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From Degradation to Restoration: Reclaiming Problem Soils through Gypsum, Green Manuring and Climate-Resilient Agronomy

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INTRODUCTION

Soil is the foundation of agricultural production, yet its productive capacity can decline when natural resources are poorly managed or when environmental stresses become severe. Soil degradation occurs through several processes, including erosion, salinity, sodicity, nutrient depletion, decline in soil organic matter, compaction, waterlogging and deterioration of biological activity. These processes reduce the ability of soil to supply water and nutrients to crops and may ultimately result in reduced crop yields and declining farm profitability. Problem soils are particularly important in regions where irrigation, inadequate drainage, excessive evaporation, inappropriate fertilizer use and poor land management have altered soil properties. Salt affected soils can contain excessive soluble salts, while sodic soils are characterized by excessive exchangeable sodium. High sodium levels cause clay particles to disperse, resulting in poor aggregation, surface crusting, reduced infiltration and restricted root growth. Such conditions also reduce the availability of water and nutrients to plants.

The restoration of degraded soils is therefore not simply a matter of adding fertilizer. It requires correction of the specific soil constraint and simultaneous improvement of soil physical, chemical and biological properties. Gypsum is widely recognized as an important amendment for sodic soils because calcium supplied by gypsum can replace sodium on the soil exchange complex. The displaced sodium can subsequently be removed from the root zone through appropriate leaching and drainage. FAO guidance emphasizes that successful reclamation depends on the interaction among amendment application, water management, drainage and crop selection (Abrol et al., 1988). Organic resource management provides another important pathway for restoration. Green manure crops can increase organic matter inputs, stimulate microbial activity and improve nutrient cycling. Leguminous green manure crops can additionally contribute biologically fixed nitrogen.

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When combined with chemical amendments, organic matter can support gradual improvement in soil structure and biological functioning. Climate-resilient agronomy provides the broader framework within which these practices can be implemented. Climate smart agriculture seeks to increase productivity and resilience while reducing vulnerability to climatic stresses and, where possible, reducing agricultural contributions to climate change (Lipper et al., 2014).

Understanding Problem Soils

Problem soils are soils in which one or more physical, chemical or biological constraints interfere significantly with crop growth. Saline soils contain excessive soluble salts, whereas sodic soils contain excessive exchangeable sodium. Saline sodic soils contain both problems. Other degraded soils may suffer from severe acidity, compaction, nutrient depletion, erosion or loss of organic matter. Sodicity is particularly damaging because sodium affects the physical arrangement of soil particles. When sodium dominates the exchange complex, clay particles tend to disperse. This reduces the formation of stable aggregates and creates a dense soil condition with low hydraulic conductivity. Water may remain on the surface after irrigation or rainfall while the root zone remains poorly supplied with oxygen and available water.

In India, sodic soil reclamation has been an important agricultural development objective. The ICAR Central Soil Salinity Research Institute has developed gypsum based reclamation technology that combines amendment application with appropriate water and soil management. Large areas of sodic land have been brought back into agricultural production through these approaches. Problem soils should therefore be diagnosed before treatment. Soil pH, electrical conductivity, exchangeable sodium percentage, soil texture, organic carbon, available nutrients, infiltration characteristics and irrigation water quality should be evaluated. Without proper diagnosis, indiscriminate amendment application may increase production costs without providing proportional benefits.

Gypsum as a Tool for Sodic Soil Reclamation

Gypsum is calcium sulfate dihydrate and is one of the most widely used amendments for reclaiming sodic soils. Its importance arises from its ability to supply soluble calcium. When gypsum dissolves in the soil, calcium can replace exchangeable sodium associated with clay surfaces. The displaced sodium enters the soil solution and can subsequently be removed through leaching when adequate drainage is available. The basic process can be represented conceptually as:

Exchangeable sodium + soluble calcium → exchangeable calcium + soluble sodium

This process helps improve soil aggregation and creates better conditions for water movement. However, gypsum alone does not physically remove sodium from the soil. Water must move through the soil profile to carry displaced sodium below the root zone. Consequently, irrigation quality, drainage and field leveling are important components of successful reclamation. FAO recommendations emphasize that gypsum is most useful where poor infiltration is associated with sodicity and where sufficient water is available for reclamation and leaching. Application rates should be determined according to the severity of sodicity, soil properties and the required depth of reclamation rather than using a universal rate.

