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Indian Farming

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ICAR

बेटी बचाओ बेटी पढ़ाओ

Special Issue for International Salinity Conference 3.0: Worldwide Efforts on Cutting-Edge Approaches for Restoring Saline Ecosystems (WE-CARE-2025)

International Salinity Conference 3.0 (WE-CARE-2025) Goa, India

The "International Symposium on Salt Affected Soils" in 1980 marked the beginning of global collaborative efforts to combat soil salinity and improve the livelihoods of farmers in affected regions. Considering the increasing importance of salinity management for sustainable agriculture production in changing climate, the salinity experts founded the Indian Society of Soil Salinity and Water Quality (ISSSWQ) in 2008 at Karnal. This society was formed with the aim of advancing research and development in soil salinity and water quality management.

In 2019, the society organized the first International Conference "Golden Jubilee International Salinity Conference on Resilient Agriculture in Saline Environment under Changing Climate: Challenges and Opportunities (RAISE-II)," on 21–23 February. This conference marked the 50th anniversary of the ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, India. Subsequently, the second International Salinity Conference (ISC-2024) was organised during 14–16 February, 2024 at ICAR-CSSRI, Karnal. In response to the growing challenges of climate change and global food security, ISSSWQ, Karnal and ICAR-Central Coastal Agricultural Research Institute (CCARI), Goa are now jointly organizing the third International Salinity Conference 3.0 (WE-CARE-2025), in Goa, India. ICAR-CSSRI, Karnal, and ICAR-CCARI, Goa are also collaborating in this endeavour under aegis of ICAR, New Delhi. This important event aims to unite global experts, policymakers, and stakeholders to address the critical issue of salt-affected soils and ecosystems, fostering innovative solutions for sustainable agriculture in saline environments. The conference desires to explore the challenges and solutions for the sustainable management of salt-affected ecologies. It will focus on the research and technological advancements in reclamation and restoration of health of SAS, and their role in climate change adaptation and mitigation,sustaining agriculture production and food security. Following are the key thematic areas of this conference:

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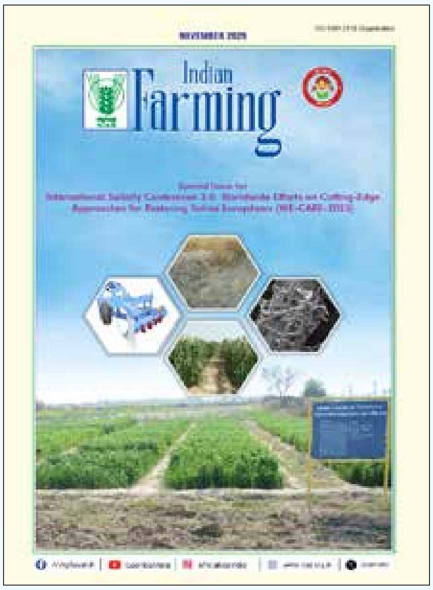

Cover I: International Salinity Conference 3.0 (WE-CARE-2025)

Cover IV: Future of Food and Agriculture

For editorial queries contact:
Editor (*Indian Farming*),
ICAR-DKMA
011-2584 2828 Extn. 617
e-mail: editorindfarming@gmail.com

For Subscription and Advertisement contact:

Bhupender Dutt
In-charge, Business Unit, DKMA, ICAR
Krishi Anusandhan Bhavan I, Pusa
New Delhi 110 012
Telefax: 011-2584 3657
e-mail: bupinder.icar@nic.in,
businessuniticar@gmail.com

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In This Issue

PRESIDENTIAL MESSAGE

SECONDARY salinization and sodification of agricultural land are indeed significant contributors to unsustainable farming practices. Worldwide, the total area of salt affected soils amounts to 1381 million ha (Mha) which is 10.7% of the total global land area. It has severe impact on the livelihoods of over 2.6 billion people (about 74% of resource-poor farmers). This issue causes an annual economic loss of around US$ 6.3 billion. Predictions indicate a further considerable spread of salt-affected soils in the coming decades, threatening global food security. The largest extent of salt affected area exists in Australia (357 Mha), Argentina (153 Mha), Kazakhstan (94 Mha), the Russian Federation (77 Mha), the United States (73.4 Mha), the Islamic Republic of Iran (55.6 Mha), the Sudan (43.6 Mha), Uzbekistan (40.9 Mha), Afghanistan (38.2 Mha), and China (36 Mha). These ten countries account for 70 percent of the total salt affected area of the world. In India, 6.73 million hectares are affected by salinity, with 2.95 million hectares of saline land across 16 states. Annual crop production losses due to salinity and sodicity are estimated at 16.84 million tonnes, amounting to a loss of ₹2300 (~$27) million. The situation is expected to further worsen, with projections suggesting that the affected area may increase to 16.2 million hectares by 2050. The primary causes of soil salinization are inadequate drainage systems, waterlogging, unsustainable farming practices, and the growing use of low-quality groundwater for irrigation.

The ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, India, has made significant contributions to the development of technologies for the reclamation and productive management of salt-affected soils and waters. The ICAR-CSSRI is one of the world's leading institutions fully dedicated to the development of technologies for managing saline lands for agricultural production. For decades, it has been at the forefront of developing integrated solutions for the management of salt-affected soils and waters, reaching millions of farmers through effective extension programs. As such, nearly 2.2 million ha salt affected lands have been reclaimed and put to productive use. It has been estimated that reclaimed area is contributing more than 15 million tonnes of foodgrains to the national pool.

The Indian Society of Soil Salinity and Water Quality (ISSSWQ), was founded on 6th August 2008 at Karnal under the Societies Registration Act XXI, 1860 (Registration No. ROS-088). The society pursues for the advancement of research and development in soil salinity and water quality, and it aims at providing a forum for scientists, researchers, students and different stakeholders on the emerging scientific themes for exchange of ideas and knowledge on sustainable management of salt affected ecologies. It also acts as a link between research institutions, development organizations, industries, and farmers. The society has organized two International Salinity Conferences and six National Conferences/Seminars on the important topical issues. During these events, the society engaged its members, and domain experts, stakeholders and farmers to deliberate and develop road map for solving the multifaceted issues of the saline ecosystems.

Rajender Kumar Yadav
President

Editorial

IN the present era, soil salinity presents a significant and widespread challenge and implications that affect agricultural production and food security, and biodiversity conservation and environmental sustainability in arid and semi-arid regions across globe. Currently, worldwide more than 835 million hectares of land, approximately 20 and 33% of total and irrigated agricultural land, respectively, is affected by problem of salts. Salt-affected soils (SAS) comprise of sodic (438 Mha) and saline (397 Mha) soils spread over more than 100 countries. Out of the total SAS, ~76 Mha area is affected by human-induced salinization and sodification. The coastal areas are vulnerable to sea water intrusion and inundation due to the climate change. Intensive and faulty agricultural practices, and long-term climate shifts are major factors that induce escalating salt stress in soil and crops.

Livelihoods of more than 2.6 billion (about 74%) resource poor peasants is threatened due to moderate to severe degradation of nearly 52% of the world's agrarian land. This results in an annual economic loss of ~US $ 6.3 billion. Sustainable land management is vital for ecological sustainability,mitigate the process of further soil deterioration, and to meet the national targets of the Sustainable Development Goals (SDGs). India remains committed to achieving land degradation neutrality and has set target for restoring degraded lands (26.0 million hectares) by 2030.

The aforesaid challenges underscore the urgent need for sustainable management of salt-affected lands. Land restoration practices play a crucial role in preventing further expansion of soil salinization and ensuring food security and wellbeing of agrarian community, especially in the backdrop of climate change. At ICAR-CSSRI, Karnal, we strive to bring hope and prosperity to the farmers, inhabiting in salt-affected regions and exemplify our unwavering dedication to the society. Hence, this issue of Indian Farming addresses the emerging challenges in salt-affected lands and their sustainable management.

Guest Editors

- Priyanka Chandra
- Parul Sundha
- Gajender Yadav
- Arvind Kumar Rai
- Rajender Kumar Yadav

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Role of arbuscular mycorrhizal fungi in enhancing soil health and plant resilience

Priyanka Chandra[1]*, Parul Sundha[1], Nirmalendu Basak[2], A. K. Rai[1] and R. K. Yadav[1]

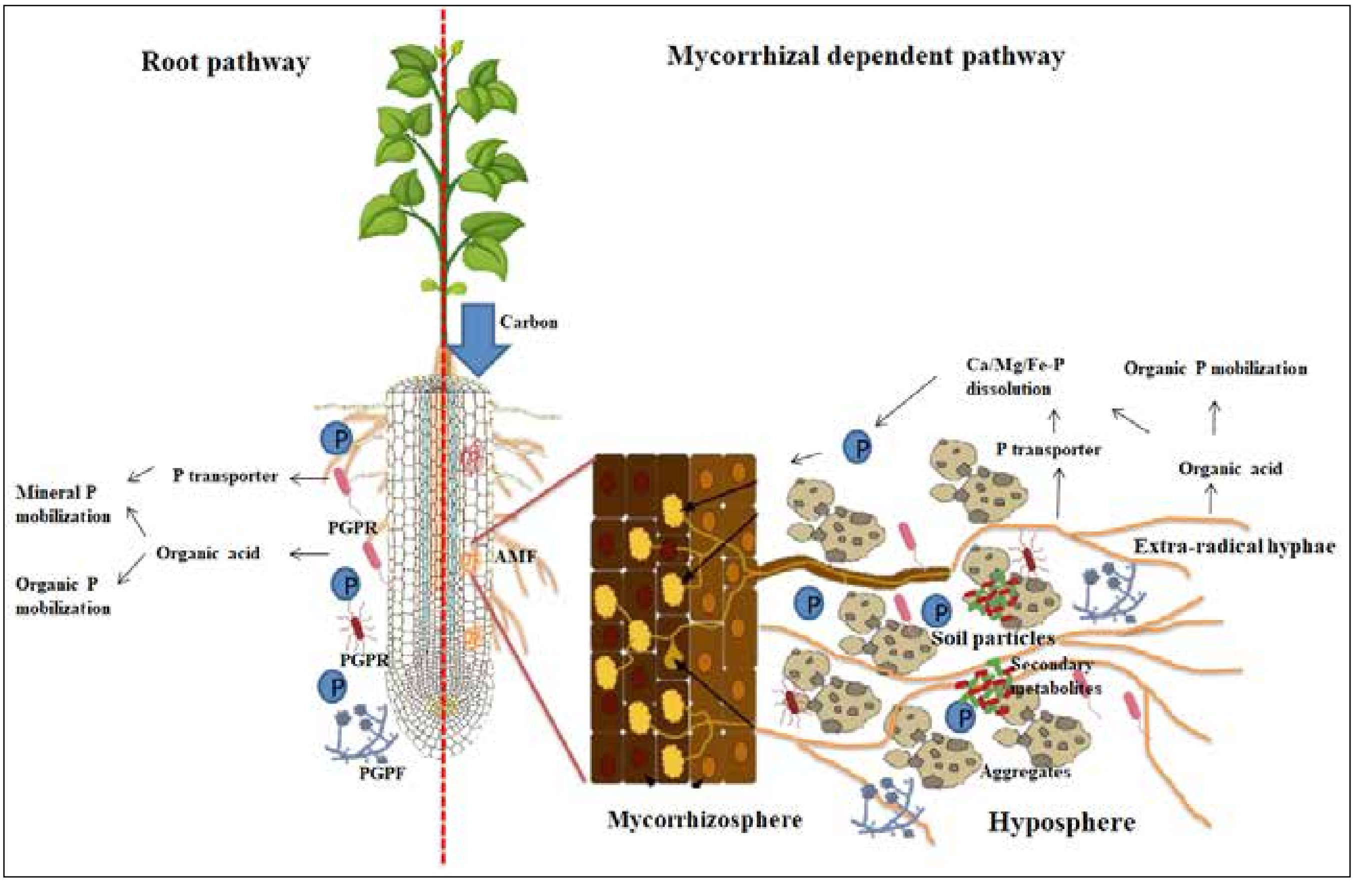
[1]*ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001*

[2]*ICAR-National Bureau of Soil Survey and Land Use Planning, Regional Centre, Kolkata 700 064*

Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with the roots of most terrestrial plants and play a pivotal role in maintaining soil health and ecosystem stability. Through their extensive hyphal networks, AMF enhance plant access to key nutrients particularly phosphorus and nitrogen while receiving carbohydrates in return, thus, supporting a mutualistic exchange. Their role in improving soil structure is mediated by glomalin production, which stabilizes soil aggregates, enhances porosity, and fosters microbial activity. AMF also contribute to organic matter decomposition and carbon sequestration, further influencing nutrient cycling. Importantly, AMF have emerged as effective agents for mitigating salinity stress in plants by improving phosphorus acquisition, reducing sodium uptake, and maintaining optimal K^+/Na^+ and Mg^{2+}/Na^+ ratios in plant tissues. Despite observed genotype-dependent variability in AMF effectiveness, their integration into sustainable agricultural practices such as reduced tillage, crop rotation, and inoculation offers a promising strategy for improving soil fertility, minimizing chemical inputs, and enhancing crop resilience under abiotic stress conditions. Understanding the functional mechanisms of AMF is thus vital for leveraging their potential in agroecological systems.

Keywords: Arbuscular mycorrhizal fungi, Carbon sequestration, Crop resilience, Ecosystem stability

ARBUSCULAR Mycorrhizal fungi (AMF) form symbiotic associations with the roots of the majority of terrestrial plants, playing a crucial role in shaping soil conditions and influencing soil health. AMF establish intricate networks within the rhizosphere, facilitating nutrient uptake, improving soil structure, and enhancing plant resilience to environmental stressors. As such, exploring the effects of AMF on soil conditions and soil health is essential for understanding the intricate relationships between plants, microbes, and their surrounding environment. AMF belong to the phylum Glomeromycota and form mutualistic relationships with a wide range of plant species, including crops, grasses, and trees. Through these symbiotic associations, AMF extend the reach of plant roots, increasing their access to water, nutrients, and minerals, particularly phosphorus and nitrogen. In return, plants provide AMF with carbohydrates synthesized through photosynthesis, sustaining their growth and reproduction. This mutualistic exchange benefits both partners and contributes to the overall productivity and resilience of terrestrial ecosystems. One of the key contributions of AMF to soil conditions is the enhancement of soil aggregation and structure. By secreting glomalin, a glycoprotein that acts as a binding agent, AMF promote soil aggregation, leading to the formation of stable soil aggregates. These aggregates improve soil porosity, water infiltration, and aeration, creating a favourable environment for root growth and microbial activity. Additionally, AMF play a vital role in organic matter decomposition, accelerating the breakdown of organic residues and contributing to soil carbon sequestration. Moreover, AMF influence soil nutrient cycling and availability, particularly phosphorus cycling. Through their extensive hyphal networks, AMF scavenge phosphorus from the soil, making it accessible to plants with high phosphorus requirements. This nutrient mobilization not only



Description of functioning of AMF in the rhizosphere (Chandra *et al.* 2025)

benefits mycorrhizal plants but also enhances the nutrient status of the soil, supporting the growth of associated plants and promoting ecosystem diversity.

