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Hydrogeochemical drivers of salinity intrusion in coastal paddy fields: Soil-water interactions and irrigation implications

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Abstract

Salinity intrusion is a major constraint in coastal paddy agroecosystems, where the dynamic interplay of groundwater, surface water and soil processes determines the quality of irrigation water and crop performance. While previous studies have examined hydrogeochemical processes, soil salinity and crop responses individually, their integration at the field scale remains limited. This review integrates the hydrogeochemical drivers of salinity intrusion, such as seawater mixing, groundwater abstraction, tidal forcing and land-use change and links them explicitly to root-zone salinity dynamics, soil transformations and irrigation suitability. Evidence indicates that salinisation is not a constant process, but rather a spatiotemporally variable phenomenon controlled by groundwater–surface water connectivity, microtopography and in-season hydrological variability under flooded conditions. We argue that root-zone salinity, rather than bulk irrigation water salinity, is the primary determinant of rice stress and productivity in coastal systems. Management strategies such as irrigation–drainage coupling, blended water use, soil amendments and adaptive cropping systems can partially regulate salinity distribution, but single-component interventions often fail under dynamic coastal hydroclimatic conditions. This synthesis highlights the need to reframe salinity intrusion as a coupled hydrogeochemical–soil–crop process and emphasises integrated water–salt balance approaches for sustaining irrigation and productivity in coastal rice agroecosystems.

Keywords: coastal paddy systems; hydrogeochemistry; irrigation water quality; root-zone salinity; salinity intrusion; seawater intrusion; water-salt balance

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Introduction

Rice, a staple food of more than half of the world's population, is predominantly cultivated in fertile alluvial soils and water-abundant deltas and coastal lowlands, where engineered irrigation and water management systems support intensive paddy cultivation (1). Salinity intrusion, drought and storm surges collectively reduce irrigation suitability and accelerate land degradation (1, 2). Salinity intrusion in coastal paddy systems is intensified by sea-level rise, reduced river discharge and excessive groundwater extraction, which disrupt surface and subsurface freshwater flow regimes (3). Low-lying deltas are especially vulnerable because hydraulic connectivity facilitates inland seawater movement. Groundwater over extraction lowers piezometric heads and promotes landward movement of saline fronts into irrigation water sources. Hydrogeochemical processes such as seawater mixing, ion exchange, silicate weathering and evaporation further increase groundwater salinity through sodium (Na), chloride (Cl) enrichment (4).

Irrigation and drainage networks may also transport saline water during dry periods, further degrading water quality (5). Salinisation of groundwater, reflected by rising electrical conductivity, reduces irrigation reliability and paddy yields, particularly when salinity intrusion coincides with drought-induced water shortages (6, 7). Landscape-scale evaluations identify salinity intrusion as a major challenge, but they frequently treat soil, water and crop responses as separate issues rather than interconnected processes within agroecosystems (8). Rice-focused research has largely examined plant responses to salinity in controlled conditions but has rarely incorporated realistic soil–water salinity distributions under field conditions. Landscape-scale evaluations identify salinity intrusion as a major challenge, but they frequently view soil, water and crop responses as distinct issues rather than

interconnected processes in controlled agroecosystems (8). Similarly, soil-based reviews concentrate on physicochemical remediation or nature-based solutions, but do not pay sufficient attention to irrigation limitations and rice sensitivity under unpredictable pedoclimatic conditions (9, 10).

Root-zone salinity remains poorly conceptualised as the interface linking hydrogeochemical processes with crop stress under field conditions. This review synthesises hydrogeochemical drivers, root-zone salinity dynamics, crop responses and management strategies in coastal paddy systems and evaluates their implications for irrigation water quality and sustainable rice production.

Methodology of literature review

This review was conducted using a structured literature search approach to synthesise current knowledge on hydrogeochemical drivers of salinity intrusion and their implications for soil–water interactions, irrigation water quality and rice productivity in coastal paddy systems. Relevant literature was retrieved primarily from the Scopus and Google Scholar databases. Additional studies were identified through backward and forward citation tracking of key publications to ensure comprehensive coverage of the subject.

The literature search was performed using combinations of keywords such as “salinity intrusion”, “seawater intrusion”, “coastal aquifers”, “coastal paddy fields”, “rice cultivation”, “hydrogeochemistry”, “groundwater salinisation”, “root-zone salinity”, “irrigation water quality”, “soil–water interactions” and “coastal agriculture”. Only peer-reviewed articles published in English were considered for inclusion.

Studies were included when they addressed one or more of the following themes: (i) hydrogeochemical processes governing salinity intrusion, (ii) groundwater and surface-water interactions in coastal agricultural environments, (iii) impacts of salinity on paddy soils and rice production, (iv) irrigation water suitability under saline conditions and (v) management and adaptation strategies for salinity mitigation in coastal agroecosystems. Studies focused exclusively on non-agricultural coastal systems or lacking relevance to soil, water or crop responses were excluded.

The review primarily covered literature published between 2000 and 2025, while selected earlier studies were included where they provided a foundational understanding of seawater intrusion processes and hydrogeochemical evolution. An initial screening of approximately 100 publications was conducted based on titles, abstracts and relevance to the review objectives. Following a detailed evaluation, 58 highly relevant studies were selected and synthesised. The selected literature was critically examined to identify major hydrogeochemical mechanisms, root-zone salinity dynamics, irrigation implications, management strategies and future research priorities for coastal paddy agroecosystems.

Coastal salinity intrusion: Process and mechanisms

Aquifer properties, thickness and geological heterogeneity determine the extent of saline intrusion and explain the strong spatial variation in groundwater salinity over short distances at the coast (11). Seawater-intruded coastal aquifers commonly exhibit sodium–chloride (Na–Cl) hydrochemical facies with elevated electrical conductivity (EC) and total dissolved solids (TDS). The predominance of Na–Cl facies serves as a diagnostic indicator of seawater intrusion and is generally associated with reduced irrigation suitability due to increased salinity and sodicity hazards. The major pathways of seawater intrusion and salinity transport in coastal aquifers underlying paddy fields are illustrated in Fig. 1.

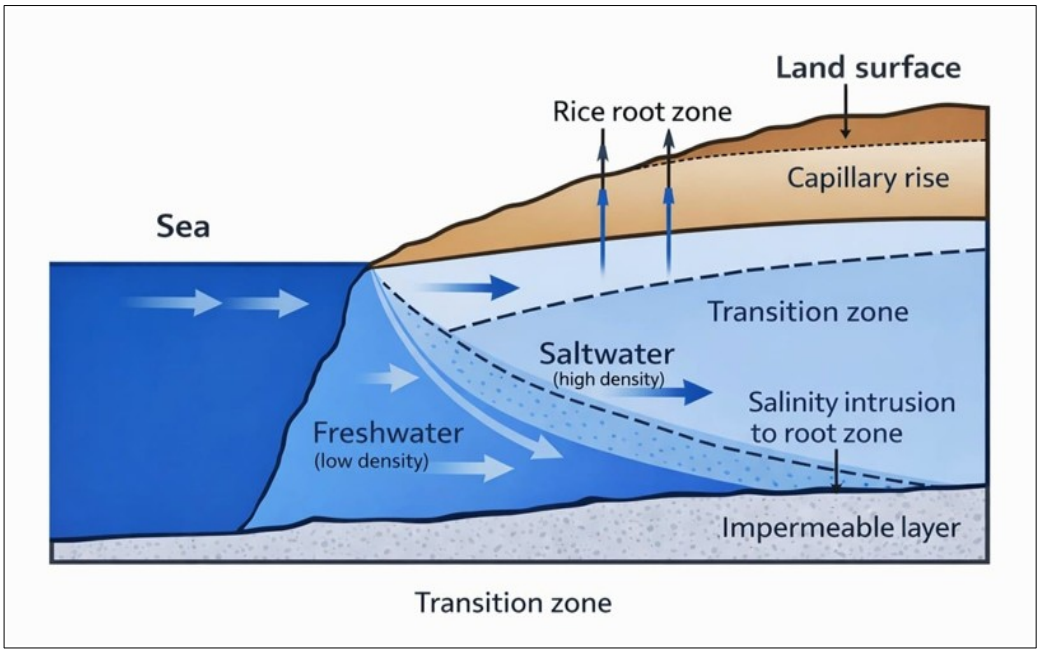

Fig. 1. Schematic representation of seawater intrusion and salinity transport pathways in coastal aquifers underlying paddy fields. Created by the authors using AI-assisted visualisation tools.

