



Advances in Soil Health and Salinity Management: Modern Indicators Biological Approaches and Biotechnological Innovations

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INTRODUCTION

Soil is a fundamental natural resource that supports terrestrial ecosystems, agricultural production, biodiversity and human livelihoods. The capacity of soil to sustain plant growth while maintaining environmental quality and ecosystem functions is commonly described as soil health. Unlike the traditional concept of soil fertility, which primarily emphasizes the availability of nutrients for crop production, soil health represents a broader and more integrated view that includes physical, chemical and biological properties, as well as the soil's capacity to resist stresses, recover from disturbances and perform essential ecosystem services. In recent decades, increasing pressure on agricultural land from intensive cultivation, excessive use of agrochemicals, erosion, compaction, organic matter depletion, climate variability and salinity has generated considerable interest in improving and monitoring soil health.

Soil degradation is particularly serious in arid and semi-arid agricultural regions, where salinity and sodicity are major constraints to crop productivity. Soil salinity refers to the accumulation of soluble salts in the soil to concentrations that adversely affect plant growth. Saline soils commonly contain elevated concentrations of ions such as sodium, chloride, calcium, magnesium and sulfate. Sodic soils are characterized by excessive exchangeable sodium, which deteriorates soil structure and reduces water infiltration. Salinity can originate from natural geological processes, seawater intrusion, poor-quality irrigation water, inadequate drainage and inappropriate irrigation practices. Climate change may further intensify salinity through increased evapotranspiration, drought, sea-level rise and changes in rainfall patterns.

2. Concept of Soil Health

Soil health is generally understood as the continuing capacity of soil to function as a living ecosystem that sustains plants, animals and humans. A healthy soil should provide an adequate medium for root development, regulate water movement, store and cycle nutrients, support biological diversity, filter pollutants, sequester carbon and maintain structural stability. Soil health is therefore multidimensional and cannot be represented by a single property.

Physical health includes soil structure, aggregate stability, bulk density, porosity, water-holding capacity, infiltration rate and resistance to compaction and erosion. Chemical health involves soil pH, electrical conductivity, cation exchange capacity, organic carbon, nutrient availability, salinity, sodicity and concentrations of potentially toxic elements. Biological health encompasses microbial

biomass, microbial diversity, enzyme activity, earthworm abundance, respiration, decomposition and other biological processes.

3. Major Threats to Soil Health

Agricultural soils face multiple interacting threats. Soil organic matter decline is one of the most important because organic matter contributes to aggregation, water retention, nutrient supply, microbial activity and carbon sequestration. Continuous removal of crop residues, intensive tillage and inadequate organic inputs accelerate organic matter depletion.

Soil erosion is another major concern. Wind and water erosion remove fertile topsoil and associated organic matter and nutrients. Intensive cultivation without adequate soil cover increases erosion risk, particularly on sloping land. Conservation agriculture practices such as minimum tillage, residue retention and crop diversification can reduce these losses.

Table 1: Major Soil-Health Indicators and Their Applications

Soil-health dimension	Indicator	Major information provided	Application
Physical	Bulk density	Degree of compaction	Detect compaction and root restrictions
Physical	Aggregate stability	Structural resilience	Assess erosion and structural degradation
Physical	Infiltration rate	Water movement	Irrigation and drainage management
Chemical	pH	Soil reaction	Nutrient and amendment management
Chemical	Electrical conductivity	Soluble salt concentration	Salinity diagnosis
Chemical	Exchangeable sodium percentage	Sodicity status	Sodic-soil reclamation
Chemical	Organic carbon	Soil carbon status	Soil-quality and carbon management
Biological	Microbial biomass carbon	Living microbial pool	Biological soil-health assessment
Biological	Soil respiration	Microbial activity	Monitor biological functioning
Biological	Enzyme activity	Nutrient cycling processes	Detect functional changes
Biological	Earthworm abundance	Soil biological condition	Ecological assessment
Molecular	Microbial diversity	Community structure	Microbiome assessment
Molecular	Functional genes	Biogeochemical potential	Nutrient-cycle monitoring
Digital	Remote sensing indices	Vegetation/soil stress	Salinity mapping
Digital	Sensor-derived EC	Spatial salinity variation	Precision management

4. Soil Salinity: Causes and Mechanisms

Salinity develops when soluble salts accumulate in the soil profile. Primary salinity originates from natural processes, including weathering of parent materials, mineral deposits, groundwater movement and marine influence. Secondary salinity is largely associated with human activities, especially irrigation without adequate drainage.