As key components of soil-plant ecosystems, AMF play a crucial role in improving plant responses to salinity, benefiting both growth and yield. This makes AMF valuable candidates for mitigating salt stress through bio-amelioration. The enhanced growth observed in mycorrhized salt-stressed plants is largely attributed to AM fungi-mediated improvements in nutrient acquisition, particularly phosphorus, as Pi absorption tends to decline under saline conditions.

AM symbiosis has also been shown to reduce sodium (Na^+) uptake and translocation while promoting the absorption of essential cations such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). This interaction leads to an increase in K^+/Na^+ and Mg^{2+}/Na^+ ratios in plant shoots, which contributes to improved physiological stability under salt stress. However, significant variability has been reported in the effectiveness of AM symbiosis in addressing salinity and phosphorus deficiency, depending on the specific plant and AM fungi genotypes involved.

In recent years, there has been growing interest in harnessing the potential of AMF to improve soil health and agricultural sustainability. By inoculating soils with AMF or adopting practices that promote their proliferation, such as reduced tillage and cover cropping, farmers can enhance soil fertility, reduce nutrient leaching, and reduce the need for chemical fertilizers and pesticides. Understanding the mechanisms underlying the effects of AMF on soil conditions and soil health is essential for optimizing their use in agroecosystems and maximizing their benefits for sustainable agriculture.

Functioning of AMF

- ***Nutrient uptake:*** AMF enhance nutrient uptake by extending the root system's reach into the soil, increasing the surface area available for nutrient absorption.
- ***Nitrogen uptake:*** AMF enhance nitrogen uptake plants, particularly in nitrogen-poor soils, through increased root exploration and nutrient absorption.
- ***Phosphorus solubilization:*** AMF release organic acids and phosphatase enzymes into the rhizosphere, which solubilize phosphorus from minerals such as apatite and rock phosphate.
- ***Induced systemic resistance:*** Mycorrhizal associations induce systemic resistance in plants, activating defence mechanisms that enhance plant resilience to pathogen attack.
- ***Disease suppression:*** AMF protect plant roots from infection by soil-borne pathogens, forming a physical barrier and enhancing plant defence against pathogen invasion.
- ***Water relations:*** AMF improve water uptake efficiency by accessing water from deeper soil layers and transporting it to the plant host.
- ***Enhanced root exploration:*** AMF hyphae extend into the soil, accessing micronutrients from mineral sources and soil organic matter.
- ***Soil structure:*** By secreting glomalin and

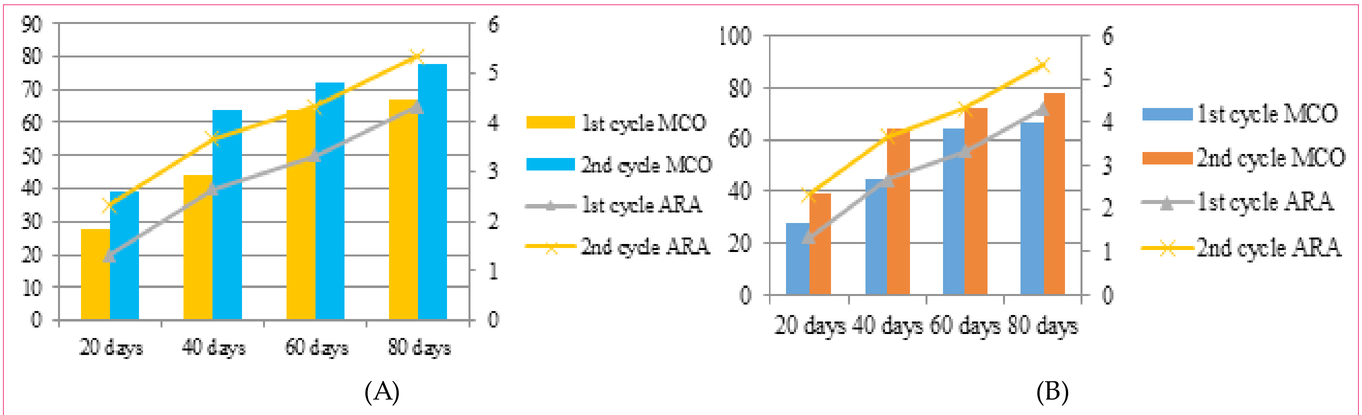
promoting soil aggregation, AMF contribute to soil structure formation, enhancing soil fertility and plant growth.

- ***Stress tolerance:*** AMF enhance plant resilience to environmental stressors such as drought, salinity, and nutrient deficiency, through improved nutrient acquisition and water relations.
- ***Drought tolerance:*** AMF enhance plant drought tolerance by improving water uptake efficiency, regulating stomatal conductance, and enhancing plant osmotic adjustment mechanisms.
- ***Salinity tolerance:*** Mycorrhizal associations can alleviate salt stress in plants by enhancing ion homeostasis, facilitating sodium exclusion, and promoting osmotic adjustment, thereby improving plant growth and productivity in saline soils.
- ***Heavy metal remediation:*** AMF contribute to heavy metal remediation by immobilizing toxic metals in the soil, facilitating metal uptake by plants, and promoting metal detoxification and sequestration in plant tissues and rhizosphere microorganisms.
- ***Carbon sequestration:*** AMF play a significant role in soil carbon sequestration by enhancing plant productivity, promoting root biomass accumulation, and increasing soil organic matter content.

Case study in salt affected soils

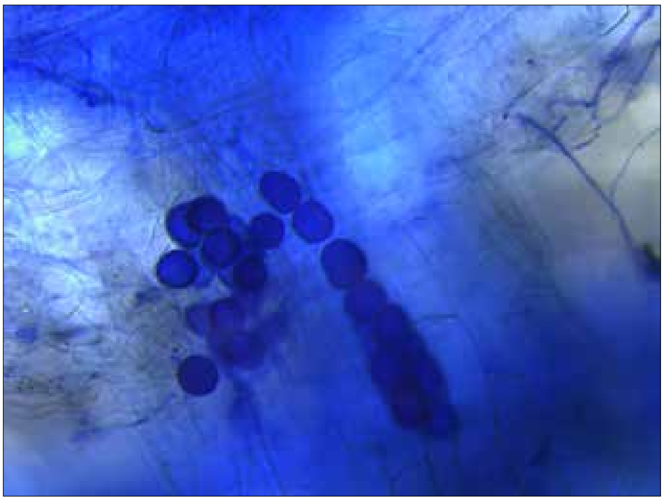
Suitable host: Propagation of native AMF by soil trapping method was studied using sorghum and maize as trap crops in two cycles. For the first cycle, both the crops were grown in pots for 60 days and the plants were uprooted and some roots were collected for confirmation of mycorrhizal associations. For the second cycle, the roots obtained from first cycle were chopped and mix as inoculum in the same pots. Sorghum and maize seeds were sown in the same pots. Again after 2 months, the plants were uprooted and roots were examined for mycorrhizal associations. Sorghum and maize are the two distinct host plants which possess the ability to associate with arbuscularmycorrhizal fungi (AMF), both are also commonly used for AMF propagation. In the study, mycorrhizal association and colonization increased in both cycles of propogation for both hosts. However, maize exhibited higher propagation and colonization compared to sorghum. Previous studies, have also indicated that maize facilitates AMF propagation. The higher percentage of root colonization in maize is largely attributed to the unique composition of its root exudates. Some flavones, exclusively produced by maize roots, play a significant role in plant-fungal interactions and symbiotic relationships. These compounds are known to attract mycorrhizal germ tubes to the roots, potentially enhancing AMF colonization by promoting spore germination and germ tube growth. Mycorrhizal colonization varies depending on AMF communities, crop type, variety, and environmental factors such as soil and climate conditions. The primary factor influencing these interactions is the fungal requirement for photoassimilates, which affects both root associations and fungal reproduction. In the second cycle of propogation, both colonization levels and arbuscule abundance were higher than in the first cycle. The extensive root density, branching, and spread of sorghum and maize roots support a broad proliferation of AMF within their root systems. This facilitates a richer and more diverse fungal community, increasing the number of infection points and enhancing contact with spores, ultimately leading to improved colonization.

Plant growth, and phosphorus status: Plants inoculated with AMF exhibited significantly improved growth compared to control plants in terms of various growth parameters highlighting the role of AM colonization in enhancing plant growth and nutrient uptake. The findings further suggested that AMF exert a positive effect under salt stress conditions. AMF inoculation also enhanced P uptake in sorghum plants under stressed conditions. AM fungi possessing specialized phosphorus transporters with high affinity, which help solubilize P under moderate and severe salinity conditions and when P availability is low. These fungi achieve this by producing organic acids that facilitate P absorption, making it more accessible to plants. AMF inoculation also reduced Na^+/K^+ ratio in sorghum plants under stressed conditions. Studies have shown that AM symbiosis increases sodium (Na^+) exclusion by sequestering it within intraradical hyphae, thereby preventing its translocation to the shoots. This enhanced Na^+ exclusion capacity is likely

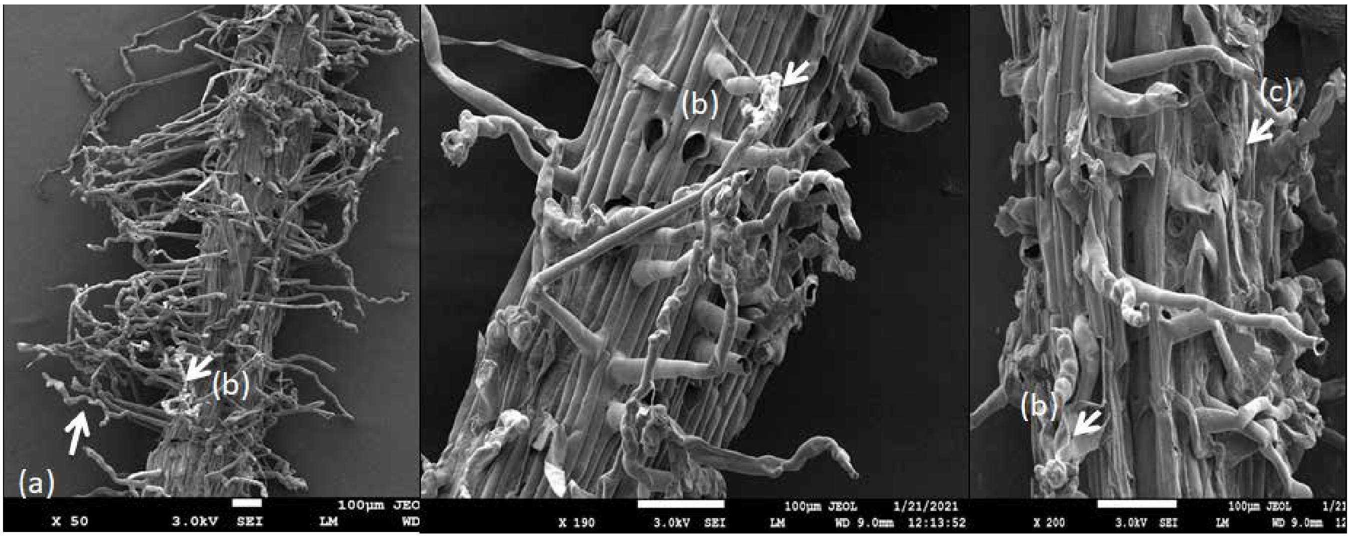


The interaction of AMF colonization (MCO) with the roots of maize (A) and sorghum (B) in first and second cycle of propagation of and number of arbuscules (ARA) formed with respect to time a contributing factor to the improved growth observed in AM-inoculated plants. Additionally, AM fungi have been proposed to limit Na^{+} uptake either by selective absorption from the soil or by controlling its transfer within the plant.

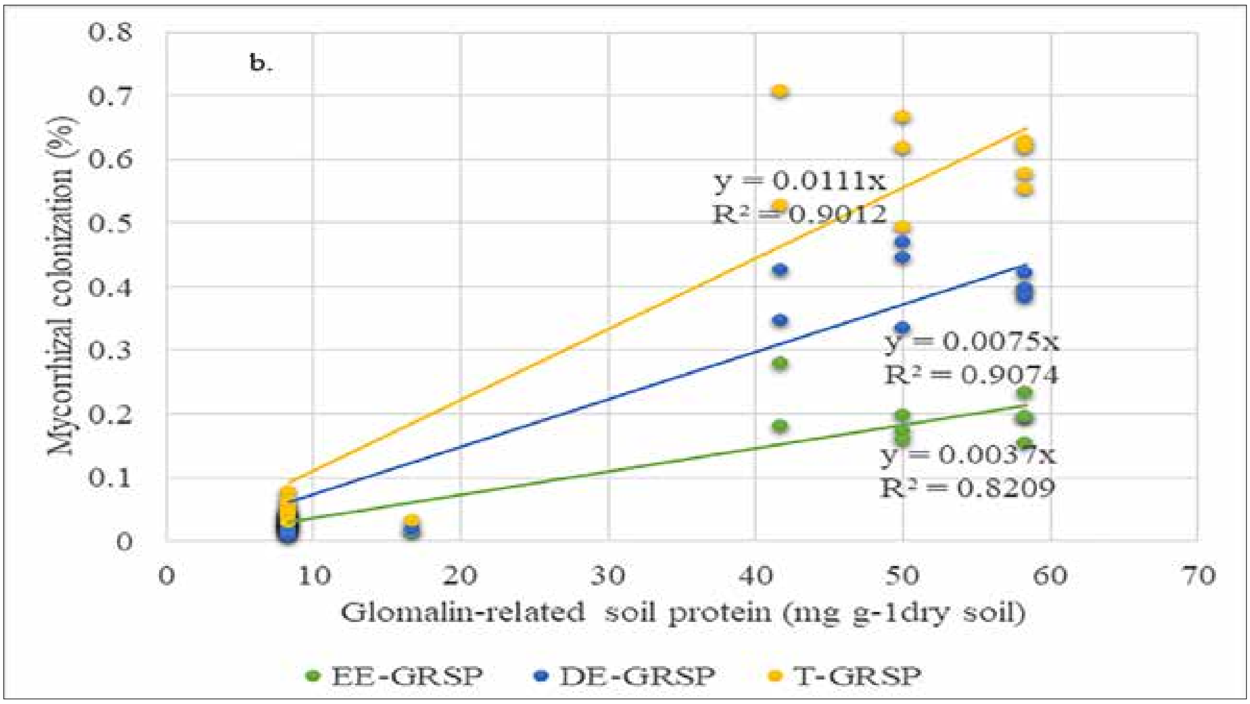
Mycorrhizal colonization and soil properties: Microscopic observations confirmed the presence of various growth stages of mycorrhizal development within plant roots, including intraradical and extraradical hyphae, arbuscules at different formation stages, and vesicles. The overall colonization of sorghum roots inoculated with AMF ranged from 8.3% to 58.3%. Arbuscularmycorrhizal fungi (AMF) generally exhibit a higher tolerance to salinity compared to plants. Under stress conditions, plants reduce root biomass and invest more in AMF associations, allowing the fungi to take over essential water and nutrient acquisition. AMF's beneficial role is closely linked to the production of a fungal protein



Roots of AMF-inoculated sorghum plants demonstrated AMF colonization and abundance as their typical fungal structures were found under microscope



Electron micrograph (5000X) of root with visualization of (a) root hairs (b) mycorrhizal hyphae coiling the root hairs (c) root exudates through Scanning Electron Microscope (SEM)



Relationships between arbuscular mycorrhizal (AM) colonization and Glomalin related soil proteins content in soil

View of the experiment at experimental farm Nain, Haryana

Propagation of mycorrhiza in sorghum roots

called glomalin, which is quantified in soil as glomalin-related soil protein (GRSP). In this study, GRSP content was significantly higher in AM-inoculated soil compared to non-inoculated soil. The presence of AMF strongly correlates with microbial activity in the soil, as inoculated treatments exhibited higher microbiota populations. This suggests that AMF colonization efficiency may be influenced by bacterial communities acting as a third symbiotic partner. Soil microbial enzymes serve as indicators of microbiological activity, and the significantly higher dehydrogenase and phosphatase enzyme activity in AMF-inoculated soil can likely be attributed to increased microbial populations. These findings further highlight the role of phosphatase enzymes released by AMF in enhancing plant phosphorus nutrition through hyphal transport.

