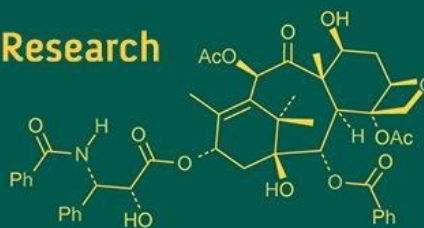


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Salinity intrusion as a growing threat to coastal ecosystems and livelihoods in Gujarat, India

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Abstract

Salinity intrusion in Gujarat's coastal aquifers is a significant and growing threat to both livelihoods and ecosystems, primarily driven by over-extraction of groundwater, sea-level rise, and climate change. Studies show that seawater intrusion leads to increased salinization, deteriorating groundwater quality, and shifts in hydrogeochemical processes, which adversely affect agriculture by reducing crop productivity and soil fertility. Notably, districts such as Surat, Kachchh, Porbandar, Anand, Valsad, Navsari, and parts of south Gujarat have experienced significant salinization due to seawater mixing with groundwater and over-extraction of aquifers. Management strategies proposed include artificial recharge techniques, physical barriers to reduce intrusion, integrated water resource management, and location-specific programs focusing on sustainable groundwater use and crop selection. Remote sensing and IoT-based monitoring have identified high-risk areas including Dabhor, Dari, Somnath, and Veraval for critical salinization, emphasizing the need for real-time management strategies. Recent advances incorporate remote sensing, IoT sensors, and machine learning for real-time monitoring of salinity intrusion hotspots to support early warning systems and sustainable management efforts.

Keywords: Salinization, sea water intrusion, coastal aquifers, groundwater quality, crop productivity

Introduction

Farmers along vast coastal region of Gujarat are increasingly facing a harsh truth as their underground water sources, once crucial for irrigation, are now showing higher salinity levels. This widespread environmental change poses a threat to agricultural sustainability and causes considerable concern among farming communities. At the same time, the aquaculture industry, especially shrimp farming, is dealing with unstable water quality, resulting in reduced productivity and significant financial strain for producers. This gradual environmental decline in an area known for having India's longest coastline, about 2340 km (Survey of India, 2024) ^[39] clearly indicates a serious ecological and socioeconomic risk. Gujarat's distinct geographical features, along with intricate hydrogeological conditions and growing human activities, make it particularly vulnerable to the advancing saline intrusion (Parmar and Patel, 2024) ^[32].

Saltwater intrusion refers to the movement of saline water into freshwater aquifers, a process driven by both natural events and human actions. This phenomenon is intricate and occurs worldwide, with its characteristics changing based on the hydrological conditions, the distribution of saline water, and the rates of freshwater extraction and replenishment in coastal regions.

Gujarat leads the country with 2.23 million hectares of salt-affected soil, followed by Uttar Pradesh (1.37 million ha), Maharashtra (0.61 million ha), West Bengal (0.44 million ha), and Rajasthan (0.38 million ha); combinedly these states account for nearly 75% of India's total salt-affected area (Mandal *et al.*, 2018). Bhagat *et al.* (2021) ^[6] surveyed groundwater levels, electrical conductivity and sea surface temperature and identified 9 of 14 coastal districts as vulnerable to seawater intrusion (SWI). While Siddha and Sahu (2020) ^[38] compiled Central Ground Water Board and state data and listed Bhavnagar, Una, Madhavpur, Maliya, Lakhpat, Surat, Bharuch, Vadodara and Kachchh districts as seawater-influenced coastal areas of Gujarat. Here are factors responsible for salinity intrusion in Gujarat:

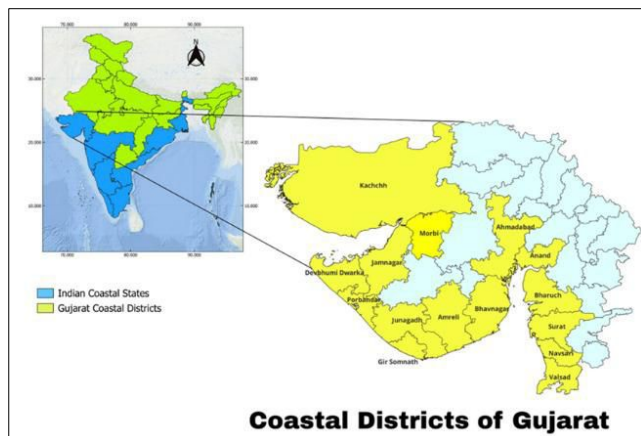


Fig 1: Coastal states of India and Coastal Districts of Gujarat

Natural Factors

Gujarat has the extensive 2340 km coastline along the Arabian Sea naturally subjects its low-lying and porous coastal areas to the influence of seawater (Parmar and Patel, 2024) [32]. The region's arid to semi-arid climate, characterized by low and irregular rainfall, restricts the replenishment of aquifers with freshwater. Consequently, the pressure from freshwater that typically prevents the movement of saltwater diminishes. Rising sea levels further intensify the problem by increasing oceanic pressure, allowing saline water to migrate inland (Ashrafuzzaman *et al.*, 2022) [5].

Human Activities

Human activities significantly worsen the problem. Excessive extraction of groundwater for agriculture, industry, and urban use lowers the freshwater table, creating conditions that draw saltwater into aquifers. In many coastal regions, over-pumping has a more significant impact than the rise in sea levels. Furthermore, the reduction in freshwater flow from rivers caused by dams, irrigation diversions, and industrial use weakens the natural barrier that limits saline intrusion (Safi *et al.*, 2018) [36] (Chithra *et al.*, 2021) [11] (Tessemma *et al.*, 2022) [40].

Ghyben-Herzberg relationship

The Ghyben-Herzberg relationship is a fundamental principle used to describe the equilibrium between freshwater and saltwater in coastal aquifers, based on the density difference between the two fluids. It estimates that for every meter of freshwater above sea level, there is approximately 40 meters of freshwater below sea level, preventing seawater intrusion until pressure balances (Kahsef, 1972; Siddha and Sahu, 2020) [1, 38]. This sharp interface model is extensively used in both analytical and numerical models to forecast the depth and reach of saltwater intrusion and to refine groundwater extraction methods to avoid contamination (Mantoglou, 2003; Karatzas and Dokou, 2015) [26, 19, 1]. However, the traditional Ghyben-Herzberg model presumes a distinct boundary and overlooks mixing effects, potentially leading to overestimations of saltwater encroachment; thus, correction factors that consider hydrodynamic dispersion have been suggested to enhance precision (Pool and Carrera, 2011; Siaka *et al.*, 2018) [34, 37].

This relationship is also employed in assessing vulnerability and mapping the risk of seawater intrusion in coastal

aquifers, often in conjunction with geostatistical and GIS techniques for improved spatial analysis (Trabelsi *et al.*, 2016; Mujib *et al.*, 2024) [41, 28]. Management strategies derived from this relationship include artificial recharge, physical barriers, and regulated pumping to lessen the effects of seawater intrusion on groundwater quality (Karatzas and Dokou, 2015; Maity *et al.*, 2018; Siddha and Sahu, 2020) [19, 25, 38].

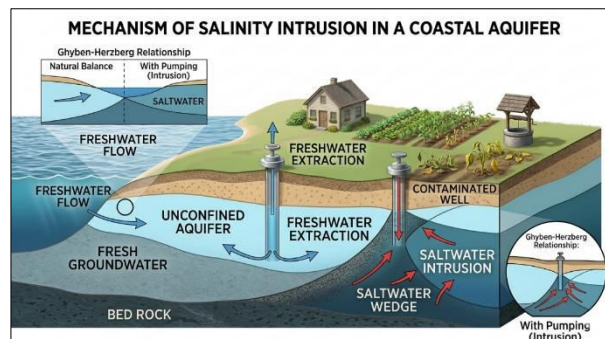


Fig 2: Mechanism of salinity intrusion

Impacts of salinity intrusion on Nature

Agriculture

Mixing of even small amounts of seawater with groundwater makes it unsuitable for irrigation, causing sharp declines in productivity. Studies from coastal Gujarat report crop yield reductions up to 62% in worst-affected areas (Kathrani *et al.*, 2017) [21]. On a statewide level, soil salinity results in an annual crop loss of approximately 4.83 million tons, ranking as the second-highest in India. In terms of financial impact, Gujarat suffers the most, with losses amounting to around ₹100.6 billion each year (Kumar and Sharma, 2020) [22].