In irrigated agriculture, even relatively low concentrations of salts in irrigation water can accumulate over time because plants primarily absorb water while many salts remain in the soil. In regions with high evaporation and

inadequate rainfall, upward movement of saline groundwater can further increase salt accumulation near the root zone.

Salinity affects plants primarily through osmotic and ionic stress. Increased salt concentration in the soil solution reduces its water potential, making it more difficult for roots to absorb water. Plants therefore experience physiological drought even when sufficient water is present in the soil. Prolonged salinity can cause sodium and chloride toxicity, disrupt nutrient balance and damage cell membranes.



5. Modern Indicators of Soil Health

5.1 Physical Indicators

Physical indicators provide information about the structure and water relations of soil. Bulk density is widely used to assess compaction, while aggregate stability indicates resistance of soil aggregates to breakdown. Infiltration rate and saturated hydraulic conductivity provide information about water movement.

Soil texture is relatively stable and is therefore considered a basic soil property rather than a dynamic indicator. In contrast, aggregate stability, penetration resistance, water

infiltration and soil structure respond more readily to management changes.

5.2 Chemical Indicators

Soil pH is one of the most widely measured chemical indicators. It influences nutrient availability, microbial activity and chemical reactions. Electrical conductivity is particularly important for salinity assessment because it provides an estimate of the concentration of soluble ions.

Soil organic carbon is an important indicator of long-term soil quality. Total organic carbon can be complemented by particulate organic carbon, dissolved organic

carbon and other labile carbon fractions that respond more rapidly to changes in management.

Cation exchange capacity reflects the soil's ability to retain positively charged nutrients. Exchangeable sodium percentage and sodium adsorption ratio are important indicators in saline-sodic soil assessment.

5.3 Biological Indicators

Biological indicators are among the most promising tools for modern soil-health

assessment. Microbial biomass carbon represents the living microbial pool and can respond relatively rapidly to changes in management.

Soil respiration measures biological activity and carbon mineralization. Enzyme activities such as dehydrogenase, phosphatase, urease, β -glucosidase and arylsulfatase provide information about specific biochemical processes.

Table 2: Biological and Biotechnological Strategies for Salinity Management

Approach	Principal mechanism	Potential benefit	Major consideration
Organic amendments	Improve carbon and aggregation	Better soil structure and water retention	Quality and application rate
Compost	Adds stabilized organic matter	Enhances microbial activity	Nutrient variability
Biochar	Improves retention and habitat	May improve soil physical properties	Feedstock-specific response
PGPR	Hormones, nutrient mobilization, stress reduction	Improved plant growth	Field establishment
Mycorrhizal fungi	Enhanced nutrient and water acquisition	Improved salinity tolerance	Host and soil dependence
Halotolerant microbes	Adaptation to saline environments	Better plant performance under salt stress	Strain selection
Biofertilizers	Biological nutrient mobilization	Improved nutrient-use efficiency	Compatibility with soil conditions
Salt-tolerant crops	Osmotic and ionic tolerance	Maintains productivity under salinity	Yield trade-offs
Marker-assisted breeding	Tracks useful alleles	Faster cultivar development	Requires reliable markers
Genomic selection	Predicts breeding value	Accelerates complex-trait improvement	Requires training populations
Genome editing	Targeted gene modification	Precise improvement of stress traits	Regulatory and biosafety issues
Metagenomics	Profiles microbial genes	Identifies functional communities	Data complexity
AI and machine learning	Integrates multiple datasets	Predictive soil management	Data quality and validation
Remote sensing	Detects spatial stress patterns	Rapid salinity mapping	Requires ground validation

6. Digital and Precision Approaches for Soil-Health Assessment

Digital agriculture is transforming soil-health monitoring. Proximal soil sensors, electromagnetic induction, spectroscopy, satellite imagery, drones and geographic information systems can generate spatially detailed information.