SUMMARY

Arbuscular mycorrhizal fungi (AMF) are integral part of soil ecology in the maintenance and improvement of soil health, plant nutrition, and ecosystem resilience. Their symbiotic associations with plant roots facilitate enhanced nutrient acquisition particularly phosphorus and promote soil structural stability through glomalin-mediated aggregation. AMF also play a significant role in mitigating salt stress by regulating ion uptake and improving physiological balance in plants. Although the efficiency of AM symbiosis can vary depending on host plant and fungal genotypes, the ecological and agricultural benefits of AMF are well-documented. Harnessing their potential through targeted inoculation strategies and AMF-friendly agronomic practices offers a sustainable pathway for enhancing soil fertility, reducing reliance on synthetic inputs, and improving crop productivity under both normal and stress-prone conditions. Continued research into the functional dynamics of AMF will be critical for optimizing their application in diverse agroecosystems and advancing sustainable agricultural practices.

*Corresponding author email: priyanka.chandra921@gmail.com

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Harnessing genome editing for developing climate-resilient crops

Anita Mann*, S. K. Sanwal, Ashwani Kumar, Nitish Ranjan Prakash, Avni Dahiya, Arvind Kumar and R. K. Yadav

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Climate change poses a serious threat to world agriculture and food security due to the increasing frequency of drought, salinity, heat, and other biotic or abiotic stresses. As a result, the development of climate-resilient crops has become an urgent priority to maintain productivity in vulnerable ecosystems. Recent technologies of genome editing using CRISPR/Cas are precise, accurate and efficient tools for accelerating crop improvement. With genome editing, stress-responsive genes, regulatory components, and metabolic pathways can be specifically altered without the hassles of linkage drag or drawn-out breeding cycles. Recent advancements have successfully edited genes linked to osmotic adjustment, antioxidant regulation, ion homeostasis, disease resistance and stress signalling pathways in cereals, legumes, and oilseeds, leading to improved crop plants. In addition to resilience against abiotic stresses, editing for characteristics such as nitrogen-use efficiency, photosynthetic performance, and yield stability in variable climates presents a promising pathway for sustainable agriculture. The integration of genome editing with genomic selection, speed breeding, and high-throughput phenotyping can further expedite the creation of resilient varieties. This article emphasizes significant breakthroughs, potential gene targets, and translational strategies for implementing genome editing in crop breeding initiatives. Leveraging these innovations can greatly enhance global food and nutritional security in the context of climate change.

Keywords: Abiotic stress, Cas9, CRISPR, Crop improvement, Genome editing

AGRICULTURAL productivity is increasingly threatened by various abiotic stresses such as drought, salinity, extreme temperatures (heat and cold), and nutrient imbalances. These environmental stressors significantly affect plant growth, development, and yield, posing a major challenge to global food security especially in the face of climate change and a growing world population. Although, conventional breeding methods have been employed for decades to develop stress-tolerant crop varieties, but the major limiting factor is the time, as to develop improved varieties takes years.

In recent years, genome editing technologies have emerged as revolutionary tools for precise and targeted genetic modifications, offering new avenues for enhancing crop resilience to abiotic stress conditions. Unlike conventional breeding or transgenic approaches, genome editing allows for the direct manipulation of specific genes or regulatory elements responsible for stress responses, without necessarily introducing foreign DNA. This precision reduces unintended effects and accelerates the development of improved crop varieties.

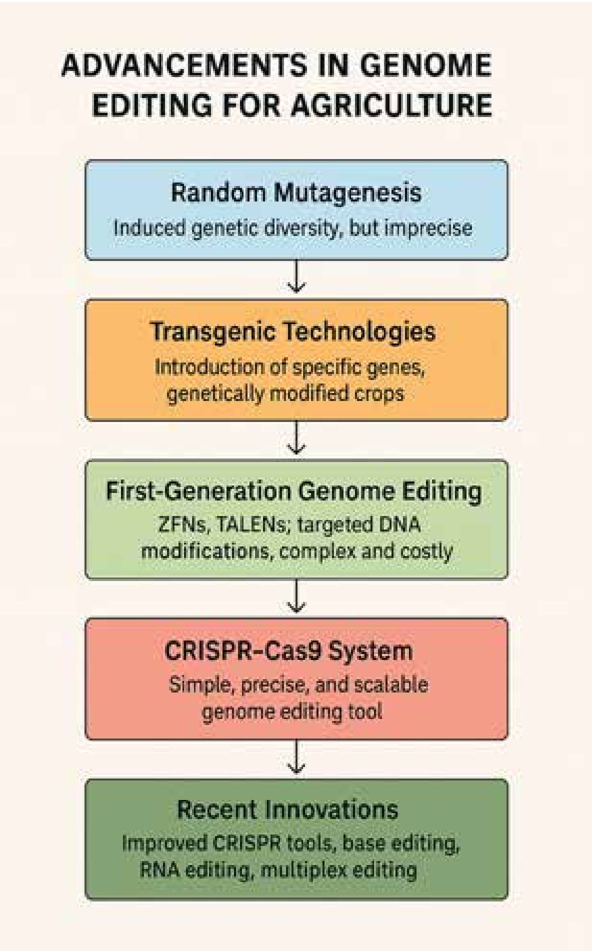
The most prominent genome editing tool, CRISPR-Cas9, along with other systems such as TALENs (Transcription Activator-Like Effector Nucleases) and ZFNs (Zinc Finger Nucleases), has been successfully applied to a wide range of crops including rice, wheat, maize, tomato, and soybean. These technologies are being used to knock out negative regulators, enhance expression of stress-responsive genes, or even introduce beneficial alleles for improved stress tolerance. In addition to providing greater control over plant traits, genome editing offers the possibility of multiplex gene editing-modifying multiple genes simultaneously to address complex stress responses.

As a result, genome editing holds tremendous promise not only for improving abiotic stress tolerance but also for contributing to sustainable agriculture, reducing the need for chemical inputs, and supporting adaptation to changing environmental conditions. Recent studies have highlighted the potential of CRISPR/Cas system (cas9, 12, 13) in enhancing crop resilience to various biotic or abiotic stresses, including diseases, drought, salinity, heat, and cold. Furthermore, advancements in genome editing techniques, such as base editing and prime editing, offer even more precise and efficient tools for crop improvement.

Advancement in genome editing technologies

Early methods, such as random mutagenesis using radiation or chemicals, were crucial in generating diversity but lacked precision. The introduction of transgenic technologies in the 1980s enabled the insertion of specific genes, leading to genetically modified crops like Bt cotton, though public and regulatory concerns limited their adoption.

A major shift came with first-generation genome editing tools-ZFNs and TALENs which allowed targeted DNA modifications but were complex and costly. The real breakthrough was CRISPR-Cas9 in 2012, offering a simple, precise, and scalable system guided by RNA. Since then, tools like Cas12a, base editors, and prime editing have expanded capabilities to include fine-tuned gene changes without cutting DNA, or even editing RNA.



Recent innovations include epigenome editing, RNA editing, synthetic biology integration, and multiplex editing, enabling simultaneous modification of multiple genes for complex trait improvement. Together, these tools mark a shift toward precision agriculture, with the potential to sustainably boost crop performance and global food security in the face of climate challenges.

Genome-editing enzymes

Genome-editing enzymes can be broadly categorized into two main types:

- Site-specific recombinases (SSRs)
- Site-specific nucleases (SSNs)

Table 1. Comparison of site-specific recombinases and site-specific nucleases in plants

Features	Site-specific Recombinases (SSR's)	Site-specific Nucleases (SSN's)
Definition	Enzymes that catalyse recombination between specific DNA sequences (recombination without cutting)	Enzymes that introduce double-strand breaks at specific DNA sequences
Mechanism	DNA rearrangement: excision, integration, inversion	DNA cleavage followed by repair (NHEJ or HDR)
DNA Cut	No, recombination without breaks	Yes, induces double-strand breaks (DSB)
Repair Pathway	Direct recombination	Requires DNA repair (NHEJ or HDR)
Examples	Cre/loxP, FLP/FRT, R/RS	ZFNs, TALENs, CRISPR-Cas9, CRISPR-Cas12a, Cas13
Target Sites	Specific recombination sites	Custom-designed DNA sequences (can be any sequence)
Precision	Very high (recombines only defined sites)	High, but off-target effects may occur
Use in Plants	Marker gene removal, transgene stacking, reversible gene expression	Gene knockout, gene replacement, base editing, trait improvement
Delivery in Plants	Requires transformation methods (e.g. Agrobacterium or particle bombardment) to introduce recombinase genes	Delivered via plasmids, Agrobacterium, RNPs, or virus-based vectors; some edits can be DNA-free (transgene-free)
Flexibility	High if sites are pre-inserted	Variable (depends on design, delivery, and repair pathway)
Applications	Gene cassette excision, conditional expression, transgene stabilization	Trait modification, genome editing, targeted mutagenesis

Types of site-specific nucleases

There are four types of site-specific nucleases- i) Meganucleases ii) Zinc finger nucleases (ZFNs) iii) Transcription activator like effector nucleases (TALENs) iv) CRISPR-Cas

- ***Meganucleases:*** Meganucleases, a rare class of endonucleases which recognise and cleave long DNA sequences ranging from 14-–30 base pairs. Their high specificity makes them powerful tools in gene editing. Originating from microbial sources like yeast and bacteriophages, meganucleases are naturally involved in intron and intein mobility. In gene editing, they induce double-strand breaks (DSBs) at specific genomic locations, which are repaired by the cell's mechanisms (NHEJ or HDR) leading to gene disruption or precise sequence insertion. Meganucleases' exceptional target specificity minimises off-target effects, but designing new ones for each target is complex and time-consuming.
- ***Zinc finger nucleases:*** Zinc finger nucleases (ZFNs) are engineered gene-editing tools that combine a DNA-binding zinc finger protein with the FokI endonuclease's cleavage domain. Each zinc finger domain recognises a specific three-base pair DNA sequence, and multiple domains can target longer sequences. When two ZFN construct bind opposite DNA strands at the target site, the FokI domains dimerize, creating a double-strand break (DSB). This activates the cell's repair pathways, leading to gene disruption or precise sequence modification. ZFNs, among the first programmable nucleases, have been applied in various crops, viz. for improving herbicide tolerance in maize and oil quality in soybean. Their high specificity, achieved through careful zinc finger domain design, is strength. However, developing effective ZFNs for new targets is labour-intensive and requires significant protein engineering expertise.
- ***Transcription activator like effector nucleases:*** Transcription Activator-Like Effector Nucleases (TALENs) are customizable gene-editing tools composed of two main parts: A DNA-binding domain derived from transcription activator-like effectors (TALEs) and a FokI nuclease domain that cuts DNA. Each TALE repeat binds to a single nucleotide, allowing researchers to design TALENs that target nearly any DNA sequence with high precision. To function, two TALENs bind to opposite strands of DNA flanking the target site. The FokI domains then dimerize to introduce a double-strand break (DSB) at the specified location. The cell repairs this break through either non-homologous end joining (NHEJ), which can disrupt genes, or homology-directed repair (HDR), which allows precise genetic changes. TALENs are known for their accuracy and versatility, with fewer off-target effects compared to earlier tools. However, TALENS mechanism of gene editing is costly, labour intensive and time consuming.
- ***CRISPR-Cas system:*** CRISPR-Cas is a gene-editing technology that allows scientists to make precise, targeted changes to the DNA of living organisms. The term CRISPR stands for Clustered Regularly Interspaced Short Palindromic Repeats, which are specific sequences found in the genomes of bacteria and archaea. These sequences are part of a natural defence mechanism used by microorganisms to identify and cut viral DNA during an infection. The Cas9 protein (short for CRISPR-associated protein 9) is an endonuclease enzyme that functions as molecular scissors. It cuts double-stranded DNA at locations defined by a guide RNA (gRNA), which is engineered to match a specific sequence of interest. When introduced into a cell, the CRISPR-Cas9 complex can locate the target DNA, introduce a double-strand break, and allow for gene modification through the cell's own repair pathways-typically non-homologous end joining (NHEJ) or homology-directed repair (HDR).This programmable system enables precise editing of genes and has wide applications in research, medicine, and biotechnology. Because of its efficiency, simplicity, and versatility compared to earlier tools like zinc finger nucleases (ZFNs) and TALENs, CRISPR-Cas9 has become the method of choice for many genetic engineering tasks.The importance of this discovery was recognized in 2020 when Doudna and Charpentier were awarded the Nobel Prize in Chemistry, marking a milestone in the history of genetic engineering. There are other Cas enzymes also like, Cas12a, which is a Type V enzyme that creates staggered DNA cuts and recognizes a T-rich PAM. Cas13 is a Type VI enzyme that targets and cleaves RNA molecules.