Mangroves and wetlands

Salinity intrusion significantly affects mangroves and wetlands by altering species composition, reducing productivity, and disrupting ecosystem functions. Increased salinity can cause declines in mangrove forest cover, favouring salt-tolerant species like *Avicennia* and *Excoecaria* while leading to the loss of salt-sensitive species such as *Heritiera fomes*, which reduces biodiversity and timber value (Haque *et al.*, 2017; Chowdhury *et al.*, 2019; Ahmed *et al.*, 2022) [17, 12, 2]. Extreme salinity stress can cause mangrove dieback, reduce photosynthetic capacity, and alter leaf nutrient content, indicating physiological stress even beyond visibly affected areas (Dittmann *et al.*, 2022) [14]. Zheng *et al.* (2025) [44] identified that Salinity intrusion further disrupts carbon sequestration by reducing microbial necro mass carbon in sediments, which is crucial for long-term soil organic carbon storage in mangrove wetlands. Wetlands experience similar shifts, with freshwater marshes converting to brackish or saline systems, resulting in loss of native vegetation and altered microbial communities.

Salinity intrusion in Gujarat's mangroves and wetlands affects species composition, growth, and ecosystem functioning, with impacts shaped by local salinity levels and species tolerance. Studied the southern Gulf of Kachchh region and founded that salinity between 37 and 39 ppt influencing natural regeneration patterns in mangrove recruitment (Das *et al.*, 2019) [13].

Fisheries and Aquaculture

Salinity intrusion significantly impacts fisheries and aquaculture by reducing the survival and growth of freshwater species and altering coastal water quality. Alam *et al.* (2020) ^[3] reported that Freshwater aquaculture species like *Ompok pabda* show decreased hatching success, larval deformities, and high mortality rates at salinities above 2.5 ppt, with complete fry mortality at 10 ppt, indicating severe vulnerability to increased salinity. Expansion of shrimp farming in coastal Gujarat contributes to groundwater salinization through infiltration of saline pond water, which exacerbates saltwater intrusion and affects freshwater availability for aquaculture (Patil and Dedaniya, 2024) ^[33]. Overall, salinity intrusion poses complex challenges to Gujarat's fisheries and aquaculture sectors by affecting species survival, water resources, and soil health, necessitating integrated management approaches.

People's livelihood

Salinity intrusion in Gujarat adversely affects people's lives by degrading agricultural productivity, reducing access to safe drinking water, and threatening rural livelihoods. Nathani (2021) ^[29] identified that groundwater salinization in areas like Gandhidham makes many wells unfit for drinking and threatens long-term irrigation sustainability. Contaminated coastal groundwater with metals and other pollutants, posing ecological risks and potential health hazards, especially for children exposed through drinking water (Bhagat *et al.*, 2022) ^[7]. Soil salinization leads to loss of fertile land and challenges in agriculture and fisheries, which are critical for local economies and food security (Gururaja Rao *et al.*, 2019) ^[16]. Salinity intrusion in coastal Gujarat poses multifaceted socio-economic and public health challenges, underscoring the urgent need for integrated management approaches that harmonize engineering interventions with community-based support systems.

Salinity intrusion as rising threat

Salinity intrusion is becoming a more significant threat, mainly due to the combined impact of rising sea levels, decreased river discharge, and human activities like excessive groundwater extraction and changes in land use. The rise in sea levels contributes approximately twice as much as the reduction in river flow to the spread of saltwater intrusion in coastal estuaries globally, pushing saline water further inland and increasing salinity concentrations (Adams *et al.*, 2024; Lee *et al.*, 2025) ^[1, 3]. Excessive groundwater extraction lowers freshwater levels, making it easier for seawater to infiltrate aquifers, while land subsidence worsens the situation by altering aquifer characteristics such as porosity and permeability (Loc *et al.*, 2021; Chala *et al.*, 2022) ^[9]. Urbanization and water shortages exacerbate the issue by increasing water demand and reducing natural recharge, creating a synergistic effect that worsens salinization in coastal aquifers (Rachid *et al.*, 2021) ^[35]. Overall, climate change-induced sea-level rise, combined with human pressures on water resources, is driving the escalating global threat of salinity intrusion to freshwater availability and ecosystem health.

Solutions for salinity intrusion in Gujarat

Salinity intrusion in Gujarat's coastal aquifers is primarily driven by over-extraction of groundwater, sea-level rise, and

climate change, leading to significant environmental and socioeconomic challenges. Solutions include artificial recharge techniques to dilute saline water, construction of subsurface physical barriers, and integrated water resource management that considers groundwater budgets and sustainable use (Maurya *et al.*, 2019; Siddha and Sahu, 2020) ^[27, 38]. Infrastructure measures such as tidal regulators, bandharas (check dams), recharge reservoirs, and spreading channels have been implemented in Saurashtra to reduce salinity ingress, improve irrigation potential, and restore agricultural productivity (Panchal and Patel, 2013) ^[31].