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Natural drivers of salinity intrusion

Climate-change-driven reductions in recharge and surface inundation with saltwater have intensified seawater intrusion in coastal aquifers beyond the effects of sea-level rise alone, primarily in arid and semi-arid regions (12). High groundwater demand and weak regulation further threaten paddy irrigation sustainability in coastal South Asia, where groundwater salinity often exceeds irrigation thresholds even during the monsoon season (13).

Existing studies indicate a systematic underestimation of future salinity risks due to the omission of interactions among sea-level rise, recharge variability, land subsidence and groundwater abstraction (12). Tidal pumping and seasonal water-table fluctuations enhance saltwater intrusion into shallow coastal groundwater, increasing salinity risks to paddy irrigation (13). Hydrochemical evolution from calcium–bicarbonate ($Ca–HCO_3$) to Na–Cl facies indicate increasing salinity and declining irrigation suitability near coastal zones (10). These processes have been widely documented in major rice-growing deltas such as the Mekong Delta of Vietnam and the Ganges–Brahmaputra Delta of Bangladesh, where seasonal salinity intrusion increasingly threatens irrigation water quality and rice productivity. Cyclonic storm surges introduce large salt loads into deltaic rice fields (14).

Anthropogenic drivers of salinity intrusion

Anthropogenic activities such as shrimp aquaculture, canal modification and expanded drainage networks accelerate salinity intrusion. Excessive groundwater extraction lowers hydraulic heads, promoting lateral seawater intrusion and vertical seawater upconing in coastal aquifers. Land subsidence caused by sediment compaction and groundwater extraction further weakens hydraulic barriers against seawater intrusion (5). Remote sensing analyses show that the seasonal salinity intrusion is expanding and extending upstream along river channels during the dry season. This is driven by intensified tidal amplification and reduced upstream discharge (15). Irrigation returns flows redistribute accumulated salts within irrigated areas (16). Land-use modifications, including the conversion of rice fields to aquaculture ponds, further accelerate surface salinity transfer by facilitating intentional or accidental movement of saline water into adjacent rice systems (5).

Implications for salinity exposure in the rice root zone

In coastal aquifers, seawater intrusion adversely affects paddy irrigation through subsurface salinisation along hydraulic gradients and the inland migration of saltwater fronts driven by reduced aquifer recharge, abstraction and sea-level rise (12).

Transmission and spatiotemporal variability

Rhizosphere salinity is strongly influenced by flooded paddy conditions. Shallow groundwater connectivity and prolonged flooding convert hydrological salinity inputs into dynamic root-zone stress. Salts transferred from surface water and shallow groundwater accumulate in the flooded root zone, directly driving crop stress (3).

Shallow groundwater tables in coastal agroecosystems result in high hydro-hydraulic connectivity among saline groundwater, soil pore water and ponded surface water, which facilitates high-rate vertical and lateral salt flux into the rice root zone. Saltwater intrusion alters the ionic composition of porewater, enriching it with Na^+, $Cl^–$, magnesium (Mg^{2+}) and sulphate ($SO_4^{2–}$) (17). Root-zone salinity in coastal paddy fields exhibits strong spatiotemporal variability owing to microtopography, field location and seasonal hydrological processes within the flooded paddy system. Minor elevation differences can create persistent root-zone salinity hotspots (18).

Temporal observations indicate that root-zone salinity can be highest in the early vegetative period, when the influence of saline groundwater peaks and evaporative concentration is highest, thereby increasing rice susceptibility during critical developmental stages. Water-seeded rice systems also show that salts are redistributed in the fields in response to the intra-field movement of water and downstream basins accumulate higher salt concentrations than upstream basins (19).

Root-zone salinity as the primary stress environment for rice

Root-zone salinity is a more sensitive indicator of field-scale rice salinity stress than bulk soil salinity or pre-season EC measurements because it directly reflects the root environment during crop growth. Field evidence shows that rice roots can tolerate salinity levels below the thresholds reported in literature from controlled experiments; however, spatiotemporal analysis reveals that root-zone electrical conductivity frequently exceeds critical levels during sensitive growth phases, even in paddy fields with seasonally moderate average salinity.

Comparative field studies further demonstrate that irrigation-water salinity alone is often a poor predictor of rice performance because the salinity experienced by roots is modified continuously by ponded-water dynamics, rainfall, soil hydraulic properties, groundwater influence and drainage conditions. In flooded paddy systems, identical irrigation-water salinity levels can produce substantially different root-zone salinity environments depending on field position, water management practices and seasonal hydrological conditions. Spatiotemporal monitoring of water-seeded rice fields showed that yield reductions were more closely associated with root-zone electrical conductivity during sensitive growth stages than with average irrigation-water salinity alone (19). Similarly, studies conducted in reclaimed coastal paddy soils indicate that prolonged root-zone salt exposure exerts stronger control over soil fertility dynamics and crop productivity than generalised measures of irrigation-water quality (20). These findings support the concept that root-zone salinity represents the most direct and agronomically relevant indicator of salinity stress in coastal rice agroecosystems.

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Long-term field experiments have shown an inverse correlation between rising root-zone salinity and soil organic carbon accretion, as well as rice biomass, underscoring biogeochemical and physiological productivity limitations in coastal paddy fields. Salinity in reclaimed coastal paddy soils has been found to impose a more dominant influence on the dynamics of root-zone fertility, with respect to the duration of cultivation, suggesting the importance of salinity exposure over management history as a determinant of soil-crop interactions (20).

Feedback between rice cultivation and salinity dynamics

Long-term rice cultivation can enhance the capacity of paddy soils to regulate salinity by improving macroporosity, pore connectivity and hydraulic conductivity, thereby promoting vertical drainage and salt leaching (21). Transformation of lithogenic to pedogenic carbonates reflects changing root-zone chemical conditions in coastal paddy soils. These changes suggest that root-zone salinity does not remain constant but rather develops feedback between the hydrology, soil structure and biogeochemical processes due to rice farming (20).

Hydrogeochemical drivers of salinity

The interaction of marine, geological, hydrological and anthropogenic processes operating at different spatial and temporal scales controls groundwater salinisation in coastal rice systems and generates complex salinity signatures that directly influence irrigation water quality (22, 23).

Seawater-freshwater mixing

Seawater intrusion occurs when groundwater abstraction lowers freshwater hydraulic heads and reverses natural land–sea hydraulic gradients, allowing lateral and vertical seawater intrusion into coastal aquifers (24, 25). This process is particularly common in unconfined and semi-confined alluvial aquifers underlying coastal plain and deltaic rice systems, which are characterised by low topographic gradients and high irrigation pumping intensity (26, 27). Salinity intrusion also occurs through upconing of deeper saline groundwater. In heavily farmed rice belts, where very shallow lenses of freshwater overlie brackish or marine-derived groundwater, this process is exacerbated by prolonged agricultural pumping from bores during dry seasons.