Mechanism in plants

CRISPR-Cas9, a system similar to its animal counterpart, enables precise genome editing in plants using RNA guidance. The guide RNA matches a specific target site in the plant genome, directing the Cas9 protein, an endonuclease from *Streptococcus pyogenes*, to the intended location. Once attached, Cas9 induces a double-strand break (DSB) at the targeted site.Plant cells activate their DNA repair machinery, employing non-homologous end joining (NHEJ) or homology-directed repair (HDR). NHEJ introduces small insertions or deletions (indels), potentially disrupting gene function, while HDR can introduce specific DNA sequences if a repair template is provided, enabling more precise gene insertions or replacements. Delivery of CRISPR-Cas9 components into plant cells poses a unique challenge. *Agrobacterium tumefaciens* mediated transformation is commonly used in dicotyledonous plants, while biolistic delivery, or the gene gun method, is used in monocots and recalcitrant species. The choice of delivery method depends on the plant species, the targeted tissue, and the desired outcome. CRISPR-Cas9 offers a powerful and precise tool for plant genetic engineering, revolutionising plant biology and crop improvement.

Key applications in plants

Crop yield enhancement: CRISPR-Cas9 can be used to enhance crop yield by targeting genes limiting grain size and improving fruit size.

Disease resistance: CRISPR-Cas9 confers disease resistance in crops by editing susceptibility genes, leading to resistance against diseases like powdery mildew and cassava brown streak virus or any other targeted disease.

Stress tolerance and nutrition: CRISPR-Cas9 enhances abiotic stress tolerance in crops and improves nutritional content by editing stress-response regulators and metabolic pathways.

Challenges in plant CRISPR applications

- ***Delivery efficiency:*** Unlike animal cells, plant cells have rigid walls, making gene delivery more difficult.
- ***Regulatory hurdles:*** Many countries have complex laws regarding genome-edited crops; some regulate CRISPR-modified crops similarly to GMOs.
- ***Off-Target effects:*** Although rare, unintended mutations are a concern, especially in polyploid species.
- ***Multi gene copy:*** In many crops like wheat, there may be more than one gene copy for one trait which makes it difficult to edit all copies.

Future perspectives

Advancements in genome editing, like CRISPR-Cas12a, base editing, and prime editing, significantly improve precision and efficiency in plant genome engineering. Unlike CRISPR-Cas9, these newer tools enable precise gene modifications without DSBs, reducing the risk of off-target effects and unintended mutations. CRISPR-Cas12a has a unique PAM recognition and staggered cuts, making it suitable for targeting inaccessible genomic regions and multiplex editing with higher specificity. Base editing directly converts one DNA base to another, correcting single-nucleotide polymorphisms or introducing subtle variations. Prime editing, often called a "search-and-replace" tool, combines a catalytically impaired Cas9 with a reverse transcriptase, enabling precise insertions, deletions, and substitutions without donor templates or DSBs. Integrating these technologies with high-throughput phenotyping, artificial intelligence, and epigenome editing will create climate-smart and resource-efficient crops. Breeders will gain access to traits like nitrogen-use efficiency, improved photosynthesis, and abiotic stress tolerance. Innovations in delivery systems, like nanocarriers or DNA-free genome editing, could address regulatory challenges and public concerns related to genetically modified organisms (GMOs).

SUMMARY

CRISPR-Cas9 has revolutionised plant genetics by offering a precise, cost-effective, and adaptable genome editing platform. Its successful implementation across various plant species has opened new avenues for addressing global agricultural challenges. As climate change, soil degradation, limited arable land, and population growth pose significant threats, genome editing tools provide a strategic solution for enhancing crop resilience, yield, and nutritional quality. Next-generation gene editing tools offer more refined, safe, and predictable genome modifications, paving the way for sustainable and resilient crops that reduce agrochemical dependence and improve food security in a changing climate. However, responsible and equitable use of these powerful tools requires interdisciplinary research, robust biosafety frameworks, and transparent public engagement.

*Corresponding author email: anitadgr13@gmail.com

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Nature-based solutions with ecosystem services gains for managing saline waterlogged landscapes in semi-arid regions

R. Banyal* and Varun Saini

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Soil salinity and waterlogging are major land degradation challenges, particularly in arid and semi-arid regions, severely impacting agricultural productivity and ecological stability. In India, approximately 8.5 million hectares are affected, largely due to poorly managed irrigation systems lacking proper drainage. Bio-drainage, using deep-rooted trees to remove excess water through transpiration emerges as a sustainable, low-cost, and eco-friendly alternative to traditional drainage methods. Tree-based bio-remediation models, particularly those involving Eucalyptus tereticornis, Prosopis juliflora, Acacia nilotica, and Tamarix aphylla, have been successfully implemented across varying degrees of salinity and waterlogging. These models provide multiple ecosystem services: provisioning (fuelwood, timber, fodder), regulating (carbon sequestration, groundwater control, climate moderation), supporting (biodiversity enhancement, soil health), and cultural (aesthetic and recreational value). Eucalyptus-based models in moderately affected areas demonstrated the highest biomass yield, carbon sequestration, and microclimate regulation. Despite these benefits, cultural services and social values remain under-researched. For broader adoption, future strategies should emphasize ecosystem service valuation, community participation, and location-specific species selection to ensure long-term sustainability and resilience of saline waterlogged landscapes.

Keywords: Agroforestry, Ecological restoration, Groundwater management, Soil salinity, Waterlogging

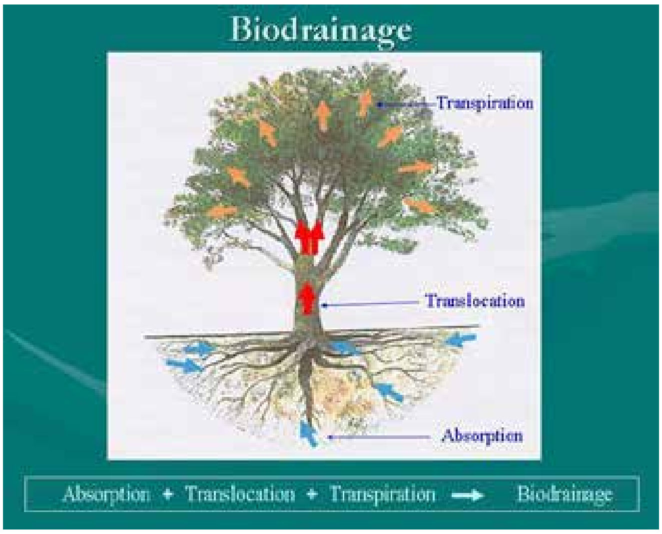
SOIL salinity and waterlogging are major forms of land degradation that threaten agricultural productivity and ecological stability, particularly in arid and semi-arid regions. Globally, about 33% of irrigated land, nearly 1.0 billion hectares is affected by these twin issues. In India, around 8.5 million hectares of lands are impacted, including 5.5 million ha with combined salinity and waterlogging problems, approximately 2.3 million ha each within and outside canal command areas. Primary cause is the introduction of irrigation systems without proper drainage. States such as Haryana, Maharashtra, Gujarat, Odisha, Uttar Pradesh, Punjab, West Bengal, Bihar, Andhra Pradesh, Tamil Nadu, Rajasthan, and Kerala are significantly affected. Waterlogging severity is defined by groundwater depth potentially waterlogged (≤3 m), waterlogged (≤1.5 m), and severely waterlogged (0–30 cm). Traditional drainage methods, though effective, are capital-intensive and raise environmental concerns. In contrast, bio-drainage offers a cost-effective, low-input, and eco-friendly solution. Nature-based bio-remediation strategies, including agroforestry, have shown promise in managing saline waterlogged areas by providing both reclamation and a range of ecosystem services.

Bio-drainage as a solution for saline waterlogged areas

Bio-drainage is the process by which deep-rooted plants use their bio-energy to absorb excess soil water and release it into the atmosphere through transpiration. While primarily explored for water table control, bio-drainage also offers both curative and preventive applications. However, its economic viability and the broader benefits, including tangible and ecosystem services, remain largely unexamined in current literature.

Tree based bio-remediation models

Tree-based models using *Eucalyptus tereticornis, Prosopis juliflora, Acacia nilotica,* and *Tamarix aphylla* were adopted across saline waterlogged areas, with species distribution varying by salinity severity. *Eucalyptus* thrived in less to moderately affected areas, while *Prosopis, Acacia,* and *Tamarix* were suited to severely impacted




Eucalyptus in block model

areas. In less affected regions, boundary plantations (1.5–2.0 m spacing) were common, transitioning to block plantations (1.0 × 3.0 m) in moderately affected areas. Severely affected zones lacked structured planting geometry. Block and boundary models were widely used in such conditions. Block plantations followed spacings of 1.5 × 3.0 m, 1.5 × 4.0 m, or 1.5 × 6.0 m, while boundary models employed single-row planting at 1.5 m spacing and strip plantations with 1.5 × 2.0 m (parallel rows) or 1.5 × 1.5 m (staggered rows).

Ecosystem services associated with bio-drainage models in saline waterlogged areas

There is no universally accepted typology of ecosystem services, but they are broadly understood as the benefits humans derive from ecosystems. These services are categorized into four types: provisioning, regulating, supporting, and cultural. Tree-based bio-remediation models on waterlogged saline soils offer multiple benefits, including food, fodder, fuelwood, and income. Through leaf litter and root decomposition, they improve soil health, sequester carbon, moderate the local climate, and enhance landscape aesthetics. These are part of a broader range of ecosystem services delivered by tree-based land uses.

Provisioning services: Plantations in saline waterlogged areas provide vital services such as food, fodder, fuel, fibre, and timber. *Eucalyptus tereticornis* based bio-drainage model yielded up to 28.65 Mg/ha of timber and 1.84 Mg/ha of fuelwood.Total biomass (above and below ground) ranged from 102 to 186 Mg/ha, outperforming other species. *Eucalyptus* based models on moderately saline and waterlogged sites produced 30 Mg/ha of biomass which was 62.3% and 84.5% higher than those on less and severely affected areas in Haryana, respectively.

Regulating services: Trees planted for bio-drainage play a significant role in climate change mitigation through carbon sequestration and groundwater regulation. *Eucalyptus globulus* has been reported to sequester 3.3 to 11.5 Mg C/ha/yr over 10 years, while *Eucalyptus tereticornis* on saline waterlogged soils accumulated 15.5 Mg C/ha in 5 years. It was found that agroforestry systems on waterlogged soils sequestered 15.82 Mg C/ha and 58.03 Mg CO_2/ha, and bio-saline systems captured 6 Mg CO_2 eq./ha. Groundwater drawdown of up to 15.7 m was recorded under plantations, with *Acacia mangium* and *Casuarina* systems lowering water levels by 3.2 m. Additionally, tree canopies moderate microclimates, reducing


Eucalyptus in boundary model


Sporadic trees in waterlogged saline soil

summer temperatures by 2–4°C and slightly raising them in winter. Species like *Dalbergia sissoo* and *Casuarina equisetifolia* enhance soil nutrient availability (NPK) through improved litter decomposition. Bio-remediation models in these areas can help in reduction of greenhouse gas emissions. *Eucalyptus* based bio-remediation models in moderately saline waterlogged areas showed superior regulating services, including higher carbon stock, carbon sequestration, and better regulation of air and soil temperatures. The greenhouse gas (GHG) emissions were reduced under tree canopies, with the lowest CO_2 flux observed in *Eucalyptus* models at moderately affected sites, lowest N_2O flux in isolated tree models at severely affected sites, and lowest CH_4 flux in *Eucalyptus* models at less affected sites. Soil properties were comparatively better in less affected sites, declining with increasing salinity and waterlogging. Higher ECe values were observed under isolated tree based models, particularly in the topsoil (0–15 cm). Soil organic carbon (SOC) was highest under *Eucalyptus* (boundary) models in less affected areas (0.33%) and block models in moderately affected areas. Available nitrogen and potassium were generally low, while phosphorus remained in the medium range. *Eucalyptus* based models in moderately affected site gave higher soil microbial count (MBC) values than *Eucalyptus* based models in less and isolated tree based models in severely affected sites.

Supporting services: Biodiversity studies in saline waterlogged areas are limited, but it is well established that tree plantations in such regions support key ecosystem services. *Eucalyptus* based models on moderately affected sites showed higher site stability (Shannon-Wiener index) and plant diversity (Simpson's index). *Eucalyptus* emerged as the dominant species across all less, moderately and severely affected sites, contributing 93%, 67%, and 82% of the total basal area, respectively.

Cultural services: Cultural ecosystem services, non-material benefits such as spiritual, cognitive, recreational, and aesthetic experiences are often difficult to quantify despite being well recognized. A pilot study in saline waterlogged areas of Haryana found that tree-based land use systems (LUS) offered the highest cultural services (aesthetics and social recreation), while fallow lands recorded the lowest. Cultural services were found to be more prominent in Eucalyptusbased models on less affected sites, and comparatively lower in isolated trees on severely affected sites. Despite these insights, cultural services remain underrepresented in the available literature and merit further research.

SUMMARY

Saline and waterlogged soils threaten agricultural sustainability, especially in poorly drained in-land irrigated areas. Bio-drainage, using deep-rooted tree species to remove excess water through transpiration, offers a costeffective and eco-friendly solution. Tree based bio-drainage models support land reclamation while delivering a range of ecosystem services viz. provisioning, regulating, supporting, and cultural. *Eucalyptus* based models particularly in moderately affected areas have shown high biomass yields and ecosystem benefits. However, cultural and social values of such systems remain underexplored. Future efforts should prioritize holistic ecosystem valuation, community involvement, and site-specific species selection to enhance the sustainability and acceptance of these models in managing saline waterlogged landscapes.