In India, gypsum is commonly used for alkali soil reclamation. ICAR recommendations indicate that gypsum application should be preceded by appropriate field preparation and followed by irrigation and leaching. The technology has demonstrated substantial benefits in bringing sodic soils back into crop production. Recent research also indicates that combining gypsum with organic materials can improve soil quality and crop productivity. A long term soybean and mustard study in sodic soil found that combinations involving gypsum and organic

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amendments improved soil physical and chemical properties and nutrient use efficiency (Rashmi *et al.*, 2024).

Green Manuring for Biological Restoration

Chemical reclamation addresses an important part of sodicity, but restoration must also rebuild the biological quality of soil. Green manuring is an effective method for increasing organic matter inputs while supporting nutrient cycling. A green manure crop is grown primarily to be incorporated into the soil rather than harvested as a commercial product. Leguminous plants such as sesbania, sunn hemp and other locally adapted species can be used depending on climate, soil condition and cropping system.

Green manure contributes fresh organic material to soil. During decomposition, microorganisms transform plant residues into simpler compounds and gradually contribute to soil organic matter formation. This process can improve aggregate formation, microbial activity and nutrient cycling. Green manure crops may also help protect the soil surface from erosion and reduce the impact of intense rainfall. Their root systems create biological channels that can contribute to improved soil structure and water movement. In nutrient depleted soils, green manuring can gradually improve nitrogen availability and reduce dependence on external nutrient inputs.

Research and extension experience in India have emphasized the importance of green manuring for restoring soil fertility, particularly in degraded and shifting cultivation systems. Kumar and Upadhyay (2019) reported that green manuring can contribute to improvement in organic matter and nutrient status and provide a sustainable pathway for restoring soil fertility. Green manuring is especially valuable when integrated with gypsum. Gypsum addresses the chemical problem associated with exchangeable sodium, while organic residues support biological and physical recovery. The two processes therefore complement each other.

Interaction Between Gypsum and Green Manuring

The restoration of degraded soil becomes more effective when chemical and biological approaches are combined. Gypsum can rapidly improve the chemical environment of sodic soil by supplying calcium, whereas green manure provides carbon and nutrients that support biological recovery. Organic matter can improve aggregate stability and infiltration and may enhance microbial processes involved in nutrient cycling. Root growth from green manure crops can create additional biological pathways through compacted or poorly structured soil. At the same time, improved soil structure resulting from gypsum application can support better root development of subsequent crops.

The combined approach can therefore create a positive restoration cycle. Improved soil structure increases infiltration; better infiltration facilitates leaching; lower sodium stress promotes root growth; greater root biomass increases organic matter input and improved biological activity enhances nutrient cycling. Field research has demonstrated that reduced rates of chemical amendments combined with organic materials can provide useful alternatives where the cost of full amendment application is a constraint. Singh *et al.* reported improvements in soil properties through the combined use of reduced gypsum and organic amendments, demonstrating the potential for integrated reclamation approaches.

Climate Resilient Agronomy in Restored Soils

Soil reclamation should not be considered a one time intervention. Once soil productivity begins to recover, appropriate agronomic management is necessary to prevent renewed degradation. Climate-resilient agronomy provides a framework for maintaining restored soil under variable rainfall, temperature and water availability. Climate-resilient agriculture emphasizes efficient resource use, adaptation to climatic variability, maintenance of productivity and improvement of system resilience. According to Lipper *et al.* (2014), climate smart agriculture focuses on increasing productivity and resilience while addressing climate related risks.

For reclaimed soils, climate-resilient agronomy can include:

1. Selection of crops and varieties tolerant to residual salinity or sodicity.
2. Efficient irrigation methods that minimize unnecessary water application.
3. Improved drainage to prevent secondary salinity and waterlogging.
4. Crop rotation involving legumes and crops with different rooting characteristics.
5. Green manuring and crop residue incorporation.
6. Conservation tillage where suitable for local soil conditions.
7. Mulching to reduce evaporation and moderate soil temperature.
8. Balanced fertilizer application based on soil testing.
9. Rainwater harvesting and improved soil moisture conservation.
10. Weather based planning of sowing, irrigation and nutrient application.