Seasonal hydrology controls seawater-freshwater interface movement, with salinity fronts advancing inland during dry periods and partially retreating during monsoonal recharge (26). Coastal paddy margins can also act as secondary sources of salinity due to anthropogenic inputs such as irrigation return flows, leached fertilisers, aquaculture effluents and domestic wastewater, with a high level of nitrate under the NaCl groundwater facies signifying coupled salinisation and agrochemical pollution (25).

Mineral dissolution and precipitation

Water-rock interactions involving dissolution of silicate minerals, gypsum, halite and carbonate minerals significantly influence hydrogeochemical evolution during the salinisation of coastal paddy aquifers. These processes increase TDS beyond direct seawater mixing and alter the ionic composition through the release of Ca^{2+}, Mg^{2+}, SO_4^{2-} and Na^+ into the groundwater (24, 28). Regionally, palaeo-seawater entrapment, marine transgression deposition and deep-seated brine movement are among the factors that lead to the continuous occurrence of baseline salinity in most coastal aquifers. This phenomenon is particularly evident in deltaic regions characterised by thick Quaternary sediments.

Seawater intrusion further accelerates mineral dissolution by increasing groundwater ionic strength and altering pH conditions of the evaporite and carbonate minerals found within coastal sediments. Groundwater salinisation is therefore driven by both seawater mixing and secondary geochemical reactions, resulting in systematic temporal changes in groundwater ionic composition.

Cation exchange in paddy soils

Ion exchange strongly modifies groundwater chemistry during seawater intrusion. Incoming Na^+ in saline water displaces Ca^{2+} and Mg^{2+} adsorbed on aquifer sediments and reverse exchange reactions release Na^+ from exchange sites to the groundwater. Common products of these processes are Na–Cl or mixed Na–Ca–Cl hydrochemical facies (29, 30). Cation exchange reactions thus serve as an important buffering mechanism during seawater intrusion events, which temporarily alter the ionic ratios of groundwater despite continued rising salinity. As exchange sites in aquifer sediments become progressively depleted of divalent cations over repeated flushing cycles, sodium-dominated groundwater compositions can progressively develop in coastal aquifers undergoing intensive irrigation-pumping (24, 28).

Redox and biogeochemical processes

Saltwater intrusion alters the biogeochemical environment of flooded paddy soils by modifying redox conditions under prolonged inundation of the soil and the low groundwater table, promoting nutrient and metal mobilisation in the rice root zone. High ionic strength in saline conditions enhances ion exchange and mobilisation of nutrients, releasing ammonium and phosphorus (P) into soil pore water, which further alters nutrient availability, impacting rice roots (3).

In flooded paddy environments, the occurrence of anoxic conditions over a prolonged period also promotes microbial-mediated redox reactions of iron and sulphur minerals, which can modulate the mobility of nutrients and trace elements in the saline groundwater. The reduction of iron (Fe) (III) oxides and sulfate in the presence of saline and waterlogged conditions may mobilise previously sorbed ions into soil pore water, thus altering water chemistry in groundwaters and contributing to the complex hydrogeochemical signatures in coastal rice-growing aquifers.

Linking hydrogeochemical evolution to physiological stress in rice

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Hydrogeochemical evolution during salinity intrusion directly influences rice physiology through changes in the concentration and composition of dissolved ions in groundwater, soil porewater and ponded irrigation water. As coastal aquifers evolve toward Na–Cl hydrochemical facies through seawater mixing, mineral dissolution and ion-exchange processes, concentrations of Na^+ and Cl^- increase in the rice root environment. These changes alter both the osmotic and ionic conditions experienced by rice plants.

Elevated salt concentrations reduce the osmotic potential of the soil solution, making water uptake more difficult even under flooded conditions. This osmotic stress induces a physiological drought effect, reducing cell expansion, tillering and overall vegetative growth. Prolonged exposure to high salinity further promotes ion toxicity through excessive accumulation of Na^+ and Cl^- within plant tissues. Sodium competes with potassium (K^+) uptake and disrupts enzyme activity, while Cl accumulation may impair photosynthesis and accelerate leaf senescence.

Hydro geochemically driven salinity also contributes to nutrient imbalances by reducing the uptake efficiency of essential nutrients such as K, Ca, nitrogen (N) and P. High Na concentrations can destabilise root membrane integrity and alter membrane selectivity, thereby limiting nutrient transport and reducing root metabolic activity. Consequently, rice productivity in coastal paddy systems is controlled not only by the total salinity level but also by the hydrogeochemical composition of the root-zone environment and the duration of exposure during sensitive growth stages.

Spatial variability of salinity in coastal paddy systems

The salinity of coastal rice agroecosystems is characterised by intensive spatial and temporal fluctuations due to the interplay of the hydrogeological environment, proximity to the coast, elevation gradient, seasonal hydrology and human water use, which leads to extremely heterogeneous salinity exposure of paddy areas (18, 31). Minor topographic differences can create sharp salinity gradients in coastal paddy fields (19). Specifically, low-lying plots and downstream basins accumulate salts through side inflow and low drainage and slightly elevated fields are less likely to accumulate salts because of freshwater flushing and hydraulic gradient (18, 19). Salinity has high seasonal dynamics, which are associated with monsoon-driven recharge, abstraction by dry-season groundwater and tidal forcing (15, 31). Salinity is usually highest in dry seasons when freshwater heads are lower due to reduced recharge and increased pumping and saline water moves further inland, elevating total dissolved solids (21, 32). Conversely, monsoonal precipitation and river outflow encourage partial saline front dilution and displacement to the sea, although the degree of recovery tends to be incomplete in intensively farmed coastal rice systems (15, 31). Over long-term observation, coastal rice areas have been shown to experience progressive salinity increase because of groundwater overexploitation, land subsidence and climatic fluctuations. According to multi-decadal analysis, electrical conductivity has increased 1.5–2 times over the past 20 years. The most significant increase occurs in coastal wells and low-elevation paddy zones (21, 31).

Remote sensing shows long-term expansion of salinity-affected coastal rice areas during drought and El Niño periods (21). Aquifer characteristics and well water quality strongly influence spatial salinity variability, leading to localised hotspots in areas where intensive groundwater abstraction for irrigation occurs. Risk-based spatial evaluation indicates that the intensity of pumping frequently surpasses natural influences like sea-level rise in establishing present-day salinity distribution, especially in shallow seaside aquifers that feed rice systems (32). Similar salinity-intrusion challenges have been reported beyond South and Southeast Asia. In the Nile Delta of Egypt, excessive groundwater abstraction, reduced freshwater inflow and sea-level rise have accelerated coastal aquifer salinisation, threatening irrigation sustainability in low-lying agricultural lands. Mediterranean coastal regions of Spain have also experienced progressive groundwater salinisation associated with intensive irrigation and seawater intrusion into alluvial aquifers. In eastern China, coastal agricultural areas of the Yangtze River Delta face increasing salinity risks due to rapid urbanisation, groundwater exploitation and changing hydrological regimes. These observations demonstrate that salinity intrusion is a globally distributed challenge affecting diverse coastal agroecosystems and highlight the need for region-specific but integrated management approaches.

Assessment and monitoring of salinity in coastal paddy systems

Assessment of salinity stress in coastal rice irrigation systems relies on a combination of physicochemical, hydrogeochemical, isotopic and remote sensing indicators that are used to capture salt concentration and sodicity risks to the paddy soils and crop performance. Of traditional measurements, EC and TDS are the most used primary indicators of salinity in irrigation water (33). The EC-based classification distinguishes freshwater, marginal and saline groundwater sources, which serve as a quick screening tool to identify areas where rice is grown that are at risk of experiencing a decline in yield because of salinity (17, 34). Major ion chemistry can offer diagnostic information on salinity sources and irrigation suitability (30).