*Corresponding author email: drbanyal08@gmail.com

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Understanding the adverse effects of salinity on lentil growth: Mechanisms and responses

Vijayata Singh* and Jogendra Singh

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Salinity is a major abiotic stress that significantly impairs lentil (Lens culinaris Medik.) *growth, development, and productivity, especially in arid and semi-arid regions. This chapter provides a comprehensive overview of the physiological, biochemical, molecular, and agronomic responses of lentil to salinity stress. Salinity disrupts lentil growth at all stages- germination, vegetative, and reproductive- through osmotic stress, ion toxicity, and nutrient imbalances. Plants respond by accumulating osmoprotectants like proline and glycine betaine, activating antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), and modifying photosynthetic and ionic regulation mechanisms. Advanced understanding of salt tolerance is facilitated by transcriptomics, proteomics, metabolomics, and ionomics, identifying stress-responsive genes, proteins, and metabolites. Breeding efforts involving wild relatives, marker-assisted selection (MAS), and genome-wide association studies (GWAS) are underway, complemented by transgenic and genome editing tools. Integration of high-throughput phenotyping and agronomic practices, such as seed priming and soil amendments, holds promise for developing salt-tolerant lentil varieties. The article underscores a multidisciplinary approach to enhance lentil resilience under salinity for sustainable pulse production.*

Keywords: Antioxidant enzymes, Ion toxicity, Lentil, Osmotic stress

LENTIL (*Lens culinaris* Medik.) is a self-pollinated diploid legume (2n = 2x = 14) that plays a significant role in sustainable agriculture due to its ability to fix atmospheric nitrogen. As a rich source of protein (20–30%), minerals, and dietary fiber, lentil is crucial in the diet of millions, especially in South Asia and the Mediterranean region. However, salinity is a major abiotic stress limiting lentil productivity in arid and semi-arid regions, where soil and water salinization are becoming widespread due to climate change, poor irrigation practices, and high evapotranspiration rates. Salinity affects more than 20% of irrigated agricultural land worldwide, posing a serious challenge to global food security. Lentil, being moderately salt-sensitive, exhibits considerable variation in its tolerance across genotypes. Understanding the physiological, biochemical, and molecular responses of lentil to salt stress is essential for identifying resilient cultivars. In addition, the integration of conventional breeding with modern biotechnological tools offers promising strategies for improving lentil's salinity tolerance. A comprehensive evaluation of lentil performance under salt stress is crucial for designing effective breeding programmes aimed at sustaining yield in salt-affected areas.

Impact of salinity on lentil growth and development

Salinity stress is one of the most detrimental abiotic factors affecting lentil productivity, especially in arid and semi-arid regions where soil salinization is exacerbated by poor irrigation management and climate change. Salt stress disrupts physiological and metabolic functions in lentil at all developmental stages from germination to seed filling, ultimately leading to reduced plant vigour and significant yield losses. Salt stress adversely affects lentil growth at all stages, from germination to pod formation and seed filling. The primary mechanisms include osmotic stress, ion toxicity (mainly Na^+ and Cl^-), and nutritional imbalance, leading to poor germination, stunted growth, reduced nodulation, chlorosis, and ultimately lower yields. High salt concentrations reduce water uptake, disturb hormonal balances, and impair photosynthesis due to stomatal closure and chlorophyll degradation.

Germination under saline conditions is particularly sensitive. Seedlings exposed to electrical conductivity (EC) levels above 6 dS/m show drastic reductions in root and shoot length, fresh and dry weight, and vigour index.

Germination and early seedling growth: The germination stage is highly vulnerable to salinity. Saline soils lead to increased osmotic potential of the soil solution, making it difficult for seeds to absorb water, thereby delaying or inhibiting germination. Furthermore, ion toxicity, particularly from Na^+ and Cl^-, damages embryonic tissues and inhibits enzymatic activities essential for seed metabolism studies have shown that electrical conductivity (EC) levels exceeding 6 dS/m significantly impair germination parameters in lentil. Seedlings subjected to high salinity demonstrate:

- Decreased germination percentage
- Reduced root and shoot lengths
- Lower fresh and dry biomass
- Declined vigour index

Vegetative growth: During the vegetative phase, salinity causes stunted plant growth due to inhibited cell expansion and division. Ion toxicity results in chlorosis (yellowing of leaves) and necrosis due to oxidative stress and nutrient imbalances. Salt stress often induces a deficiency of essential nutrients such as K^+, Ca^{2+}, and Mg^{2+} by competitive inhibition with Na^+ and Cl^-. This imbalance interferes with metabolic activities and reduces photosynthetic capacity. Key effects observed include:

- Shortened internodes and plant height
- Reduced number of leaves and leaf area
- Disturbed water relations and turgor maintenance
- Impaired nodulation and nitrogen fixation, affecting overall plant nutrition

Reproductive development: Salt stress adversely affects flowering, pod formation, and seed filling, which are critical for yield determination. The hormonal imbalance under stress, particularly altered levels of auxins, cytokinins, and abscisic acid (ABA), leads to flower and pod abortion, reduced pollen viability, and poor fertilization. Salinity-induced stress during reproductive stages results in:

- Delayed flowering and maturity
- Reduced number of pods per plant
- Lower seed set and smaller seeds
- Poor seed quality (protein and micronutrient content)

Physiological and biochemical disruptions: High salt concentrations affect key physiological processes:

- Photosynthesis inhibition due to chlorophyll degradation and stomatal closure
- Decreased relative water content (RWC) and water use efficiency (WUE)
- Altered enzyme activities and energy metabolism
- Oxidative stress from reactive oxygen species (ROS), leading to membrane damage

These combined effects significantly compromise lentil productivity under saline conditions.

Physiological and biochemical responses

Salt stress profoundly affects the physiological and biochemical processes of lentil, disrupting normal metabolic functions and leading to growth retardation and yield loss. Plants under saline conditions experience both osmotic stress and ionic stress, which collectively impair essential physiological activities. Under salt stress, lentil plants accumulate osmolytes such as proline, glycine betaine, and soluble sugars to maintain osmotic balance. Increased antioxidant enzyme activity, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), helps mitigate oxidative stress induced by reactive oxygen species (ROS). Photosynthetic efficiency decreases significantly under salinity, with reduced chlorophyll content, disturbed gas exchange parameters (e.g. net photosynthetic rate, stomatal conductance), and altered chlorophyll fluorescence (Fv/Fm), indicating stress-induced damage to the photosystem II (PSII).

Osmolyte accumulation: One of the primary adaptive responses of lentil to salinity is the accumulation of osmoprotectants or compatible solutes, such as proline, glycine betaine, and soluble sugars. These low molecular weight compounds contribute to maintaining cellular osmotic balance, protecting macromolecules and membranes, and stabilizing proteins and enzymes under stress conditions. Among these, proline plays a particularly crucial role in osmotic adjustment, ROS scavenging, membrane stabilization, and signaling for stress responses. Glycine betaine helps protect the photosynthetic apparatus and maintain chloroplast integrity, while soluble sugars serve as both osmolytes and signaling molecules influencing stress gene expression.

Antioxidant defense mechanism: Salt stress triggers the overproduction of reactive oxygen species (ROS) such as superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH^-), which cause oxidative damage to cellular structures. To mitigate this oxidative damage, lentil plants activate an enzymatic antioxidant defense system comprising:

- **Superoxide dismutase (SOD):** Catalyzes the dismutation of superoxide radicals into hydrogen peroxide and oxygen.
- **Catalase (CAT):** Decomposes hydrogen peroxide into water and oxygen, thus preventing H_2O_2 accumulation.
- **Peroxidases (POD):** Help detoxify peroxides using various electron donors.

This enhanced antioxidant activity is vital for maintaining cellular redox homeostasis and protecting the integrity of cellular components under salinity stress.

Photosynthetic impairment: Salinity also negatively impacts photosynthesis, which is a central physiological process directly linked to plant productivity. Key photosynthetic responses under salt stress include:

- **Reduced chlorophyll content:** Due to degradation of chlorophyll pigments or inhibited chlorophyll biosynthesis, resulting in chlorosis and reduced light-harvesting capacity.

- **Disturbed gas exchange:** Decline in net photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate, primarily due to stomatal closure aimed at conserving water under osmotic stress.
- **Altered chlorophyll fluorescence parameters (Fv/Fm):** Indicating photo inhibition and damage to Photosystem II (PSII), a critical site for light energy conversion in the thylakoid membrane.

These impairments collectively lead to reduced carbon assimilation, growth, and eventually lower biomass and yield.

Ion homeostasis and membrane stability: Under salinity stress, lentil plants experience ion toxicity, primarily due to the accumulation of Na^+ and Cl^- ions in tissues, which disrupt the K^+/Na^+ balance and enzyme function. Salt-tolerant genotypes exhibit better ability to exclude Na^+, maintain higher K^+ levels, and restrict ion transport to shoots. Additionally, these genotypes demonstrate enhanced membrane stability, often assessed by parameters such as electrolyte leakage and lipid peroxidation, with lower levels indicating stronger cell membrane integrity under stress.

Molecular and genetic mechanisms: Salinity tolerance in lentil is a quantitative trait governed by multiple genes, including those involved in ion transport, osmotic regulation, and transcriptional regulation. Genes such as NHX1 (Na^+/H^+ antiporter), SOS1, HKT1, and P5CS (Δ1-pyrroline-5-carboxylate synthetase) have been studied for their roles in ion compartmentalization and proline biosynthesis under salt stress.

Transcriptome studies under salt stress have identified differentially expressed genes associated with stress signaling pathways, hormone metabolism, and transcription factors such as MYB, bZIP, NAC, and WRKY. These gene families modulate various downstream responses for cellular protection and adaptation.

Screening and breeding for salt tolerance

Conventional screening methods in lentil involve evaluating germplasm in hydroponics, sand culture, and saline field conditions for traits like germination rate, seedling vigour, Na^+/K^+ ratio, biomass, and yield components. Several landraces and wild relatives (e.g. *Lens orientalis, Lens ervoides*) have shown promise for salt tolerance and can be used in pre-breeding programmes. These wild species often possess adaptive traits such as efficient ion homeostasis, deeper root architecture, and higher antioxidant enzyme activities. To ensure reliable phenotyping, multi-environment trials and standardized protocols are crucial for identifying stable, high-performing genotypes. Controlled screening under simulated salt conditions allows for early-stage selection, reducing field-level variability. Integration of high-throughput phenotyping tools, such as imaging and chlorophyll fluorescence sensors, is enhancing the precision of salt tolerance screening.

Molecular markers (e.g. SSRs, SNPs) linked to salt-tolerance QTLs have been identified, though, limited compared to major crops. Genomic-assisted breeding using marker-assisted selection (MAS) and genome-wide association studies (GWAS) is still emerging for lentil.

Biotechnological and omics approaches

Biotechnological interventions offer promising tools for dissecting and enhancing salt tolerance. Genetic transformation studies introducing AtNHX1, BADH, or P5CS genes in lentil have improved salt tolerance, though stable transformation remains challenging due to genotype dependency and low transformation efficiency.'Omics' approaches, such as transcriptomics, proteomics, metabolomics, and ionomics, provide system-level insights into stress responses. Integration of multi-omics datasets is facilitating the identification of candidate genes and molecular pathways involved in salinity tolerance in lentil. Salinity stress exerts a significant negative impact on lentil productivity by disrupting physiological, biochemical, and molecular processes such as osmotic balance, nutrient uptake, photosynthesis, and antioxidant defense. Conventional breeding for salt tolerance has been limited by complex inheritance patterns, polygenic control, and genotype-environment interactions. In this context, biotechnological and 'omics'-based tools provide novel avenues for understanding and enhancing salt tolerance in lentils.

Biotechnological interventions: Genetic engineering has enabled the functional characterization and transfer of stress-responsive genes from model systems into lentils and other legumes. Some key transgenic strategies employed include:

- Overexpression of AtNHX1 (Arabidopsis Na^+/H^+ antiporter) gene, which mediates vacuolar sequestration of excess Na^+ ions, thereby improving cellular ion homeostasis under salinity stress.
- BADH (betaine aldehyde dehydrogenase), which catalyzes the synthesis of glycine betaine, an osmoprotectant, has been introduced into lentil and chickpea to improve osmotic adjustment under saline conditions.
- P5CS (Δ^1-pyrroline-5-carboxylate synthetase), involved in proline biosynthesis, enhances osmotic tolerance and antioxidant defense when overexpressed in legumes.

Although such transgenic approaches show promising physiological improvements (e.g. better chlorophyll retention, higher K^+/Na^+ ratio, and increased yield under salt stress), stable transformation of lentil remains a major bottleneck, owing to genotype dependency, low regeneration frequency, and poor transformation efficiency. Hence, there is a need to optimize tissue culture protocols and explore genome editing tools such as CRISPR/Cas9 for more targeted and efficient genetic manipulation.

Omics approaches: The rapid development of high-throughput omics technologies has revolutionized plant stress biology by enabling a system-level understanding of complex traits like salinity tolerance. In lentil, multiple omics approaches are being integrated to identify stress-responsive genes, proteins, metabolites, and ionomic signatures:

- **Transcriptomics:** RNA-seq studies have revealed differentially expressed genes (DEGs) related to ion transporters (NHX, SOS1), transcription factors (DREB, WRKY, NAC), and antioxidant enzymes under salinity stress in salt-tolerant vs. sensitive lentil genotypes. These data form the basis for marker development and candidate gene selection.
- **Proteomics:** Protein profiling under salt stress has identified upregulated proteins related to ROS detoxification (e.g. superoxide dismutase, peroxidase), photosynthesis, and chaperones (e.g. HSPs), supporting enhanced cellular protection mechanisms.
- **Metabolomics:** Metabolite profiling has detected higher accumulation of compatible solutes like proline, sugars, and polyols in tolerant genotypes. These metabolites help in osmotic adjustment, ROS scavenging, and maintaining membrane integrity under saline conditions.
- **Ionomics:** Ionomic analyses reveal the ability of tolerant genotypes to exclude Na^+, maintain high K^+/Na^+ ratios, and accumulate beneficial ions like Ca^{2+} and Mg^{2+}, indicating efficient ion homeostasis and signalling.

Multi-omics integration

Recent advances now allow integration of transcriptomic, proteomic, metabolomic, and ionomic datasets, enabling the construction of gene regulatory networks and the identification of hub genes or master regulators. Such integrative omics approaches are essential for the discovery of novel molecular markers, QTLs, and biotechnological targets for lentil improvement under salinity.

Tools like WGCNA (Weighted Gene Co-expression Network Analysis) and machine learning algorithms are being used to correlate molecular data with physiological traits, making omics-guided breeding more precise and effective.

Management strategies and agronomic practices

Agronomic strategies can complement genetic approaches to mitigate salt stress in lentil. These include:

- ***Soil amendments:*** Gypsum and organic matter to improve soil structure and reduce Na^+ toxicity.
- ***Seed priming:*** Using salt solutions, hormones (GA_3, SA), or osmoprotectants (proline, PEG) improves germination and early growth under salt stress.
- ***Irrigation management:*** Using saline water judiciously with proper leaching and drainage.
- ***Crop rotation:*** Including salt-tolerant crops like barley can reduce salt accumulation.

Integrated management combining tolerant genotypes with improved agronomy holds the key for sustaining lentil production in saline soils.

SUMMARY

Salt stress poses a significant threat to lentil production globally. Advances in genomics, transcriptomics, and high-throughput phenotyping are paving the way for dissecting complex salt-tolerance traits. Developing multi-stress-resilient lentil varieties through integrated breeding and biotechnological tools, along with farmer-friendly agronomic practices, will ensure sustainable lentil production in the face of increasing soil salinization.