Parmar and Patel (2024) ^[32] reported that Barda Sagar Prevention Scheme in Porbandar district demonstrated positive impacts on agriculture and water security by managing water resources effectively and promoting alternative cropping patterns. Engineering solutions like tidal regulators, check dams, spreading channels, and recharge reservoirs have been implemented in coastal districts to control salinity ingress and improve irrigation potential. Advanced monitoring approaches combining remote sensing, IoT sensors, and machine learning have been developed to track saltwater intrusion zones in real time, enabling early warning systems for better groundwater management. Additionally, location-specific programs integrating engineering, agro-interventions, afforestation, regulation of groundwater extraction, and promotion of rainwater harvesting are recommended to sustainably manage salinity issues along Gujarat's extensive coastline (Gururaja *et al.*, 2019; Bhagat *et al.*, 2021) ^[16, 8].

Nature-based solutions (NBS) for salinity intrusion focus on harnessing natural processes to reduce saltwater encroachment in estuaries and coastal areas while supporting ecosystem services. One promising approach is the use of estuarine sand dunes, which can significantly reduce salt intrusion length by enhancing vertical mixing and maintaining navigability, with steeper dunes showing stronger effects (Geerts *et al.*, 2025) ^[15]. Wetlands and halophyte plants like *Atriplex portulacoides* have also been shown to mitigate salt-wedge intrusion by absorbing salts and improving freshwater availability, potentially reducing salt intrusion by up to 16% under future climate scenarios (Verri *et al.*, 2024) ^[43]. Restoration of intertidal ecosystems and promoting biodiversity through NBS can improve flood protection, carbon sequestration, and water quality, offering sustainable alternatives to conventional agriculture in salinized coastal plains (Velilla *et al.*, 2025) ^[42].

Recent technologies involve remote sensing combined with IoT sensors and machine learning models like Support Vector Machines (SVM) enable real-time tracking and prediction of saltwater intrusion zones, improving early warning systems and sustainable groundwater use (Alruwais *et al.*, 2025) ^[4]. Additionally, comprehensive approaches involving soil amendments (e.g., gypsum), improved drainage, phytoremediation, and integrated water resource management are emphasized to sustainably manage coastal salinity challenges (Gururaja *et al.*, 2019; Kumar and Sharma, 2020; Ondrasek *et al.*, 2022) ^[16, 22, 30].

Conclusion

Salinity intrusion is quietly but significantly altering the future of Gujarat's coastline. As seawater gradually infiltrates freshwater aquifers and fertile lands, agriculture suffers, potable water becomes limited, and fisheries

experience ecological changes. For coastal residents, this results in reduced incomes, increased vulnerability, and uncertain livelihoods. In addition to human impacts, the intrusion disturbs delicate ecosystems that protect against storms and support biodiversity. Addressing this issue requires sustainable groundwater management, the restoration of mangroves and wetlands, and climate-resilient planning. Recognizing salinity intrusion as both an environmental and livelihood crisis is essential for ensuring a resilient and sustainable coastal Gujarat.