Sodium adsorption ratio (SAR) is a key indicator of irrigation water sodicity that combines the concentrations of Na ions, Ca ions and Mg ions to measure the risk of sodicity in saltwater-infiltrated rice soils. Numerous investigations indicate that irrigation water classified as moderately saline based on EC may still pose significant sodicity risks if SAR values are high. Therefore, salinity and sodicity must be assessed jointly using additional indices such as Na per cent, residual sodium carbonate (RSC), permeability index (PI), magnesium hazard (MH) and the Kelley ratio (KR), especially in the context of

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progressive seawater intrusion (33). Composite indices of water quality, such as water quality index (WQI) and pollution index of groundwater (PIG), are combinations of various parameters associated with salinity into a single diagnostic tool that can direct irrigation decision-making.

The indicators provided through remote sensing are also useful to trace both spatial and temporal variations of salinity in deltas that are under rice cultivation, where field sampling may be logistically constrained. Sentinel-2 and Landsat-8 imagery can delineate salinity intrusion fronts and identify cultivable and non-cultivable paddy zones based on the salinity of irrigation canals, with satellite reflectance in the visible and near-infrared bands showing a good correlation with changes in electrical conductivity and turbidity (15). Recent advances in digital agriculture have expanded the range of tools available for monitoring salinity in coastal paddy systems. Internet of things (IoT)-based sensor networks enable near real-time measurement of soil moisture, electrical conductivity, groundwater levels and irrigation-water quality, facilitating rapid management decisions under dynamic salinity conditions. Unmanned aerial vehicles (UAVs) equipped with multispectral and thermal sensors provide high-resolution spatial assessment of crop stress and salinity-induced vegetation changes at field scales. Machine learning and artificial intelligence approaches are increasingly being integrated with remote sensing and hydrogeochemical datasets to improve salinity prediction, risk mapping and early-warning systems. In addition, geophysical techniques such as electrical resistivity tomography and electromagnetic induction offer non-destructive methods for characterising subsurface salinity distribution and monitoring the movement of saline fronts in coastal agricultural landscapes. These emerging technologies have considerable potential to strengthen salinity surveillance and adaptive management in rice-growing coastal regions.

The principal indicators, analytical methods and emerging technologies currently used for assessment and monitoring of salinity in coastal paddy systems are summarised in Table 1.

Table 1. Indicators and tools for assessment and monitoring of salinity in coastal paddy systems

Category	Parameter	Diagnostic significance	Threshold	Reference
Bulk salinity indicators	Electrical conductivity (EC)	Represents total ionic strength and salinity hazard	< 1 dS m^{-1} (fresh), 1–2 (marginal), > 2 (salinity risk for rice)	(17, 34, 35)
	Total dissolved solids (TDS)	Quantifies total dissolved salts in irrigation water	Positively correlated with EC; used for rapid salinity screening	(34)
Major ion chemistry	Na^+, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}	Defines hydrochemical facies and salinity origin	Na–Cl dominance indicates seawater intrusion; Cl^- acts as a conservative tracer	(28)
Sodicity hazard indices	Sodium adsorption ratio (SAR)	Evaluates sodium hazard relative to Ca^{2+} and Mg^{2+}	High SAR → soil dispersion, reduced permeability, sodicity risk	(34)
	Sodium percentage (Na %)	Indicates the proportion of sodium in irrigation water	High Na % linked to soil structural degradation	(34)
	Residual sodium carbonate (RSC)	Assesses carbonate/bicarbonate hazard	High RSC promotes Ca^{2+}/Mg^{2+} precipitation, increasing Na dominance	(34)
	Permeability index (PI)	Evaluates the impact on soil permeability	Low PI indicates reduced infiltration and hydraulic conductivity	(34)
	Magnesium hazard (MH)	Assesses Mg^{2+} dominance over Ca^{2+}	High MH adversely affects soil structural stability	(34)
	Kelley's ratio (KR)	Determines the sodium suitability of irrigation water	KR > 1 indicates unsuitability for irrigation	(34)
Composite indices	Water quality index (WQI)	Integrates multiple parameters for overall water quality assessment	Classified as good, moderate, or poor for irrigation suitability	(35)
	Pollution index of groundwater (PIG)	Quantifies groundwater contamination and salinity risk	Identifies salinity hotspots and irrigation risk zones	(35)
Geospatial assessment tools	GIS-based mapping (WQI, PIG)	Maps the spatial heterogeneity of salinity in coastal aquifers	Detects localised salinity hotspots beyond regional averages	(35)
Remote sensing approaches	Sentinel-2, Landsat-8 imagery	Monitors spatial and temporal salinity dynamics	Reflectance (VIS–NIR) correlates with EC and turbidity; delineates intrusion fronts	(15)
Integrated assessment framework	Combined EC, SAR, indices, GIS and remote sensing	Provides a comprehensive salinity and irrigation suitability assessment	Enables multi-dimensional evaluation of salinity risk in coastal paddy systems	(15, 34)

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Soil-water interactions in coastal paddy systems

Saltwater intrusion, shallow groundwater tables, capillary rise, tidal flooding and irrigation water salinity lead to salinity accumulation in coastal paddy soils, where soil-water interactions regulate the redistribution, retention and leaching of salts within the soil profile. The interactions among irrigation water, groundwater, soil and the rice root zone that regulate salinity dynamics in coastal paddy systems are illustrated in Fig. 2.

Soil texture and hydraulic conductivity

During dry seasons, salts tend to be concentrated at the surface of the soil in low-lying coastal paddy fields due to their upward movement through capillary rise. Monsoonal floods and irrigation, on the contrary, promote the leaching and downward redistribution of salts in the soil profile (18, 19). Under spatially heterogeneous salt accumulation conditions of paddy soils, fine-scale topographic variation drives strong spatial variability in salinity due to centimeter-scale elevation differences, resulting in large differences in saturated paste EC and Na indices. Low-lying basin habitats are consistently characterised by greater accumulation due to poor drainage, longer duration of saline inundation and low leaching compared to higher elevation plots (18, 19).

This spatial heterogeneity results in patchy salinity redistribution within individual paddy fields despite uniform management practices.

Long-term soil quality evolution under paddy systems

The long-term rice cultivation of saline and saline-alkali soils is associated with gradual improvements in soil quality due to sustained desalinisation and upgrading of nutrient levels and structural stabilisation of paddy soils. Chrono sequence studies have demonstrated that long-term rice culture leads to reduced soil EC, exchangeable Na per cent and reduced total dissolved salts in surface and subsurface layers, which help reclaim salt-affected soils (35). The primary causes of these reductions that are realised under puddled rice systems are frequent freshwater inundation, irrigation-drainage interactions and the restriction of upward salt migration (20, 36).

High precipitation during the rice-growing season disrupts vertical salinity gradients by lowering surface salt content, leaching salts downward, or routing them into drainage networks. The chrono sequence of the saline paddy soils shows that the surface soil (0–20 cm) experiences the most extreme phases of desalination due to intense root growth, microbial activities and irrigation, while deeper layers retain residual salts over longer timescales (35).

Organic matter and soil structure

Long-term desalinisation benefits are associated with the improvement of soil fertility; sustained rice production increases soil organic carbon and P pools, improves aggregation and pore connectivity and sustains hydraulic conductivity, thereby facilitating water movement and the downward leaching of salts. Conversely, soils that are structurally degraded and have low organic content are more susceptible to accumulation of surface salts because of low infiltration and low internal drainage.

Beyond physical effects, organic matter can have an impact on the chemical processes of soils by enhancing cation exchange and buffering capacity. Greater organic carbon increases the binding of divalent cations, e.g., Ca, which offsets sodium-induced dispersion and contributes to structural stability. Moreover, microbially produced binding material like extracellular polymeric substances (EPS) would play a role in the stabilisation of aggregates, salt distribution at the microscale and in regulating the distribution of salt at the macroscale in the soil matrix. Organic amendments such as biochar, compost and crop residues are usually applied to enhance soil organic carbon, nutrient supply and aggregate stability and reduce salinity and bulk density (36).