*Corresponding author email: vijayatasingh.gpb@gmail.com

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Remote sensing applications in monitoring

and management of soil and water pollution

Krishan Kanahiya*, Parul Sundha and D. S. Bundela

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Pollution of soil and water is major problem all around the world that effects the condition of ecosystem, agricultural productivity and well-being of human lifestyles. Traditionally, tracking and managing these problems require a lotof fieldwork, which can be laborious, time consuming and has limited both spatial and geographical coverage. A useful alternative is remote sensing, offers a promising alternative by making it possible to gather data from multiple sensors on a large scale and frequently. This article addresses the newest developments, methods and data types in the field of remote sensing, which investigates how remote sensing can be used to track and control soil and water pollution.

Keywords: Ecosystem, Remote sensing, Soil and water pollution, Tracking

INDIA has achieved tremendous progress in remote sensing technology, with numerous centres and organization devoted towards the applications, research and policy creation in this area. The supreme institute for space organization for space research is Indian Space Research Organisation (ISRO). It runs a huge network of earth observation satellite, which include CartoSat, ResourseSat and RISAT series, offer useful information for tracking the soil and water pollution. Its subsidiary organisations like National remote sensing centre (NRSC), Hyderabad and Indian Institution of Remote Sensing (IIRS), Dehradun play a crucial role for development of satellites and carrying out capacity-building initiatives. The Northern Space Application centre (NESAC) covers the specific requirements of the northeast region, whereas the Ahmedabad based space application centre (SAC) emphasized on sensor development. Remote sensing technology also used in research institute and agricultural universities like Central Soil Salinity Research Institute (CSSRI), Karnal and Chaudhary Charan Singh Haryana Agricultural University (CCS HAU), Karnal to investigate the water quality and salinity parameters including estimation of areas under salt-affected soils. Organization such National Institute of Hydrology (NIH), Roorkee and Central Water Commission (CWC) utilize leverage satellite data for hydrological modelling and real-time pollution monitoring.

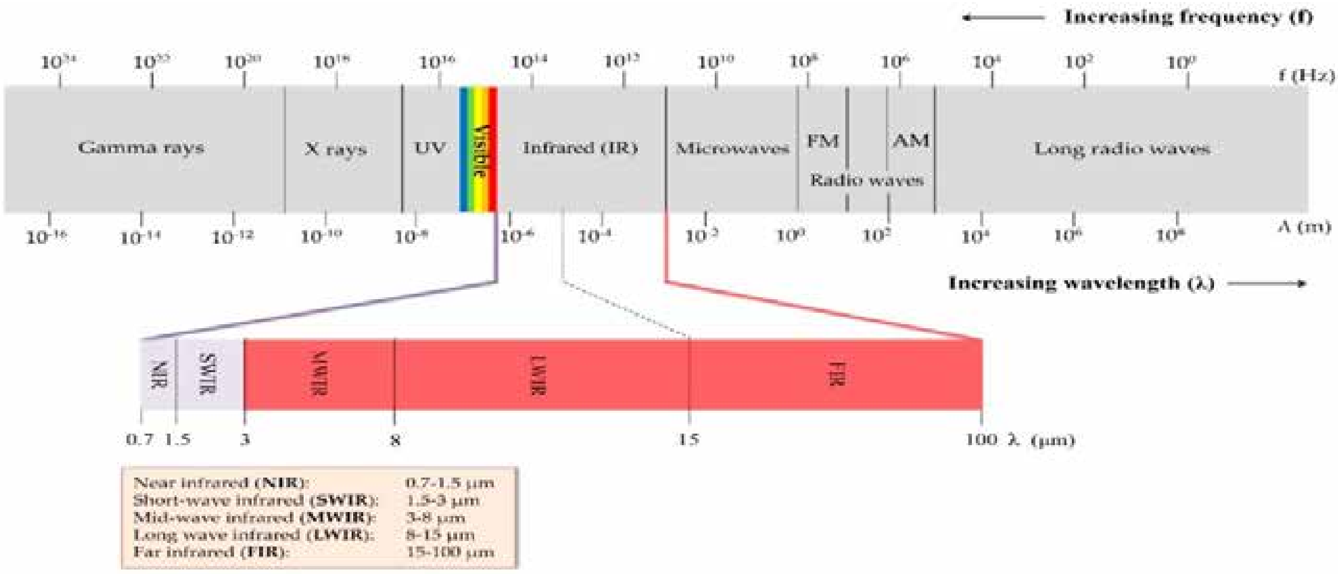
Principles of remote sensing in pollution monitoring

Remote sensing (RS) is a technique that collects data regarding the Earth's surface from afar, utilizing sensors affixed to satellites, airplanes and drones. It is based on detection and analysing electromagnetic energy that is absorbed or released by objects. Specific spectral patterns linked with pollutants or environmental changes may be helpful in the detection and quantification of soil and water contamination levels. Remote sensing collects hyperspectral, thermal and multi-spectral data that may be examined and processed for recognizing pollution anomalies.

Types of remote sensing data for pollution monitoring

Different data types are used in remote sensing applications for pollution monitoring, which have specific advantages to identify soil and water contaminations.

- ***Optical data:*** Visible and near infrared (VNIR) and shortwave infrared (SWIR) which have a wavelength (450—1350 nm) can be used to detect data for identifying vegetation indices, some soil contaminants and sedimentation. Amount of reflected sunlight captured by these sensors which changes according to the type and level of contaminants present.



Source: Image taken from: The basics of the electromagnetic spectrum: https://leadertechinc.com/basics-electromagnetic-spectrum/

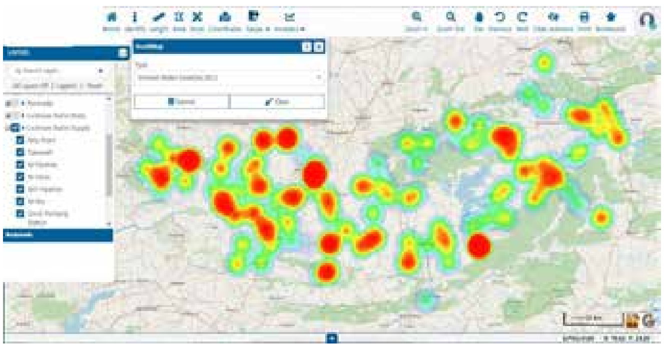
This figure explain the electromagnetic spectrum with different wavelength and frequency, which are used in remote sensing applications for examining the surface characteristics of vegetation indices and thermal radiation.

- ***Thermal infrared (TIR) data:*** It detects temperature irregularities in water bodies that could be caused by thermal pollution or industrial effluent. When soil moisture or temperature characteristics changes, thermal infrared data identifies the organic pollution.
- ***Microwave and radar data:*** Synthetic Aperture Radar (SAR) and other microwave sensors can penetrate the cloud cover to gather information on soil moisture and structural changes in the terrain, which could point to chemical spills or other disruptions.

Applications of remote sensing in soil pollution monitoring and management

Remote sensing has numerous important applications that allows us for detection, tracking and manage soil pollution:

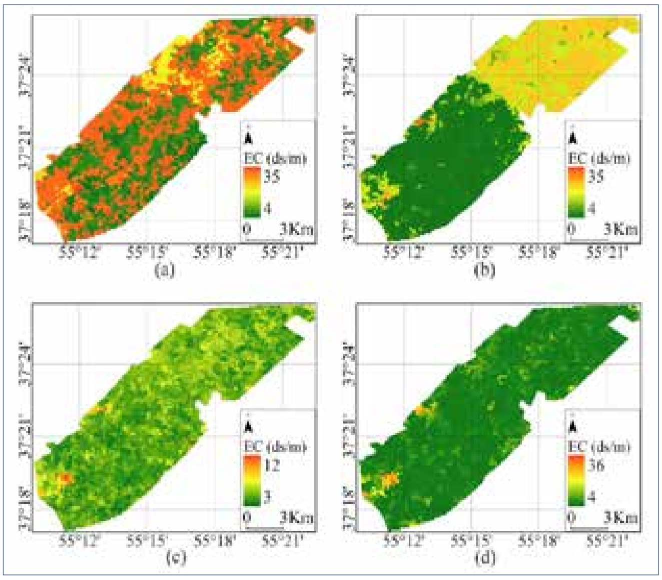
- ***Heavy metals and contaminants detection:*** Remote sensing can identify spectrum variations in soils that include heavy metals contaminants like cadmium, arsenic and lead. For this purpose, hyperspectral imaging work especially well because it can records wider spectrum of wavelengths. In particular, Sentinel-2 and Landsat imagery have been used to recognize unique spectral patterns of contaminated soils.



Source: Image adopted from role of geo-spatial technology (GIS) in water resource management:https://www.sgligis.com/gis-for-water-resource/

On the image, groundwater level monitoring using RS and GIS methods, red spots on the heatmap illustrates the critically low water levels, most likely as a result of pollution or over-extraction, while green spots denoting stable levels. These kind of visualizations are curtail for pinpointing the hotspot for groundwater stress and directing effective water resource management and pollution reduction strategies.

- ***Estimating the soil salinity:*** One common type of soil contamination that has a direct effect on agricultural productivity is soil salinity. Large-scale mapping and assessment of salinity levels are made with the help of remote sensing techniques, including those which evaluate reflectance pattern



Source: Image adopted from Scientific reports: A longitudinal analysis of soil salinity changes using remotely sensed imageries: https://www.nature.com/articles/s41598-024-60033-6 in visible and near infrared (VNIR) and shortwave infrared (SWIR) electromagnetic spectrum.

The figure represents the spatial distribution maps of soil electrical conductivity (ds/m). The colour gradient of map (a,b,c, and d) from green (low salinity), to red (high salinity) shows changes in the EC throughout the research area. These results illustrate how well satellite imagery helps to identify and monitor soil salinity at regional scales, supporting ecological management and precision farming.

- ***Monitoring agricultural runoff:*** Soil and water pollution can result in excessive use of fertilizer, pesticides and weedicides. By employing vegetation indices such as Normalised Difference Vegetation index (NDVI) to monitor the crop stress brought on by chemical usage or excessive nutrients, remote Sensing is able to track and detect the expansion of chemical contaminants from agricultural runoff.

Applications of remote sensing in water pollution monitoring and management

Remote sensing proposes numerous approaches to examine water quality, identify pollutants, and assess the ecological effects of water pollution:

- ***Observing suspended solids and turbidity:*** Higher level of suspended solids and turbidity often indicate water pollution from residue runoff, industrial discharges, or algal blooms. Remote sensors like MODIS and Landsat can monitor changes in water reflectance, helping perceive turbidity levels.
- ***Algal bloom detection:*** Harmful algal blooms (HABs) are a significant water pollution issue, often triggered by excessive nutrient runoff. Remote sensing can detect algal blooms and track their spread and severity by analyzing chlorophyll from satellite imagery.
- ***Revealing of organic and chemical pollutants:*** With the help of thermal and hyperspectral sensors certain pollutants can be identified due to their change in the thermal and spectral properties of water. Remote sensing not only track temperature anomalies but also indicates potential thermal pollution and water waste expulsion.
- ***Review of water quality parameters:*** Now a days, algorithms are developed to evaluate concentrations of turbidity, water quality indicators like chlorophyll-a, dissolved organic matter and many more of these parameters from satellite data, enabling real time monitoring

Advances in remote sensing technologies for pollution management

- ***Hyperspectral imaging:*** Advancement with time in hyperspectral sensors has provided high spectral resolution data, helping identification of precise pollutants and contamination types. With increase in spatial resolution the opportunity of hyperspectral imaging in distinguishing heavy metals and other pollutants is more precised.
- ***Unmanned aerial vehicles (UAVs):*** Drones equipped with high-resolution sensors are revolutionizing localized pollution monitoring by offering greater flexibility in data collection and enabling coverage of areas that satellites cannot reach.
- ***Machine learning in image processing:*** Introduction of artificial intelligence in remote sensing has significantly improved the accuracy of pollution detection in water. For instance, algorithms like Random Forest, Convolutional Neural Networks (CNNs) are being used to classify contaminated soils, map water quality, and assess pollution impacts.

SUMMARY

The monitoring and control of soil and water contamination through remote sensing, which provides an efficient and cost-effective method to access the environmental health on an extensive scale. Remote sensing is still developing and providing essential information for sustainable management and pollution control strategies from hyperspectral imaging to sophisticated machine learning algorithms. By combining remote sensing with field data and cutting-edge technologies, pollution problems can be managed more efficiently assisting with environmental protection and resource sustainability initiatives.

*Corresponding author email: krishantaneja24@gmail.com

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Mustard and salinity tolerance:

A resilient oilseed for the future

Archana Watts[1]*, Shaswati Sardar[1], Silky Gandhi[1], Anshul Watts[2], Pranjal Yadava[1], Soham Ray[1] and Shivani Nagar[1]

[1]*ICAR-Indian Agricultural Research Institute, New Delhi 110 012*
[2]*ICAR-National Institute of Plant Biotechnology, New Delhi 110 012*

Salinity is one of the major abiotic stresses limiting crop production and productivity, particularly in the arid and semi-arid regions of India. Indian mustard (Brassica juncea)*, a leading oilseed crop valued for its culinary and medicinal properties, is highly susceptible to salt stress, which causes significant yield losses. The adverse effects include reduced seed germination, stunted plant growth, decreased seed yield, and a decline in oil content. Exploring the genetic variation within mustard germplasm offers opportunities for developing salt-tolerant cultivars. A comprehensive understanding of morphological, physiological, and molecular mechanisms underlying salt tolerance is crucial for this purpose. Strategies such as exploiting existing germplasm, adopting improved breeding techniques, implementing effective agronomic practices, and applying advanced technologies like genome editing hold great potential for enhancing salt tolerance in mustard. Integration of conventional breeding with modern genomic tools and genome-editing approaches will facilitate the identification and functional validation of key candidate genes and regulatory networks, thereby accelerating the development of resilient mustard cultivars for saline environments.*

Keywords: Crop improvement, Genome editing, Indian mustard, Salinity stress, Salt tolerance mechanism

INDIAN mustard (*Brassica juncea*) is one of the major oilseed crops of India, valued for its high demand in edible oil production. It offers significant nutritional and economic benefits and remains a preferred cooking oil in eastern India, including the states of Bihar, West Bengal, Odisha, Jharkhand, as well as Rajasthan, Punjab, and Madhya Pradesh. Edible oils derived from Indian mustard contribute approximately 27.8% to the country's total oilseed economy. Despite its versatile applications and substantial contribution to India's agricultural economy, the nation continues to rely on the import of edible oils. This dependence is primarily attributed to the low productivity of mustard crops, which suffer significant yield losses due to abiotic stresses driven by changing climatic conditions and deteriorating soil health. Among these challenges, soil salinity poses a serious constraint, particularly in regions with low annual rainfall, poor-quality irrigation, and suboptimal land management practices. Salinity adversely affects mustard by impairing seed germination, vegetative growth, photosynthetic efficiency, lipid accumulation, ultimately reducing seed yield and oil quality. To address this issue, salt-tolerant varieties such as CS60 and CS58 have been developed by ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI), Karnal. These genotypes have demonstrated superior seed and oil yields compared to other widely cultivated varieties like CS54, Kranti, and Giriraj under saline conditions.