References

- Adams KH, Reager JT, Buzzanga BA, David CH, Sawyer AH, Hamlington BD. Climate-induced saltwater intrusion in 2100: recharge-driven severity, sea level-driven prevalence. *Geophys Res Lett*. 2024;51(22):e2024GL110359.
- Ahmed S, Sarker SK, Friess DA, Kamruzzaman M, Jacobs M, Islam MA, *et al*. Salinity reduces site quality and mangrove forest functions: from monitoring to understanding. *Sci Total Environ*. 2022;853:158662.
- Alam MR, Sharmin S, Islam SM, Alam MA, Ehiguese FO, Pattadar SN, *et al*. Salinity intrusion affects early development of freshwater aquaculture species pabda, *Ompok pabda*. *Aquac Rep*. 2020;18:100476.
- Alruwais N, Hasanin T, Burle T, Marzouk R, Vijayalakshmi J, Srinivasan S. Integrating remote sensing, IoT, and machine learning for tracking saltwater intrusion in coastal aquifers due to over-extraction: a geospatial approach. *Desalin Water Treat*. 2025;101403.
- Ashrafuzzaman M, Artemi C, Santos FD, Schmidt L. Current and future salinity intrusion in the south-western coastal region of Bangladesh. *Span J Soil Sci*. 2022;12:10017.
- Bhagat C, Khandekar A, Singh A, Mohapatra P, Kumar M. Delineation of submarine groundwater discharge and seawater intrusion zones using anomalies in field water quality parameters, groundwater level fluctuation and sea surface temperature along the Gujarat coast of India. *J Environ Manage*. 2021;296:113176.
- Bhagat C, Kumar M, Mahlkecht J, Hdeib R, Mohapatra PK. Seawater intrusion decreases the metal toxicity but increases the ecological risk and degree of treatment for coastal groundwater: an Indian perspective. *Environ Pollut*. 2022;310:119771.
- Bhagat C, Mohapatra PK, Kumar M. Unveiling the extent of salinization to delineate the potential submarine groundwater discharge zones along the north-western coast of India. *Mar Pollut Bull*. 2021;172:112773.
- Chala DC, Quinones-Bolanos E, Mehrvar M. An integrated framework to model salinity intrusion in coastal unconfined aquifers considering intrinsic vulnerability factors, driving forces, and land subsidence. *J Environ Chem Eng*. 2022;10(1):106873.
- Chambers L, Guevara R, Boyer J, Troxler T, Davis S. Effects of salinity and inundation on microbial community structure and function in a mangrove peat soil. *Wetlands*. 2016;36:361-371.
- Chithra S, Joseph S, Kannan N. A study of saltwater intrusion in the Kallada River, southwest coast of Kerala, India. *Water Supply*. 2022;22(2):2194-2211.
- Chowdhury R, Sutradhar T, Begam MM, Mukherjee C, Chatterjee K, Basak SK, *et al*. Effects of nutrient limitation, salinity increase, and associated stressors on mangrove forest cover, structure, and zonation across Indian Sundarbans. *Hydrobiologia*. 2019;842(1):191-217.
- Das L, Patel R, Salvi H, Kamboj RD. Assessment of natural regeneration of mangrove with reference to edaphic factors and water in Southern Gulf of Kachchh, Gujarat, India. *Heliyon*. 2019;5(8):e02250.
- Dittmann S, Mosley L, Stangoulis J, Nguyen VL, Beaumont K, Dang T, *et al*. Effects of extreme salinity stress on a temperate mangrove ecosystem. *Front For Glob Change*. 2022;5:859283.
- Geerts SJ, van der Sande WM, Hulscher SJ, Geurts BJ, Roos PC. Sand dunes as a nature-based solution to mitigate salt intrusion in stratified estuaries. *J Geophys Res Oceans*. 2025;130(1):e2024JC021103.
- Gururaja Rao G, Kanani AD, Purohit D, Waghela D. Coastal saline soils of Gujarat (India): problems, reclamation measures and management strategies. In: *Research developments in saline agriculture*. Singapore: Springer; 2019. p. 629-651.
- Haque MZ, Reza MIH. Salinity intrusion affecting the ecological integrity of Sundarbans mangrove forests, Bangladesh. *Int J Conserv Sci*. 2017;8(1):1-10.
- Herbert ER, Boon P, Burgin AJ, Neubauer SC, Franklin RB, Ardón M, *et al*. A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. *Ecosphere*. 2015;6(10):1-43.
- Karatzas GP, Dokou Z. Optimal management of saltwater intrusion in the coastal aquifer of Malia, Crete (Greece), using particle swarm optimization. *Hydrogeol J*. 2015;23(6):1181-1194.
- Kashef AI. What do we know about salt water intrusion? *J Am Water Resour Assoc*. 1972;8(2):282-293.
- Kathrani N, Kandya A, Koekkoek I, Kelder TOD, Rajpurohit P. From the problem of groundwater salinity towards sustainable prosperity in agricultural sector in coastal region of Gujarat, India. In: *Proceedings of the 2nd World Congress on Civil, Structural, and Environmental Engineering (CSEE'17)*; Barcelona, Spain; 2017. p. 2-4.
- Kumar P, Sharma PK. Soil salinity and food security in India. *Front Sustain Food Syst*. 2020;4:533781.
- Lee J, Biemond B, van Keulen D, Huismans Y, van Westen RM, de Swart HE, *et al*. Global increases of salt intrusion in estuaries under future environmental conditions. *Nat Commun*. 2025;16(1):3444.
- Loc HH, Van Binh D, Park E, Shrestha S, Dung TD, Son VH, *et al*. Intensifying saline water intrusion and drought in the Mekong Delta: from physical evidence to policy outlooks. *Sci Total Environ*. 2021;757:143919.
- Maity P, Das S, Das R. Remedial measures for saline water ingress in coastal aquifers of South West Bengal in India. *MOJ Ecol Environ Sci*. 2018;3:1-10.
- Mantoglou A. Pumping management of coastal aquifers using analytical models of saltwater intrusion. *Water Resour Res*. 2003;39(12):1-12.
- Maurya P, Kumari R, Mukherjee S. Hydrochemistry in integration with stable isotopes ($\delta^{18}\text{O}$ and δD) to assess seawater intrusion in coastal aquifers of Kachchh