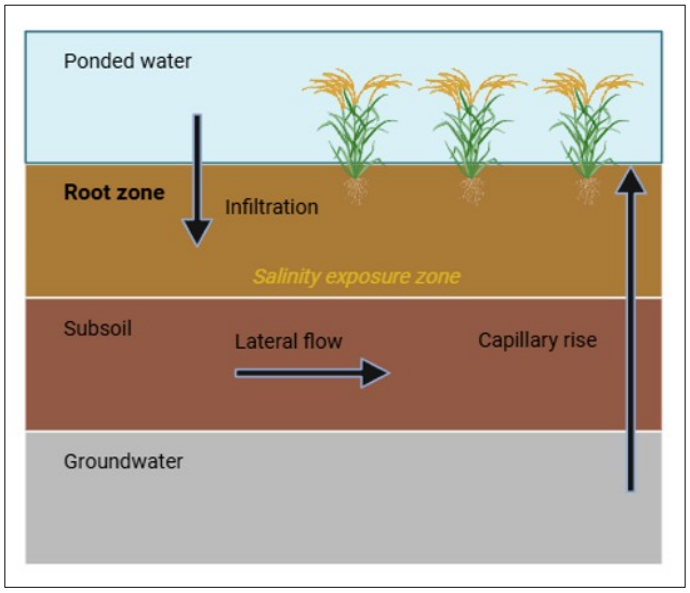

Fig. 2. Conceptual representation of soil-water interactions and root-zone salinity dynamics in coastal paddy fields. Created with BioRender.com.

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Salt accumulation and leaching dynamics

Salinity is typically highest at the onset of the growing period and midway, when evaporation is high and the freshwater flushing is minimal. Weekly monitoring reveals that salts accumulating in ponded water subsequently deposit in surface soils; that is, in-season hydrology plays a more significant role in the redistribution of salinity compared to preseason baseline salinity (19). Long-term rice production has a two-fold impact on soil salinity that leads to the leaching of the salt through the regular flooding of the soil, though at the same time altering the physical structure of the soil, leading to a higher vertical percolation of water (20).

Studies with the reclaimed tidal paddy soils have shown that there is a decline of EC over time and this implies that the topsoils are slowly desalinised due to repetitive irrigation drainage processes. Soil salinity dynamics are closely linked to the rice cropping cycle. Even so, the percentages of decline in SAR and the per cent of exchangeable sodium (ESP) decline more gradually than the linear decline in the total salinity, indicating that exchangeable sodium and soluble salts redistribute unevenly within the soil matrix (20).

Land use transitions and salinity trajectories

The history of land use strongly influences long-term soil quality dynamics of agroecosystems in the coastal lands, specifically, which are subjected to replacement by rice-shrimp systems or permanent shrimp systems. Replacement of rice agricultural production with shrimp farming increases the soil salinity and alters nutrient binding forms, leading to salt accumulation and the replacement of labile, plant-available nutrient pools by more stable ones. Conversely, alternating rice-shrimp systems show more reversible changes in the soil qualities and it is possible to allow partial restoration during rice cultivation phases and the long-term agricultural flexibility can be maintained (37, 38).

Sustainable growth in the quality of the soil in coastal rice habitats can also be attained through long-term rice regimes and specific soil management practices (35). Land-use change between permanent paddy rice and other cultures of rice, shrimp and permanent shrimp is a significant factor that controls salt accumulation dynamics in the coastal paddy systems.

Irrigation water suitability and rice response to salinity

Salinity and sodicity are the primary factors determining irrigation water suitability for rice cultivation in coastal agroecosystems (39). The EC is the primary indicator of irrigation water salinity, with EC above 2–4 dS m^{-1} intensifying osmotic stress under flooded conditions (38, 40). Sodium-based indices are critical in evaluating irrigation suitability, where soil structure reduces with increased sodium build-up and permeability and water movement are reduced in the puddling situation.

Severe sodicity risks are commonly assessed using SAR and Na per cent (17). High RSC values are also found to worsen the alkalinity risk in precipitating Ca and Mg, thereby increasing Na predominance in the soil solution during rice growing (17, 39). Progressive seawater intrusion shifts groundwater from Ca–HCO_3 to Na–Cl facies, reducing hydraulic conductivity and irrigation efficiency. Severe chloride levels also affect the water absorption of the rice plants and corrode irrigation equipment (41). Field studies show that increasing irrigation-water salinity reduces rice productivity, with groundwater salinity below 1 dS m^{-1} supporting near-optimal rice yields, whereas EC levels of 1–2 dS m^{-1} reduce yields during sensitive growth stages (6, 40). Excessively saline irrigation water can cause partial or complete crop failure in coastal paddies (40). However, some of the studies demonstrate that moderately saline irrigation water can remain conditionally suitable when rice is cultivated. Blending saline groundwater with canal or freshwater sources reduces EC and SAR to manageable levels. Controlled irrigation-drainage management and blending with freshwater help sustain rice production under saline conditions (42). The shallow depth of standing water in the root zone and frequent replacement of saline water help reduce salt accumulation, thereby extending the usability of saline irrigation water for cultivating salt-tolerant rice varieties (43). The irrigation water quality thresholds associated salinity hazards and corresponding rice responses under saline conditions are summarised in Table 2.

Table 2. Irrigation water suitability thresholds and corresponding rice response under saline conditions in coastal paddy systems

Parameter / Index	Range / Threshold	Suitability class	Impact on rice growth and yield	Management implications	Reference
Electrical conductivity (EC, dS m^{-1})	< 1	Suitable	Near-optimal growth and yield	No restriction on irrigation use	(6, 41)
	1–2	Slightly saline	Mild osmotic stress; yield reduction during sensitive growth stages	Requires careful water management and monitoring	(41)
	2–4	Moderately saline	Significant osmotic stress; reduced tillering and grain filling	Requires careful water management and monitoring	(39, 41)
	> 4	Highly saline	Severe yield reduction or crop failure; possible field abandonment	Use only with salt-tolerant varieties and strong management practices	(39, 41)
Sodium adsorption ratio (SAR)	Low (< 10)	Suitable	Minimal sodicity impact; stable soil structure	Safe for irrigation	(17)
	Moderate (10–18)	Marginal	Soil dispersion begins; reduced permeability and infiltration	Requires drainage and soil amendments	(17)
	High (> 18)	Unsuitable	Severe soil structural	Avoid continuous use; apply	(17, 40)

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			degradation; restricted root water uptake	gypsum and improved drainage	
Sodium percentage (Na %)	< 60 %	Suitable	Acceptable soil structure and permeability	Suitable for irrigation	(17)
	> 60 %	Unsuitable	Soil dispersion and reduced infiltration	Requires soil amendment and water quality management	(17)
Residual sodium carbonate (RSC)	< 1.25 meq L^{-1}	Suitable	Minimal alkalinity hazard	Safe irrigation water	(40)
	1.25–2.5	Marginal	Increasing alkalinity; Ca^{2+}/Mg^{2+} precipitation	Monitor and manage irrigation cycles	(40)
	> 2.5	Unsuitable	High alkalinity; sodium dominance in soil solution	Avoid use or apply amendments	(40)
Hydrochemical facies (Na–Cl type)	Dominant Na–Cl groundwater	Marginal to unsuitable	Reduced irrigation efficiency; osmotic and ionic stress	Requires blending and controlled irrigation strategies	(42)
Chloride concentration (Cl^-)	Elevated levels	Unsuitable at high levels	Toxicity effects; reduced water uptake; corrosion of irrigation systems	Limit usage; dilution with freshwater	(42)
Rice yield response to salinity	EC < 1 dS m^{-1}	Suitable	Yield reduction generally < 10 %	Standard management	(6)
	1–2 dS m^{-1}	Slightly saline	Yield reduction approximately 10–25 %	Improved water management	(41)
	2–4 dS m^{-1}	Moderately saline	Yield reduction approximately 25–50 %	Requires drainage and salinity management measures	(41)
	> 4 dS m^{-1}	Highly saline	Yield reduction often exceeds 50 %	Requires salt-tolerant varieties and adaptive	(41)
Management strategies	Blending saline and freshwater	Improves suitability	Reduces EC and SAR to tolerable levels	Enhances irrigation feasibility	(43)
	Alternate irrigation and drainage	Controls salt accumulation	Maintains productivity under saline conditions	Recommended for coastal paddies	(44)
	Shallow ponding and flushing	Reduces root-zone salinity		Effective under field conditions	(44)
Varietal response	Salt-tolerant varieties (CSR 36, Giza 178, BRRI dhan 47)	Conditional suitability	Maintain yield under moderate salinity	Recommended for saline irrigation systems	(43, 45)