Given the escalating problem of soil salinization, exacerbated by climate change, unsustainable irrigation practices, and excessive fertilizer application, it is imperative to investigate the physiological, biochemical, and molecular mechanisms underlying salinity tolerance in mustard. Such insights will be pivotal for developing improved, climate-resilient cultivars capable of sustaining productivity in salt-affected agro-ecosystems.

Impact of salinity on mustard cultivation

Soil salinity is a major constraint affecting the productivity of Indian mustard crops, particularly in poorly irrigated, arid, and semi-arid regions. It results from the excessive accumulation of soluble salts, primarily sodium chloride (NaCl), in the soil. Saline soils are characterized by elevated concentrations of various salts, including sodium, calcium, magnesium, potassium, carbonates, bicarbonates, chlorides, sulphates, borates, and lithium compounds.

The excessive build-up of these salts disrupts plant water uptake, leading to reduced growth, wilting, and, ultimately, plant mortality. High salt concentrations impair seed germination and hinder seedling establishment, resulting in poor field emergence and reduced plant populations. Additionally, salinity disturbs the nutrient balance within plants. The accumulation of sodium (Na^+) and chloride (Cl^-) ions interferes with the uptake of essential nutrients such as potassium (K^+) and calcium (Ca^{2+}), causing nutrient imbalances and subsequent physiological disorders. Salinity also raises osmotic potential of the soil, inducing osmotic stress that limits water availability to plants. This stress promotes the overproduction of reactive oxygen species (ROS), leading to oxidative damage to cellular structures and metabolic dysfunctions. Moreover, salinity negatively affects photosynthetic efficiency by reducing chlorophyll content and impairing enzyme activities associated with photosynthesis, thereby severely limiting plant growth and yield.

Oil quality in mustard is also compromised under saline conditions, as salt stress alters the fatty acid composition of the oil, diminishing both its commercial value and nutritional properties. Interestingly, *B. juncea* has demonstrated potential for phytoremediation of metal-contaminated saline soils, garnering attention as a candidate for sustainable agriculture and soil restoration strategies. Given these challenges, it is crucial to develop salt-tolerant mustard genotypes and systematically explore existing germplasm resources to identify and harness naturally occurring salinity tolerance traits for breeding programmes and crop improvement initiatives.

Mustard's natural salinity tolerance mechanisms

Mustard exhibits low to moderate salt tolerance, attributed to several inherent adaptive mechanisms. Natural genetic variation for salinity tolerance exists within the extensive germplasm collections of mustard, offering valuable resources for crop improvement. It is essential to identify and select elite germplasm with superior adaptability to varying climatic and saline conditions through conventional breeding approaches. In this context, ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal has reported several mustard genotypes exhibiting moderate to high salinity tolerance with minimal yield compromise under salt-affected environments. Several physiological, biochemical, and molecular traits contribute to the ability of mustard plants to withstand soil salinity:

- ***Deep root system:*** Certain mustard germplasm possesses deeper root architectures, enabling plants to access water from subsoil layers while avoiding the detrimental effects of surface salt accumulation.
- ***Osmotic adjustment:*** To mitigate osmotic stress, mustard plants accumulate osmoprotectants such as proline, glycine betaine, and polyamines. These compatible solutes help maintain cellular osmotic balance and protect cellular structures under saline conditions.
- ***Antioxidative defense system:*** Salinity-induced oxidative stress is alleviated through the enhanced activity of antioxidative enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD). Additionally, the introduction and expression of the codA gene encoding choline oxidase from *Arthrobacter globiformis* in *B. rapa* spp. have been shown to improve photosynthetic efficiency under high salinity stress by enhancing oxidative stress tolerance.
- ***Ion homeostasis and transport regulation:*** Mustard plants maintain ionic balance by regulating ion transport and minimizing toxic sodium (Na^+) accumulation. This is achieved through the action of ion transporters and antiporters such as SOS1, SOS2, SOS3, ENH, and NHX proteins, which play pivotal roles in maintaining intracellular ion homeostasis and nutrient balance under saline conditions.

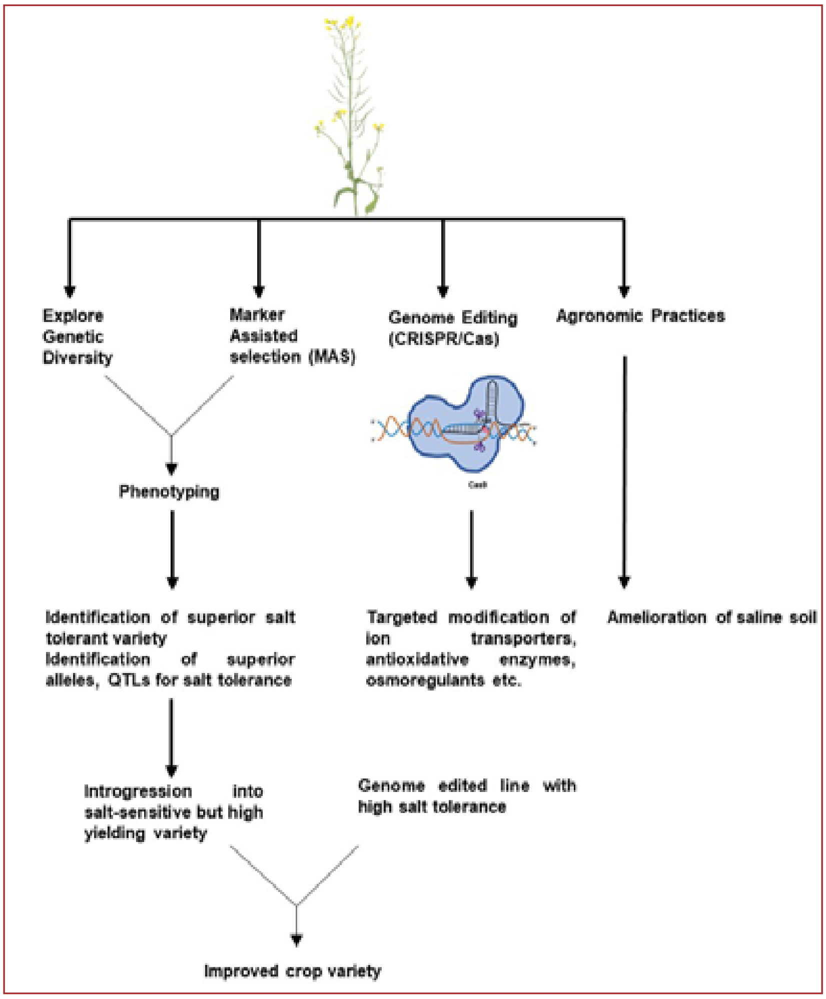
Harnessing these adaptive traits through systematic germplasm evaluation and targeted breeding strategies holds promise for developing high-yielding, salt-tolerant mustard cultivars suitable for saline and marginal agro-ecosystems.

Variation in the root length in mustard germplasm

Strategies for enhancing salinity tolerance in mustard

To reduce the nation's dependence on edible oil imports and safeguard the national economy, it is essential to achieve self-sufficiency in oilseed production, particularly mustard. In light of increasing soil salinization and unpredictable climatic conditions, the development of salt-tolerant, high-yielding mustard varieties has become a priority. Several strategies can be employed to enhance salinity tolerance in mustard crops:

- ***Conventional breeding:*** Significant genetic variability for salinity tolerance exists within local landraces, wild relatives, and traditional mustard cultivars. Systematic identification and selection of elite germplasm under saline and adverse climatic conditions can lead to the discovery of naturally tolerant lines. These tolerant genotypes can be characterized and evaluated in salt-affected soils to assess their adaptability and agronomic performance. Subsequently, selected tolerant lines can be hybridized with high-yielding but salt-sensitive cultivars to develop superior varieties with enhanced salinity tolerance through conventional breeding approaches.
- ***Marker-assisted selection (MAS):*** The existing genetic variability in mustard can be efficiently exploited using molecular markers such as RFLP, AFLP, SSR, and SNP, which reveal polymorphism and are closely associated with genes or quantitative trait loci (QTLs) governing salinity tolerance. Marker-assisted selection allows for the precise identification of plants carrying desirable alleles, bypassing the need for time-consuming and labour-intensive phenotypic screening under saline conditions. Furthermore, marker-assisted backcross breeding (MABC) can be applied to introgress identified salt tolerance QTLs into high-yielding, salt-sensitive genetic backgrounds, thereby combining salinity resilience with desirable agronomic traits.
- ***Genome editing using CRISPR/Cas technology:*** Genome editing offers a precise and efficient approach to enhance stress tolerance traits in mustard. The CRISPR/Cas9 system enables targeted modification of genes by utilizing a 20 bp single-guide RNA (sgRNA) specific to the gene of interest. The Cas9 nuclease introduces a double-strand break near the Protospacer Adjacent Motif (PAM) sequence, and during the DNA repair process, insertions, deletions, or targeted modifications are introduced. In mustard, CRISPR/Cas9 technology can be utilized to target key genes involved in ion transport (e.g. SOS1, NHX), osmoregulation (e.g. proline and glycine betaine biosynthesis pathways), and antioxidative defense mechanisms, thereby improving plant's resilience to salinity stress.



Strategies to develop salt tolerance mustard variety

Strategies to develop salt tolerance mustard variety

- ***Agronomic practices and nanotechnology:*** In addition to genetic improvement, integrated agronomic strategies can play a critical role in managing salinity stress. Intercropping mustard with salt-tolerant cover crops can reduce surface soil salinity and improve soil structure. Application of soil amendments such as gypsum, organic matter, and biochar helps neutralize excessive salts, enhancing soil fertility and water-holding capacity. Adoption of efficient irrigation methods, such as drip or alternate furrow irrigation, minimizes salt accumulation near the root zone. Utilization of plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) enhances nutrient uptake, root growth, and stress tolerance under saline conditions.Recent advancements in nanotechnology have introduced the application of nano-encapsulated nutrients and engineered nanoparticles, which improve nutrient absorption, physiological efficiency, and plant growth under saline environments.

SUMMARY

Indian mustard is a moderately resilient crop that requires relatively less irrigation and can tolerate moderate levels of soil salinity, making it a promising crop for cultivation in salt-affected areas. However, to fully harness its potential, extensive reservoir of mustard germplasm must be systematically explored to identify genotypes with superior resilience and adaptability to saline soils, without compromising seed yield or oil quality. There are relatively few reports available on the identification of novel genes and quantitative trait loci (QTLs) associated with salinity tolerance in mustard. Limited genetic and molecular information constrains the development of salt-tolerant cultivars through molecular breeding and biotechnological approaches. Therefore, there is a pressing need for comprehensive studies aimed at identifying and characterizing salt-responsive genes, QTLs, and regulatory networks in mustard. This will not only advance our understanding of the genetic basis of salinity tolerance but also facilitate the development of molecular markers and gene targets for breeding programmes focused on improving salinity resilience in mustard.

To achieve this, it is crucial to integrate conventional breeding approaches with modern biotechnological tools and sustainable agronomic practices. Advanced technologies such as genome editing, in combination with omics-based approaches including genomics, transcriptomics, proteomics, and metabolomics hold immense potential to unravel the complex mechanisms underlying salinity tolerance. The integration of these cutting-edge tools can accelerate the development of high-yielding, salt-tolerant mustard cultivars, thereby revolutionizing mustard cultivation in salt-affected agro-ecosystems and contributing to the nation's edible oil security.

*Corresponding author email: archana@iari.res.in

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Cut-soiler-preferential shallow subsurface drainage (PSSD):

A novel technique of salinity management with no residue burning

Gajender Yadav[1]*, Neha[1,2], R. K. Yadav[1], Govind Prasad[1], A. K. Rai[1] and Junya Onishi[2]

[1]*ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001*

[2]*Japan International Research Center for Agricultural Sciences (JIRCAS), Japan*

Soil salinization is a major cause of land degradation in irrigated areas, often reducing productivity and forcing field abandonment. Salinity build-up in the root zone results from saline irrigation, shallow groundwater, weathering, and poor drainage. Conventional measures such as leaching and drainage installation have limitations due to high cost and technical constraints. A novel method, cut-soiler based Preferential Shallow Subsurface Drainage (PSSD), offers an effective alternative. The tractor-operated cut-soiler uses surface residues as filling material to construct shallow (40–60 cm) drains that promote preferential removal of water and salts while simultaneously managing residues without burning. Cut-soiler was introduced in India under Japan International Research Centre for Agricultural Sciences (JIRCAS)-ICAR-Central Soil Salinity Research Institute (ICAR-CSSRI) collaborative research project. The findings of evaluation studies on salt removal effect of cut-soiler PSSD suggested that it can reduce soil salinity upto 60% in a semi controlled lysimeter simulation study and upto 50% in the field condition in three years. The subsequent effect of desalination on performances of tested crops is prominent and consistent. Unlike conventional subsurface drainage, it is low-cost, farmer-friendly, and can be applied at the individual farm level, making it a promising option for sustainable salinity and residue management.

Keywords: Cut-soiler, Drainage, PSSD, Salt affected soil, Salinization

THE Sustainable Development Goals emphasize the need to enhance food production, restore soil and ecosystem health, improve water management, and address climate challenges by promoting the multifunctional use of natural resources within their ecological limits, thereby preventing further land degradation. Among the major drivers of desertification and land deterioration, salinization is regarded as a critical environmental threat, leading to both ecological imbalance and economic losses. The problem of salt accumulation in soils and water bodies has become a major barrier to sustainable agriculture, particularly in arid and semi-arid regions, where it restricts crop productivity. Globally, salt-affected soils are distributed across more than 100 countries, covering an estimated 835 million hectares of which 438 million hectares are sodic and 397 million hectares are saline. In India, approximately 6.7 million hectares are classified as salt-affected, while 32–84% of groundwater resources are considered unsuitable due to poor quality.

In India, salt-affected soils have been present since time immemorial but recorded evidences are available only after middle of 19th century when salinization started adversely affecting crop yields and economic well-being of people and system ecology. The problem has origin in natural processes as well as secondary human induced factors. Presently the salt-affected soils exist in fourteen states and one union territory of the country. In the coming years, the extent of salt-affected soils is likely to expand due to factors such as secondary salinization in canal command and lift-irrigation areas, greater reliance on poor-quality water in semi-arid and arid zones, seawater intrusion driven by climate change, and the growing practice of brackish water aquaculture in coastal regions.