Integrated Restoration Pathway

The transition from degradation to restoration should follow a systematic process. First, the soil should be diagnosed to determine whether the major constraint is salinity, sodicity, acidity, compaction, nutrient depletion or a combination of problems. Second, an appropriate reclamation plan should be developed. Third, gypsum or another suitable amendment should be applied according to the calculated requirement. Fourth, irrigation and drainage should be managed to facilitate the movement of salts from the root zone. Once the initial chemical constraint has been reduced, green manure and organic residues can be introduced to strengthen biological recovery. Suitable crops can then be established using climate-resilient agronomic practices.

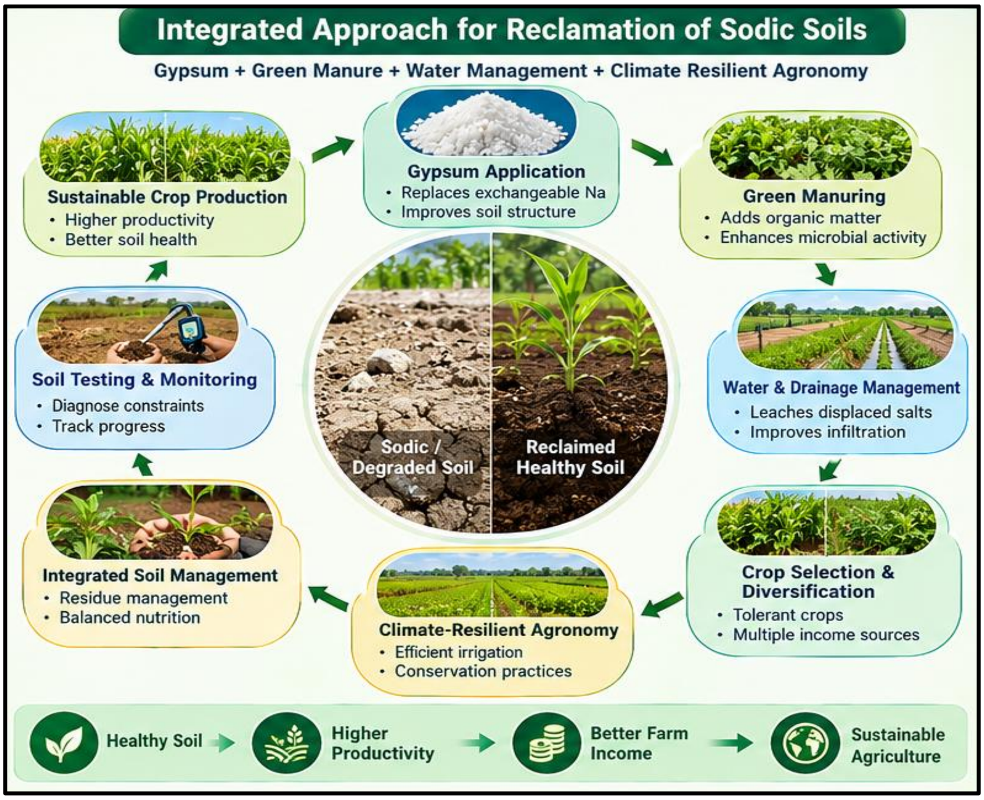

Figure 1: Integrated pathway for the reclamation of sodic soil through gypsum application green manuring, water management and climate-resilient agronomy.

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Table 1: Integrated strategy for restoration of problem soils

Restoration component	Major purpose	Important practices	Expected soil and crop benefit
Soil diagnosis	Identify the major soil constraint	Test pH, EC, ESP, organic carbon, nutrients and irrigation water	Correct treatment selection
Gypsum application	Reduce sodicity	Apply according to gypsum requirement and soil condition	Calcium supply, sodium replacement and improved structure
Water and drainage management	Remove displaced salts	Field leveling, controlled irrigation and adequate drainage	Improved infiltration and reduced salt accumulation
Green manuring	Restore organic matter	Grow and incorporate suitable green manure crops	Better microbial activity, nutrient cycling and soil structure
Crop residue management	Maintain carbon input	Retain and incorporate suitable residues	Increased organic matter and improved aggregation
Crop diversification	Improve system resilience	Rotate cereals, legumes and tolerant crops	Better nutrient cycling and reduced production risk
Climate-resilient agronomy	Maintain productivity under climate stress	Efficient irrigation, conservation practices and suitable varieties	Greater water use efficiency and climate resilience
Monitoring	Maintain restored soil condition	Periodic soil testing and crop performance assessment	Prevention of renewed degradation