Visible and near-infrared spectroscopy can be used to estimate soil organic carbon, moisture and other properties after appropriate calibration. Hyperspectral sensing provides a large number of spectral bands that can improve discrimination of soil conditions.

7. Organic Matter and Carbon-Based Approaches

Organic matter management is central to soil-health improvement. Organic inputs improve aggregation, increase microbial activity, enhance water retention and contribute to nutrient cycling. Farmyard manure, compost, crop residues, green manure and other organic materials can increase soil organic carbon.

8. Biological Approaches to Salinity Management

Biological management aims to improve soil function and plant performance through living organisms and biologically derived materials. It can complement physical and chemical reclamation and is particularly valuable where conventional inputs are expensive or environmentally undesirable.



8.1 Plant-Growth-Promoting Rhizobacteria

Plant-growth-promoting rhizobacteria (PGPR) colonize plant roots and influence plant growth through several mechanisms. They may produce phytohormones, solubilize nutrients, fix atmospheric nitrogen, produce siderophores and induce systemic resistance.

Under saline conditions, selected PGPR can improve root development, nutrient acquisition and plant water relations. Some bacteria produce exopolysaccharides that help stabilize soil particles and may contribute to improved soil aggregation. Other

microorganisms can regulate plant ethylene levels through ACC deaminase activity, reducing stress-associated growth inhibition.

8.2 Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi form symbiotic associations with plant roots. Their extensive hyphal networks increase the effective soil volume explored by roots and can improve acquisition of phosphorus and micronutrients.

Mycorrhizal associations may also improve plant tolerance to salinity by enhancing water uptake, maintaining nutrient balance and influencing antioxidant systems.

Fungal hyphae contribute to soil aggregation through physical binding and biochemical processes.

8.3 Halotolerant Microorganisms

Halotolerant bacteria, fungi and archaea are adapted to environments containing high salt concentrations. Their stress-adaptation mechanisms can include compatible-solute production, ion regulation and antioxidant protection.

The use of salt-tolerant microbial inoculants is an emerging strategy for saline agriculture. However, field performance depends on environmental conditions, crop genotype, native microbial communities and inoculant formulation. Therefore, microbial consortia may sometimes perform more consistently than individual strains.

8.4 Biofertilizers

Biofertilizers contain beneficial microorganisms that contribute to nutrient availability. Nitrogen-fixing organisms, phosphate-solubilizing microorganisms and potassium-solubilizing bacteria can reduce dependence on chemical fertilizers.

Integrated use of biofertilizers with organic amendments and balanced mineral fertilization can improve nutrient-use efficiency. Under saline conditions, selecting strains that are both nutrient-efficient and salt-tolerant is particularly important.

10. Biotechnology for Soil Health and Salinity Management

Biotechnology provides tools for understanding and manipulating both plants and soil microorganisms. Molecular breeding has accelerated the identification of genes associated with salt tolerance, nutrient-use efficiency and root-system architecture.

Marker-assisted selection can be used to track desirable alleles during breeding. Genomic selection uses genome-wide marker information to predict breeding values and can accelerate improvement of complex traits.

12. Enzyme-Based and Biochemical Indicators

Soil enzymes are closely associated with nutrient cycling and microbial functioning. Dehydrogenase activity is often used as a broad indicator of microbial metabolic activity. Phosphatases are associated with phosphorus cycling, while urease participates in nitrogen transformation.