Salt-tolerant rice varieties maintain higher yield and grain quality under saline irrigation. Varieties such as CSR 36, Giza 178 and BRRI Dhan 47 can maintain acceptable productivity under moderately saline irrigation when sodicity is controlled (42, 44). However, in cases where irrigation water is poorly managed and is used over an extended period, this will result in further soil degradation, making the water and the land in question less suitable for long-term rice cultivation (39, 40).

The management interventions also play a crucial role in sustaining long-term improvement of the soil quality and the productivity of the coastal saline soils (36, 45). The productivity gains in the long term are also enhanced when soil amendments are combined with controlled saline water or wastewater irrigation, especially in aquaculture-based rice systems (45). The productivity of long-term rice farming is much higher than that of saline paddies that have recently been brought back into cultivation, with yield improvement of 30–55 % being observed along cultivation chrono sequences (46). Nevertheless, the relationship between yield responses and the local salinity status seems to be stronger than that between yields and cultivation age, which indicates that even decades of rice cultivation might be limited by incomplete desalinisation (20).

Agronomic and water management strategies for saline coastal rice

Irrigation and drainage management in saline coastal rice systems

The salinity of ponded water rather than soil salinity during the pre-season is an important determinant of rice yield in flooded conditions. Blended irrigation water-mixing saline drainage or groundwater with fresher canal or surface water can effectively reduce salinity exposure and increase the irrigable area in the paddy systems under freshwater scarcity. Experimental trials using deltaic rice systems demonstrate that grain yield and yield-related traits improve and surface salt accumulation can be minimised when drainage water and canal water are used alternately or mixed, compared to a scenario where only drainage water is used (42).

Field studies show that controlled drainage reduces salinity stress and long-term soil salinisation. Excessive groundwater extraction accelerates seawater intrusion, highlighting the need for integrated surface- and groundwater management (47). Groundwater management is also closely associated with paddy-field irrigation and environmental conditions in coastal lowlands (48). Irrigation timing to avoid sensitivity of growth stages to salinity is a very efficient adaptation measure, especially in dry-season paddy cultivation. Earlier transplanting helps rice avoid peak salinity periods and improves grain yield

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under coastal conditions. Long-term paddy cultivation can improve soil physical properties and salt leaching (49). Long-term flooded paddy systems increase soil macropore structure and saturated hydraulic conductivity and help in leaching salts downwards, reducing the salt accumulation on the surface (49). Subsurface drainage can prevent upward salt movement and stabilise root-zone salinity during critical growth stages (48). Effective management of saline coastal paddies requires control of ponded-water salinity, blended water use, periodic drainage and irrigation scheduling (19, 40).

Soil amendments and nutrient dynamics under saline water regimes

Soil and nutrient management support paddy productivity by improving leaching and nutrient availability under saline conditions. Coastal saline soils often require amendments and optimised fertilisation due to low organic carbon, poor aggregation and low nutrient-use efficiency. Organic amendments effectively improve soil properties in saline coastal paddy systems by lowering electrical conductivity and improving physical, chemical and biological characteristics of the soil under flooded conditions that promote salt leaching (36).

Biochar can moderate ponded-water salinity and enhance salt leaching under saline irrigation regimes (45). Soil and nutrient management are closely linked with water management, resulting in better organic amendments and leaching under regulated irrigation-drainage conditions, rather than simply using chemical fertilisers (36).

Cropping system adaptations in coastal rice landscapes

Wet-season paddy monocropping remains common in coastal saline regions due to monsoonal desalinisation and shallow ponding conditions (4). However, increasing dry-season salinity and freshwater scarcity often leave coastal lands fallow during the dry season (50). Rice-based cropping system intensification, especially with the inclusion of short-duration pulses, has become a possible adaptation where residual soil moisture remains available and salinity is not too high during the early dry season. Field-scale evidence is available from coastal saline areas about the benefits of early sowing of wet-season rice to achieve timely establishment of relay or sequential crops of pulses such as lathyrus and lentil to avoid late-season salinity and drought stress. Such systems increase the productivity of the system, nutrient absorption and profitability of the farm while preserving the function of the soil under saline conditions (4).

Rice-shrimp systems are a primary land-use solution to irreversible or worsening salinity in areas where the dry-season salinity is beyond the crop tolerance limit. Alternating rice-shrimp systems cultivate rice during freshwater monsoon periods and shrimp during saline dry seasons. Rice-shrimp systems may increase soil salinity but can also improve nutrient status through organic residue accumulation. On the other hand, permanent shrimp systems produce continuous high salinity and lead to additional structural changes in the soil and sediment characteristics, which reduce the potential to revert to rice agriculture and increase long-term lock-in in land use. This contrast indicates that alternating rice-shrimp systems are a no-regret adaptation strategy, which is important in the transition regions where the saline intrusion is slow but not irreversible (37).

Crop diversification can improve resilience to climatic and salinity stress. Diversified systems such as rice-mungbean and rice-maize rotations are often more productive and profitable than rice-fallow systems. Traditional rice systems may remain more stable during extreme salinity years, which points to the significant trade-offs between risk exposure and intensification. Successful diversification requires coordinated water governance and salinity management (50). Cropping-system adaptation in coastal rice ecosystems generally follows increasing salinity intensity, from rice intensification to rice-shrimp diversification (37). Aligning with salinity dynamics and water management capacity, strategic diversification and adaptive land-use transitions are significant pillars towards maintaining the sustainability of rice-based livelihoods in coastal agroecosystems (50).

Economic and practical considerations for salinity management

The effectiveness of salinity-management strategies depends not only on their technical performance but also on their economic feasibility and ease of adoption by farming communities. Practices such as irrigation scheduling, blended water use, crop diversification and improved drainage management are generally considered cost-effective because they leverage existing farm resources and infrastructure while reducing exposure to salinity. In contrast, large-scale drainage systems, groundwater-control structures and advanced engineering interventions often require substantial capital investment and institutional support, limiting their adoption by resource-constrained farmers.

Smallholder farmers frequently face barriers related to financial resources, access to freshwater, technical knowledge and maintenance requirements. Consequently, management strategies that combine low implementation costs with operational simplicity are more likely to achieve widespread adoption in coastal rice-growing regions. The effectiveness of salinity-management interventions may also vary depending on farm size, hydrological setting and local water availability.

Policy support plays a critical role in facilitating long-term salinity adaptation. Investments in irrigation infrastructure, groundwater regulation, salinity-monitoring programs, extension services and climate-resilient agricultural planning can significantly enhance the adoption and effectiveness of management practices. Therefore, sustainable salinity management requires integration of technical solutions with economic incentives, institutional support and region-specific policy frameworks. The major salinity management strategies, together with their mechanisms, advantages, limitations and practical applicability in coastal paddy systems, are summarised in Table 3.