Crop Selection on Reclaimed Soils

Crop selection plays a central role during the transition period. Highly sensitive crops may perform poorly if soil constraints remain severe. Therefore, tolerant crops should be selected during the early stages of reclamation. Rice has historically been important in the reclamation of many sodic soils because its flooded conditions can support certain reclamation processes when combined with appropriate amendment and drainage management. Other relatively tolerant crops can also be introduced according to regional conditions. As soil properties improve, farmers can gradually diversify into more sensitive and higher value crops. This creates an economic pathway from initial reclamation to profitable agriculture. Crop diversification also reduces dependence on a single crop and distributes climatic and market risk. Inclusion of legumes can contribute additional nitrogen through biological fixation and provide valuable biomass for soil improvement.

Water Management as the Missing Link

One of the most important principles of soil reclamation is that amendment application must be accompanied by appropriate water management. Gypsum releases calcium, but the sodium displaced from exchange sites must be moved away from the root zone. If drainage is inadequate, dissolved salts may accumulate again near the soil surface. Therefore, field leveling, drainage channels, appropriate irrigation scheduling and good quality irrigation water are essential.

Excessive irrigation should also be avoided because it may increase waterlogging and raise production costs. The objective is not simply to apply more water but to ensure that water enters the soil effectively and moves through the profile in a controlled manner. FAO guidance emphasizes that reclamation success depends on the relationship among soil properties, amendment application, irrigation and drainage.

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Economic Importance of Soil Restoration

- Soil reclamation involves an initial investment in amendments, land preparation, irrigation and sometimes drainage infrastructure. Farmers may therefore hesitate to invest in severely degraded land unless the expected economic benefits are clear.
- Integrated reclamation can improve the economic feasibility of restoration by reducing dependence on expensive inputs over time and increasing crop productivity. The use of locally available organic resources and green manure crops can reduce the need for repeated external inputs.
- Research from India has demonstrated that integrated amendment strategies can reduce reclamation costs while improving crop performance. For example, combinations of reduced gypsum rates with organic amendments have shown potential for improving soil properties while reducing the quantity of chemical amendment required.
- The economic objective should therefore be to maximize the long term return from restored land rather than simply minimizing the initial reclamation cost.

Future Prospects

- Future soil restoration programs should move toward integrated, site specific approaches. Soil testing can be combined with geographic information systems, remote sensing and digital soil mapping to identify degraded areas and prioritize reclamation.
- Decision support systems can help determine amendment requirements, irrigation schedules and crop choices. Low cost soil testing and mobile based advisory services may improve access to soil management recommendations.
- There is also considerable scope for integrating organic amendments, green manuring, biofertilizers and suitable mineral amendments. Such combinations can reduce dependence on individual inputs while improving soil biological functioning.
- Climate-resilient agriculture should become an integral part of reclamation programs rather than being treated as a separate concept. Restored soils should be managed in ways that conserve organic carbon, reduce erosion, improve water use efficiency and maintain biological diversity.
- The restoration of degraded soils also contributes to broader environmental objectives. Increased soil organic matter can improve soil structure and water retention while contributing to carbon storage. FAO emphasizes that degraded soils have considerable potential for restoration of soil organic carbon when appropriate land and soil management practices are adopted.

CONCLUSION

Restoring degraded and problem soils requires an integrated approach rather than reliance on a single practice. Proper soil diagnosis, gypsum application, green manuring, effective water and drainage management, suitable crop selection and climate-resilient agronomy can together restore soil health and improve crop productivity. Combining chemical amendments with organic and biological practices can enhance the physical, chemical and biological quality of soil while reducing the risk of further degradation. Healthy soils are the foundation of resilient agriculture and their restoration is an investment in sustainable productivity, farmer livelihoods and future food security.

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