- district, Gujarat, India. *J Geochem Explor.* 2019;196:42-56.
28. Mujib MA, Astutik S, Apriyanto B, Muhammad IN, Fitra AA. Geostatistical mapping of groundwater salinity and seawater intrusion in coastal aquifers of Jember Regency using physicochemical parameters and seawater fraction. *Geomedia.* 2024;22(2):196-212.
 29. Nathani M. Study of groundwater quality, its impact on human health and agriculture and salt water intrusion in and around Gandhidham, Kachchh, Gujarat. *Int J Res Appl Sci Eng Technol.* 2021.
 30. Ondrasek G, Rathod S, Manohara KK, Gireesh C, Anantha MS, Sakhare AS, *et al.* Salt stress in plants and mitigation approaches. *Plants.* 2022;11(6):717.
 31. Panchal RS, Patel BG. Ingress of salinity in coastal area of Junagadh. *Indian J Res Parip.* 2013;2(3):1-2.
 32. Parmar VK, Patel DB. Socio-economic impact assessment of salinity prevention structure-Bardasagar scheme in Porbandar district of Gujarat, India. *Int J Environ Clim Change.* 2024;14(10):505-515.
 33. Patil D, Dedaniya A. Impact of shrimp farming and government policy implications on rice production in Navsari district of Gujarat, India. *J Sci Res Rep.* 2024;30(8):464-469.
 34. Pool M, Carrera J. A correction factor to account for mixing in Ghyben-Herzberg and critical pumping rate approximations of seawater intrusion in coastal aquifers. *Water Resour Res.* 2011;47(5):1-12.
 35. Rachid G, Alameddine I, El-Fadel M. Management of saltwater intrusion in data-scarce coastal aquifers: impacts of seasonality, water deficit, and land use. *Water Resour Manag.* 2021;35(15):5139-5153.
 36. Safi A, Rachid G, El-Fadel M, Doummar J, Abou Najm M, Alameddine I. Synergy of climate change and local pressures on saltwater intrusion in coastal urban areas: effective adaptation for policy planning. *Water Int.* 2018;43(2):145-164.
 37. Siaka M, Dokou Z, Karatzas GP. Management of the saltwater intrusion phenomenon in the alluvial aquifer of Katapola, Amorgos, Greece. *Water Sci Technol Water Supply.* 2018;18(3):936-949.
 38. Siddha S, Sahu P. Status of seawater intrusion in coastal aquifer of Gujarat, India: a review. *SN Appl Sci.* 2020;2:1-12.
 39. Survey of India. Length of coastline of India: standardisation draft notification. Government of India; 2024.
 40. Tessema N, Yadeta D, Kebede A, Ayele GT. Soil and irrigation water salinity, and its consequences for agriculture in Ethiopia: a systematic review. *Agriculture.* 2022;13(1):109.
 41. Trabelsi N, Triki I, Hentati I, Zairi M. Aquifer vulnerability and seawater intrusion risk using GALDIT, GQISWI and GIS: case of a coastal aquifer in Tunisia. *Environ Earth Sci.* 2016;75(8):669.
 42. Velilla E, Snethlage J, Poelman M, van der Meer IM, van der Werf A, Deolu-Ajayi AO, *et al.* Too salty to farm: rethinking coastal land use in response to soil salinization. *Restor Ecol.* 2025;33(4):e70006.
 43. Verri G, De Lorenzis A, Santos da Costa V, Sorolla A, Löchner A, Ribot M, *et al.* Salt-wedge estuary's response to rising sea level, reduced discharge, and nature-based solution. *Front Clim.* 2024;6:1408038.
 44. Zheng L, Su M, Zhang X, Wang L, Hong H, Zhang Q, *et al.* Salinity and inundation drivers shift microbial necromass carbon distribution patterns in estuarine mangrove wetlands. *Geoderma.* 2025;460:117413.