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Table 3. Comparative assessment of salinity-management strategies in coastal paddy systems based on effectiveness, economic feasibility and applicability

Management strategy	Relative cost	Effectiveness	Smallholder feasibility	Large-scale applicability	Major limitation	References
Improved drainage management	Medium	High	Moderate	High	Infrastructure requirements	(47)
Blended irrigation and conjunctive water use	Low–Medium	High	High	High	Availability of freshwater sources	(42)
Salt-tolerant rice cultivars	Low	Moderate–High	High	High	Genetic yield limitations under severe salinity	(44)
Alternate wetting and drying (AWD)	Low	Moderate	High	Moderate	Requires careful water management	(40)
Crop diversification and rice-based systems	Low–Medium	Moderate	High	Moderate	Market and management complexity	(50)
Soil amendments (gypsum, organic amendments)	Low–Medium	Moderate	High	Moderate	Repeated application may be required	(36)
Groundwater regulation and abstraction control	Medium–High	High	Low	High	Institutional and policy constraints	(13)
Large-scale engineering interventions (sluice gates, embankments)	High	High	Low	High	High capital and maintenance costs	(49)

Environmental outcomes of integrated salinity management in rice production

Secondary salinisation risks in coastal paddy agroecosystems

In coastal paddy agroecosystems, a shallow water table, residual marine salts within the soil profile and intensive irrigation water use contribute to persistent salinity challenges (22). Engineering-based measures, particularly drainage management and irrigation control strategies, can effectively reduce surface-water salinity in these systems. However, incomplete salt removal may promote downward or lateral redistribution of salts, resulting in subsurface accumulation and delayed root-zone salinity exposure during later crop stages or dry periods (49). In reclaimed coastal paddy systems, post-desalinisation soil chemical transformations may reduce leaching efficiency, allowing persistent salt retention under intermittent saline irrigation inputs (51). At wider area scales, over-exploitation of groundwater for agricultural use (especially paddy cultivation) is the major cause of secondary salinisation by causing increased seawater intrusion and upward saline fluxes. Coastal paddy intensification without coordinated management of groundwater recharge accelerates salinity reaccumulation at the expense of reclamation progress achieved at the field level and leads to an escalated reliance on expensive engineering approaches (22).

Cross-regional studies indicate that coastal paddy systems that lack consistency between the implemented strategies of remediation and the local hydroclimate environments increase the chances of secondary salinisation. In humid coastal regions, arid-optimised approaches (aggressive drainage) may disrupt soil-water balances and promote salt redistribution rather than long-term reclamation (10). Nature-based approaches remain effective only when integrated with hydrological and water-management strategies that prevent secondary salinisation (9).

Synthesis: Pathways toward resilient coastal rice production

Integrating hydrogeochemistry, soil and crop responses

Seawater intrusion in coastal paddy systems involves interconnected hydrogeochemical, soil–water and crop-response processes (22). When seawater infiltrates into groundwater and stagnant water, seawater intrusion alters pore-water chemistry and nutrient dynamics in flooded soils by a rise in Na^+ and Cl^- (45). These hydrogeochemical modifications of the irrigation and the pore water balance regulation directly control the effect of salinity of the ponded water during critical rice growth stages, rather than baseline soil salinity alone. Seasonally flooded paddy system experiments prove that seasonal conditions of maximum salinity were related to the most vulnerable growth stages, which increase yield losses regardless of overall soil saltiness (19). Paddy cultivation modifies soil physical properties and biological processes, which influence salt redistribution and salinity dynamics under flooded conditions. The flooded paddy conditions enhance macroporosity and hydraulic conductivity of the soil, which promotes high leaching of salts and less build-up of salinity on surfaces in coastal salt-alkaline soils (48). Declining salinity under long-term paddy management modifies cation exchange processes in the soil structure, which modifies the long-term salt-buffering of the flooded soils (51).

There are examples of Asian mega-deltas that show that the concept of resilience is linked to the interconnection of hydrogeochemical processes, development of soil structure and responses to crop stages, rather than optimisation of one of the aspects (8). Collectively, these findings demonstrate that the effective adaptation to salinity in coastal paddy systems must take into account the co-evolution of the mechanisms of salination, groundwater intrusion, physicochemical changes in soils and specific responses of crops to particular stages of development because these interacting processes collectively determine system resilience (19, 22).

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The need for integrated, multi-faceted strategies over single-solution approaches

Salinity management in coastal paddy systems is complicated by the interaction of hydrological, hydrogeochemical, climatic and management-related factors. Consequently, interventions targeting only one component of the system may provide short-term benefits but may not always ensure long-term sustainability. Several studies indicate that approaches focused exclusively on soil amendments, irrigation improvement, or crop tolerance can be constrained by local hydrological conditions, freshwater availability, economic limitations and institutional capacity (52). The effectiveness of technological interventions such as chemical amendments, physical desalination measures and engineered drainage systems, therefore, varies considerably among regions depending on pedoclimatic conditions and resource availability.

For example, drainage improvement alone may not adequately control salinity where shallow saline groundwater continuously contributes salts to the root zone, while reliance solely on salt-tolerant cultivars may provide limited benefits when salinity levels exceed crop tolerance thresholds or when irrigation and drainage management remain inadequate (10, 53). Similarly, irrigation-based interventions may be less effective during periods of freshwater scarcity or under increasing climate-induced variability. These observations suggest that individual management options should be viewed as complementary components of broader salinity-management frameworks rather than as universally applicable standalone solutions.

An integrated approach that combines salinity monitoring, water-management strategies, drainage improvement, crop adaptation and institutional support is therefore more likely to enhance long-term system resilience. Such strategies can better address the multiple pathways through which salinity affects coastal rice agroecosystems while reducing the risk of unintended consequences associated with reliance on a single management intervention (52, 53). An integrated conceptual framework linking hydrogeochemical drivers, salinity evolution, soil–water interactions, rice responses and management interventions is presented in Fig. 3.

Implications for sustainable rice intensification in saline coastal regions

The concept of sustainable rice production in saline coastal regions should be reframed around the resilience-oriented system development, where the priority is put on the long-term water–salt balance stability and the environmental sustainability in the long run, rather than short-term yield maximisation (54). The rice-based intensification systems have been demonstrated to be more resilient to salinity and water scarcity than the traditional intensification systems, because they integrate varietal selection, crop timing and diversification as one of the means to accommodate the seasonal salinity changes and water availability. By redistributing seasonal water demand and minimising crop exposure to high salinity during sensitive growth stages, diversified rice-based systems can buffer seasonal salinity variability (50, 55). The sustainability of agronomic innovations on the coastal paddy systems depends on the presence of low-salinity water supplies, effective drainage and salinity-aware management plans (54, 55).

Both the model-based and scenario analyses demonstrate that the sustainability transitions in the salinity-challenged rice cultivation must be integrated within water–salinity management frameworks that cooperatively regulate the rates of productivity, resilience, as well as future salinity risks.

Research gaps and future directions

Critical process-level gaps remain in integrating groundwater salinisation, soil transformation and rice responses across the soil–water–crop continuum under field conditions. One major limitation is the lack of adequate representation of coupled groundwater–surface water interactions governing salinity exposure in paddy fields. Seawater intrusion and excessive groundwater extraction interact with irrigation scheduling, river discharge and waterlogging in the fields, but these complex processes are not quantified adequately to effectively forecast salinity in the season, thereby limiting accurate prediction of in-season salinity stress and rice yield responses (22). Climate-driven factors, especially sea level rise and variable recharge, further complicate water interactions within soils, yet they remain poorly incorporated into paddy system analyses. Most hydrogeological studies assume static boundary conditions that fail to capture the rapidly changing recharge, evapotranspiration and hydraulic gradients that are typical of managed flooded paddies (12).