β -glucosidase and related enzymes contribute to decomposition of organic carbon compounds. Enzyme activity responds to changes in organic inputs, nutrient availability, pH, moisture and salinity.

13. Integrated Salinity Management

Effective salinity management requires an integrated approach rather than dependence on a single technology. The first step is accurate diagnosis through soil electrical conductivity, pH, exchangeable sodium and water-quality analysis.

Good-quality irrigation water and efficient irrigation systems can reduce salt accumulation. Drip irrigation can improve water-use efficiency when properly designed and maintained, while scheduling based on soil moisture monitoring can prevent excessive irrigation.

14. Role of Irrigation and Water Management

Poor irrigation management is one of the major drivers of secondary salinity. Efficient irrigation should supply crop water requirements while minimizing unnecessary water application.

Irrigation scheduling based on crop evapotranspiration, soil moisture sensors and weather information can improve efficiency. Precision irrigation systems can deliver water according to spatial and temporal crop requirements.

15. Nanotechnology and Soil Health

Nanotechnology offers emerging possibilities for soil and crop management. Nano-enabled fertilizers may improve nutrient-use efficiency by controlling nutrient release and increasing nutrient availability. Nano-sensors may provide

sensitive detection of soil nutrients, moisture and contaminants.

Nanomaterials have also been investigated for improving plant stress responses and remediation of contaminated soils. However, their environmental fate and potential effects on beneficial soil organisms require careful assessment.

16. Artificial Intelligence and Predictive Soil Management

Artificial intelligence can integrate large and complex datasets generated from soil sensors, laboratory analyses, satellite imagery, weather stations and crop observations. Machine-learning models can predict soil salinity, organic carbon, nutrient availability and crop response.

17. Precision Agriculture for Salinity Management

Salinity is rarely distributed uniformly across a field. Variability can arise from differences in soil texture, elevation, drainage, irrigation patterns and groundwater depth. Uniform management may therefore be inefficient.

Electromagnetic induction sensors can identify spatial patterns of apparent soil electrical conductivity. These maps can be combined with soil sampling to develop salinity-management zones.

18. Role of Climate Change in Soil Health and Salinity

Climate change is expected to intensify several soil-health challenges. Higher temperatures can increase evaporation and accelerate soil-water loss, potentially concentrating salts near the soil surface.

Changes in rainfall patterns may reduce natural leaching in some regions while intense rainfall events may increase erosion in others. Sea-level rise threatens coastal agricultural soils through seawater intrusion.

19. Socioeconomic and Practical Considerations

Although advanced technologies offer considerable potential, adoption depends on affordability, accessibility, technical capacity and local relevance. Smallholder farmers may

face difficulties in accessing sophisticated sensors, genomic technologies or specialized microbial products.

Low-cost soil testing, mobile applications, farmer field schools, extension services and community-based soil-health programs can improve accessibility. Biological approaches are often attractive because locally available organic materials and microbial resources can reduce input costs.

20. Future Prospects

The future of soil-health management is likely to be increasingly data-driven, biological and regenerative. Soil testing will move beyond conventional chemical analysis toward integrated measurements of physical structure, biological activity, microbial communities and ecosystem functions.

The soil microbiome is expected to become an important target for agricultural innovation. Improved sequencing and computational technologies will enable identification of beneficial microbial communities and their functional interactions with plants.

CONCLUSION

Advances in soil health and salinity management are transforming the way agricultural soils are understood and managed. Soil health is no longer evaluated solely through conventional chemical fertility indicators. Modern assessment incorporates physical structure, chemical properties, biological activity, microbial diversity, functional genes, soil carbon fractions and digital measurements. These indicators provide a more comprehensive understanding of soil functioning and allow early identification of degradation.

Salinity remains one of the most important constraints to agricultural productivity, particularly in irrigated, arid and semi-arid regions. Its management requires a combination of accurate diagnosis, efficient irrigation, adequate drainage, appropriate amendments, organic matter restoration, biological inputs and salt-tolerant crops.