegetation:** Vegetation cover can affect the accuracy of remote sensing-based soil salinity estimation. In regions

with dense vegetation, the spectral reflectance from the vegetation can mask or distort the signals related to soil salinity, making it difficult to obtain accurate salinity measurements.

3. **Temporal Variability:** Soil salinity can change over time due to natural and anthropogenic factors. Remote sensing data, particularly from satellites with longer revisit times, may not capture rapid changes in salinity, limiting the ability to monitor short-term variations.
4. **Spatial Resolution:** The spatial resolution of remote sensing data may not be fine enough to capture small-scale variations in soil salinity. This can be a limitation when studying areas with fine-scale heterogeneity in salinity.
5. **Atmospheric Interference:** Atmospheric conditions and aerosols can affect the quality of remote sensing data, leading to errors in soil salinity estimation. Cloud cover and haze can limit the availability of cloud-free images.
6. **Ground Truth Data:** Accurate ground truth data for calibrating and validating remote sensing models are crucial. Collecting reliable ground truth data, such as in-situ measurements of soil salinity, can be labor-intensive and may not cover the entire study area.
7. **Sensor Specificity:** Different remote sensing sensors have unique spectral characteristics and limitations. Choosing the right sensor for a specific application is essential, and the availability of suitable data may vary depending on the sensor.
8. **Complexity of Soil-Salt Interaction:** Soil salinity is influenced by various factors, including salt content, soil moisture, texture, and color. Remote sensing techniques may struggle to account for all these factors accurately.
9. **Spatial and Temporal Data Continuity:** Ensuring the continuity of remote sensing data over time is essential for long-term monitoring of soil salinity. Changes in sensor availability or data quality can disrupt monitoring efforts.
10. **Data Processing and Interpretation:** Processing and interpreting remote sensing data to derive soil salinity information can be complex and require specialized knowledge and software tools. Additionally, the choice of spectral indices or algorithms can impact the results.

Despite these challenges and limitations, remote sensing and GIS technologies continue to be valuable tools for soil salinity estimation, providing cost-effective and spatially comprehensive information. Overcoming these challenges often requires a combination of remote sensing data, ground-based measurements, and advanced modelling techniques to improve the accuracy and reliability of soil salinity estimates.

5. CONCLUSION

The review paper offers valuable insights into the detection and monitoring of soil salinity, addressing the critical need to safeguard agricultural lands and mitigate the adverse impacts of salinization. Key findings from a range of case studies demonstrate a shared preference for Remote Sensing technology, highlighting its cost-effectiveness, time efficiency, and reduced manpower requirements compared to traditional methods.

The study underscores that there is no universally superior method applicable across all contexts, emphasizing the importance of selecting an appropriate soil salinity mapping approach tailored to the specific conditions and data availability of the study area. Various approaches, such as the use of common salinity and vegetation indices, correlation and regression analysis, and machine learning models, have been effectively employed. Notably, vegetation indices excel in regions with dense vegetation cover, while soil salinity indices offer a more suitable approach for bare soils or those with minimal vegetation.

Multispectral sensors, including those from the Landsat series, Sentinel series, MODIS, IRS, ASTER, and more, have been pivotal in detecting, monitoring, and mapping saline soils. Among these, Landsat data is extensively utilized due to its global availability and the extensive temporal range it covers. Furthermore, the recent advent of medium-resolution satellites equipped with multi-spectral data collection capabilities, such as ESA Sentinel satellites, has significantly expanded the potential for their utilization in soil salinity monitoring and mapping research. Most case studies are concentrated in arid and semi-arid regions across various countries worldwide, where soil salinization significantly impacts agricultural productivity.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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