Dynamic soil chemical and physical feedback is also poorly understood, which mediate salinity responses under irrigation and drainage regimes. Salinisation is often treated as a static stress, overlooking the influence of the continuous water management practices that change the distribution of salts (9). In deltaic paddies, not only the intensity of salinity, but also the timing and its duration and the synergies and interactions with water scarcity and water inundation, collectively regulate rice productivity and stress responses (8).

Monitoring and modelling salinity dynamics in coastal paddy fields are constrained by three interrelated shortcomings such as scarce data, mismatched scales and incomplete portrayal of the groundwater-soil-crop nexus (12, 32). Groundwater salinity measurements are often too sparse to capture the spatial heterogeneity of migrating salinity fronts, making it difficult to detect the early-stage thresholds that stress rice (32). Uncertainty also remains high in climate, hydrological and salinity modelling. Thereby reducing confidence in long-term projections for paddy system management (56). Models such as Agricultural Production Systems Simulator (APSIM)–*Oryza* can simulate rice yield under saline stress, but they often have stress functions that are oversimplified and fail to capture rapid, stage-specific and cumulative salinity effects as reported in the field (57, 58).

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Lastly, salinity models have not been validated under field-scale conditions. Empirical studies indicate that management outcomes vary substantially across spatial gradients and seasonal cycles (50). Therefore, integrated salinity management technologies require rigorous field-scale validation under real paddy conditions (53).

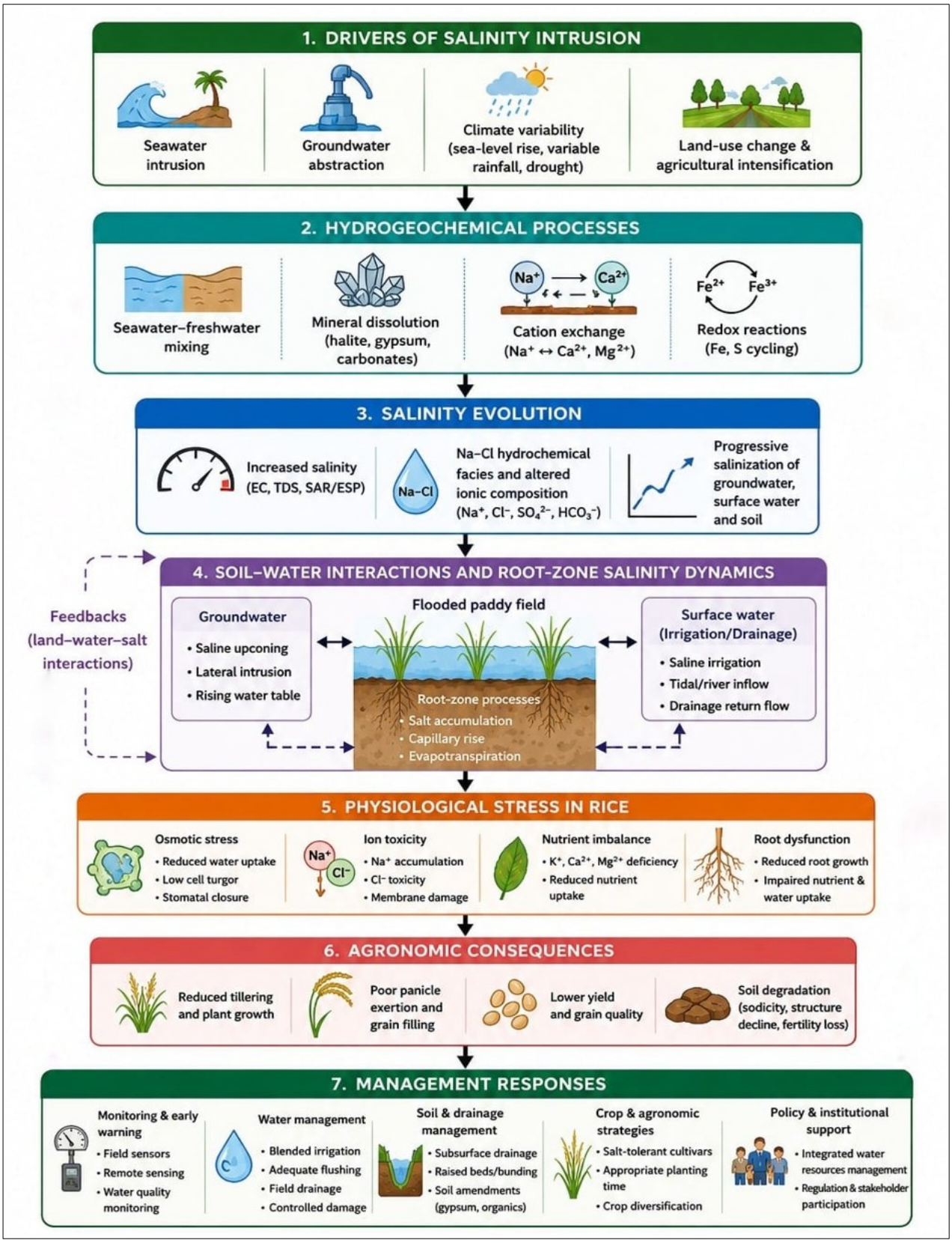

Fig. 3. Integrated conceptual framework showing the pathways linking salinity-intrusion drivers, hydrogeochemical evolution, soil-water interactions, root-zone salinity dynamics, physiological stress responses, agronomic impacts and management interventions in coastal paddy systems.

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Conclusion

Salinity intrusion in coastal paddy systems results from the combined effects of hydrogeological vulnerability, seawater intrusion, groundwater abstraction, climate variability and land-use change. These interacting drivers promote the evolution of groundwater toward sodium–chloride (Na–Cl) hydrochemical facies, increasing salinity and sodicity risks that directly influence irrigation suitability and crop productivity. Evidence synthesised in this review indicates that root-zone salinity, rather than irrigation-water salinity alone, represents the most agronomically relevant indicator of rice stress because it integrates groundwater influences, soil properties, water-management practices and seasonal hydrological variability.

This review highlights three key messages. First, salinity intrusion should be understood as a coupled soil–water-crop process rather than a groundwater-quality problem alone. Second, effective management requires integration of hydrogeochemical assessment, irrigation-water evaluation, root-zone salinity monitoring and crop-stage-specific adaptation strategies. Third, sustainable salinity management depends on combining agronomic, hydrological, engineering and policy-based interventions within a comprehensive water–salt balance framework.

Future research should prioritise coupled groundwater-surface water modelling, high-resolution monitoring of root-zone salinity dynamics, integration of emerging technologies such as internet of things (IoT)-based sensing and machine-learning approaches and improved representation of salinity processes within crop simulation models. Additional long-term field studies are needed to quantify the interactions among hydrogeochemical evolution, soil functionality and rice productivity under changing climatic and hydrological conditions.

Overall, the long-term sustainability of coastal paddy agriculture will depend on the ability to translate hydrogeochemical understanding into integrated management strategies that maintain irrigation reliability, protect soil health and enhance the resilience of rice-based agroecosystems in salinity-prone coastal environments.

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Authors' contributions

SS conceptualised the review, conducted the literature survey, synthesised the available evidence and prepared the original manuscript draft. AA contributed to the conceptual framework of the review, critically revised the manuscript for important intellectual content and supervised the study. GA, RG, BM, BA and VL contributed to the critical review of the literature, provided scientific inputs and assisted in improving the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT for limited assistance in language refinement and manuscript editing, Grammarly for grammar and language checking and BioRender for preparing schematic illustrations. All scientific content, interpretation and conclusions were developed, reviewed and verified by the authors, who take full responsibility for the content of the publication.

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