The challenge of salinity is becoming more severe, particularly in poorly drained soils with high salt content. Addressing this issue requires a practical, farm-level technology that individual farmers can easily adopt. The cut-soiler approach, which provides a low-cost preferential drainage system, offers a promising and economical option for the long-term management of salt-affected soils.

Overview of cut-soiler

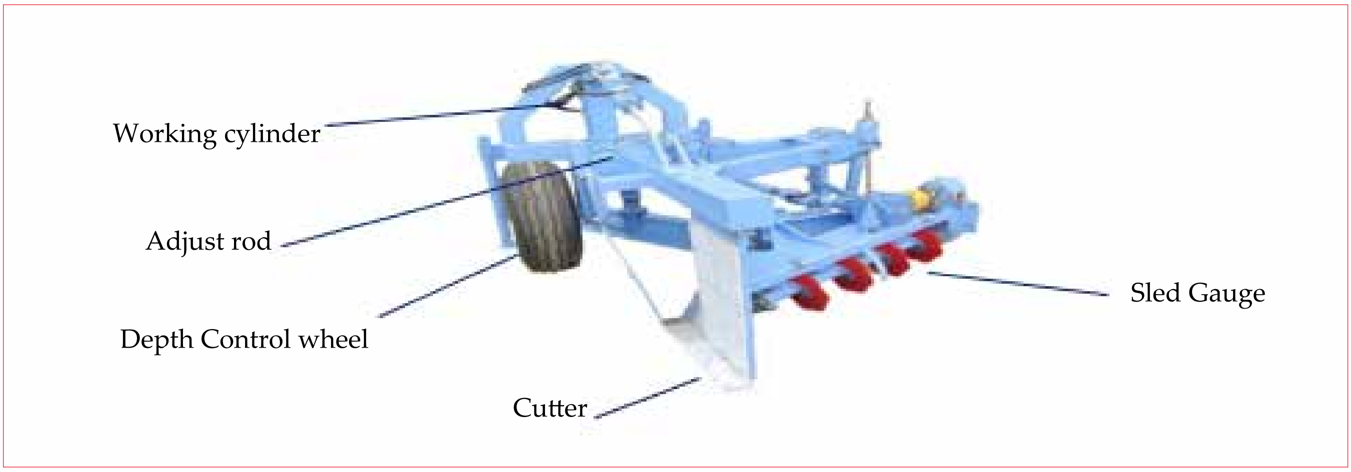
Development background and history: The cut-soiler is a tractor-operated implement designed to utilize surface residues such as straw, stems, and other plant remains to create preferential shallow subsurface drainage (PSSD) channels as it moves across the field. This system simultaneously addresses the dual challenges of waterlogging and salinity while providing an effective means of residue management. The drainage channels function through water flow, generally about 60 cm deep, and exhibit discharge efficiency comparable to conventional main drains. The technology has been successfully applied in practice, and farmers can establish these drains quickly and conveniently without requiring specialized materials.

Cut-soiler has been developed and put into commercial use jointly by National Agriculture and Food Research Organization (NARO) and Hokkai Koki Corporation, Japan (Patented in 2017). Cut-soiler was introduced in India under JIRCAS and ICAR-CSSRI collaborative research project on sustainable resource management system for waterlogged and saline arid regions of India. The project envisages evaluation, utility and standardization of this approach on salt leaching and nutrient dynamics in the field and lysimeter conditions.

Features and specifications of cut-soiler: It is mainly consisted of cutter blade and sled gauge. The cutter is working like a chisel plough that cut and lift the soil to open up space to insert filling material. The sled gauge is a whirling shaft that hard sweeps the surface residue and places it into the space opened by cutter. The cutter shaft is slightly slanting in such a way that the lifted soil filled back in the open space over the filling material (residue) without inverting the soil. The working cylinder is provided for the hydraulic lifting movement using tractor power. The depth control wheel is to control the depth of drain constructed by cut-soiler. The specifications of the cut-soiler along with its tractor power requirements are dimensions (LxWxH): 2.0 m x 1.5 m x 1.65 m and weighs 800 kg. following are some recommendations:

- Tractor capacity required: 60–120 HP
- Recommended operating speed: 2–3 km/h
- Material treatment: maximum 10 cm length
- Construction depth: 40–60 cm

Operation mechanism of cut-soiler: The cut-soiler operates by cut the soil to create a V-shaped furrow. During this process, the soil is lifted, and surface residues



Cut-soiler machine



Cut-soiler operation in the field

Mechanism of cut-soiler operation for preferential shallow sub-surface drainage construction

such as straw and plant material are placed at the base of the furrow before the excavated soil is returned. These constructed lines act as shallow subsurface drainage channels, effectively reducing surface waterlogging and mitigating soil salinity. The accompanying figure illustrates the working mechanism of the Cut-soiler in establishing these drains.

Cut-soiler can also place the soil reclamation amendments like gypsum along with residue at sub-surface and thus a practical technique to reclaim sub-surface sodicity. Cut-soiler can manage the complete surface rice residue (upto 6 t/ha) by placing it to sub surface in a single tractor operation, hence an effective tool to reduce the residue burning problem of rice-wheat belt of IGP.

Precautions during construction of cut-soiler PSSD

- To maintain the desired lateral distance between drain lines and enhance water and salt outflow, the tractor should be run straight in the direction of the natural slope.
- The filler material, such as crop residue, should be evenly spread on the ground and preferably be 8–10 cm in size. The larger size residue can clog, disrupt the consistency of cut-soiler action, and diminish the tractor pulling capacity.
- To ensure uniform depth of cut-soiler constructed drains, the field should be laser leveled with a 2% slope oriented toward the main drain, the tractor should operate at constant slow speed (2—4 km/h) and the PTO (power take-off) rotates continuously.
- The quality of the straw/residues utilised determines stability and durability cut-soiler drain. However, channels made with rice straw residue were effective for around three years.
- The recommended lateral spacing between two adjacent cut-soiler drainage channels ranges from 2.5–5.0 m. (depending on soil type and field conditions).
- Each cut-soiler lateral drain must linked to the main drain line to lay off drained water from the field.
- In case of placement of reclamation amendments into soil sub-surface, the amendment (Gypsum) should spread homogeneously over rice straw after cutting it into finer lengths using the mulcher.
- It is advisable to adjust the depth of the cut-soiler drains by depth control wheel before running in the field according to the depth of sodic layer presence or required depth of drainage.

Advantages

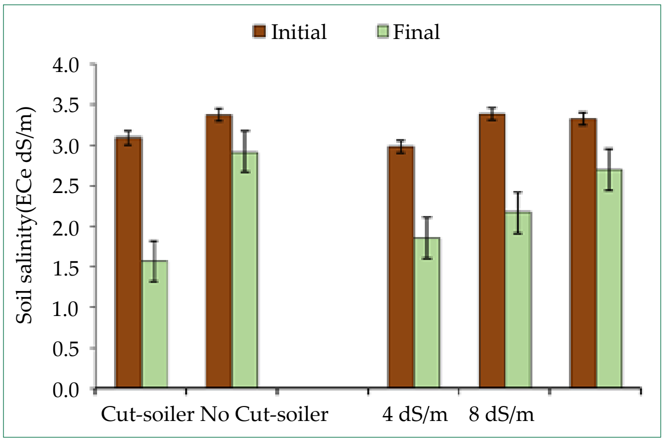
- Cut-soiler PSSD construction does not require any extra material of machinery, hence, it is low cost in operation and no requirement of large area or community approach as it can be used by individual farmer.
- It uses surface left over surface scattered residue after combine harvest as filling material, so may help in reducing residue burning.
- Placing crop residues at the base of the cut-soiler furrow contributes to carbon sequestration and enhances overall soil health.
- The cut-soiler drains being shallow, helps in reducing drainage effluent volume.
- It is a viable technique for the placement of reclamation amendment at sub surface, so helpful in managing sub-surface sodicity.

Limitations

- Higher tractor power requirement.
- Requirement for additional hydraulic point in tractor for better lifting.
- An initial hand on training is required for operating, handling procedure, functions, and precautions during the operation.

Pilot studies on performance evaluation of cut-soiler PSSD

Studies at ICAR-CSSRI, Karnal, demonstrated the effectiveness of cut-soiler based PSSD in lowering soil salinity through a semi-controlled lysimeter setup where drains were constructed manually. Results showed that this system decreased soil salinity by 50–60% within two years across different soil types. The extent of desalinization varied depending on soil texture, the quality of irrigation water, and seasonal rainfall patterns. The PSSD facilitated greater discharge of excess water and dissolved salts immediately after irrigation and rainfall events. Notably, irrigation water with salinity levels up to 8.0 dS/m could be applied without causing



Effect of cut-soiler PSSD and varying saline irrigation water on soil salinity reduction over two years

additional salt accumulation. Improved soil conditions, combining lower salinity with favourable moisture availability, enhanced crop performance. In pearl millet, grain yield increased by 23.54% and biological yield by 12.64%. Similarly, mustard showed yield improvements of 31.4% in seed, 14.41% in straw, and 18.08% in biological output.

The effectiveness of cut-soiler PSSD in salt removal and salinity management was also proved in the field validation trial at representative salt affected site at village Nain (Panipat), Haryana. In this study, upto 52% reduction in soil salinity (ECe) was recorded with cut-soiler PSSD at 2.5 m lateral interval. In this study, cut-soiler drains were installed at a depth of 60 cm, with rice residue applied as a filling material at the rate of 6 Mg/ha. The system resulted in a 50% increase in mustard yield. Moreover, it was observed that irrigation water with salinity levels up to 12.0 dS/m could be utilized under this drainage method without contributing to additional salt accumulation.

A field experiment was carried out in Bhudhmor village (Patiala, Punjab), where the cut-soiler machine was used to place gypsum and rice residues at different lateral intervals for reclaiming by 23.77%, 14.92%, and 5.95% at lateral spacings of 0.30 m, 0.60 m, and 1.25 m, respectively. When gypsum and rice straw residues were incorporated at a depth of 40 cm crop productivity also improved under this system, with rice and wheat yields showing increases of 16% and 15.5% at 2.5 m spacing, and 6% and 10.7% at 5.0 m spacing, compared with the control treatment (without cut-soiler intervention).

SUMMARY

The cut-soiler PSSD presents a promising approach for managing both soil salinity and surface residues. This preferential subsurface drainage system offers a practical solution to minimize salt build-up and can be implemented at the individual farm level in a single operation. Unlike conventional subsurface drainage, it does not require heavy machinery, high investment, collective participation, or the complex handling of large volumes of saline effluents. However, additional research is necessary to clearly establish its long-term influence on soil water and salt dynamics, as well as its economic feasibility under different soil textures, varying irrigation water salinity, and diverse types of crop residues, to ensure sustainable management of salt-affected soils.

*Corresponding author email: gajender.icar@gmail.com

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Integrated sustainable farming model

for saline and sodic soils

Rajkumar, Suresh Kumar, Ram Kishor Fagodia, Awtar Singh and Nirmal Singh*

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Saline and sodic soils significantly limit agricultural productivity due to their high salt and sodium content, which negatively affect soil health and crop growth. This article explores the effectiveness of integrated sustainable farming systems (IFS) in mitigating these challenges and enhancing farm productivity in affected regions. By combining crop diversification, efficient water management, livestock integration, and agroforestry, IFS promotes resource recycling, improves soil fertility, and maintains ecological balance. The adoption of these holistic practices results in enhanced biodiversity, climate resilience, and economic sustainability for smallholder farmers. Case studies from the Indo-Gangetic Plains highlight that enterprise diversification within IFS increases food and nutritional security, reduces environmental degradation, and boosts farm profitability. Despite challenges like limited funding and resource availability, integrated farming presents a viable solution for sustainable agriculture on saline and sodic soils, supporting both farmer livelihoods and long-term soil conservation.

Keywords: Climate resilience, Enterprise diversification, Integrated farming system (IFS), Nutritional security, Resource recycling, salt affected soils

SALINE and alkaline soils pose significant challenges to agricultural productivity worldwide. These soils are characterized by significant quantities of soluble salts as well as sodium ions, which adversely affect plant growth and soil fertility. Traditional farming practices often exacerbate soil salinity and sodicity, leading to reduced yields and environmental degradation. However, integrated sustainable farming models offer promising solutions to mitigate these challenges while promoting agricultural productivity and environmental stewardship. Saline and sodic soils are types of soil degradation characterized by high concentrations of salts. Saline soils contain soluble salts such as sodium chloride (NaCl), while sodic soils have elevated levels of exchangeable sodium ions (Na^+). These salts adversely affect soil structure and fertility, posing significant challenges to agricultural productivity.

Importance of addressing saline/sodic soils

- Ensuring the viability of agricultural land for future generations
- Mitigating the environmental impacts of soil degradation, including salinization of water bodies
- Enhancing the risk-bearing capacity of farming communities to climate change and market price fluctuation

Constraints of present agriculture

- Reduction in agriculture growth rate
- Reduction in factor productivity
- Increasing malnutrition
- Increasing environment pollution
- Increasing cost of production
- Depleting ground water table

Difference between IFS and mixed farming

IFS is that enterprise which is mutually supportive and depend on each other. Mixed farming system consists of components such as crops and livestock that coexist independently from each other. In this farming, integrating crops and livestock serves primarily to minimize the risk and not to recycle resources. Whereas in an IFS, crops and livestock interact to create a synergy, with recycling allowing the maximum use of available resources.

Advantages of IFS

***Enhanced resource efficiency*:** Integrated farming maximizes resource use by recycling nutrients, water, and energy within the system. Livestock waste serves as organic fertilizer for crops, reducing synthetic inputs, while crop residues feed livestock. Manure recycling and biogas generation further minimize waste. Diversifying crops and livestock improves land, labour, and capital use, boosting productivity and benefit-cost ratio. Water-saving practices like drip irrigation, rainwater harvesting, and recycling enhance efficiency, helping farmers manage scarcity and drought conditions.

Improved soil health and fertility: IFS improves soil health by adding organic matter and through crop rotation and cover cropping, which improve structure, nutrient cycling, and erosion control. Crop-livestock integration returns nutrients to the soil via grazing on residues and cover crops, boosting fertility. Agroforestry stabilizes soil, curbs erosion, and increases carbon sequestration, creating resilient soils. Efficient recycling of organic fertilizers, residues, and manure reduces synthetic fertilizer use and nutrient runoff, minimizing water pollution risks.

Biodiversity conservation: Integrated farming, by combining multiple crops, trees, and livestock, increases biodiversity on agricultural lands. This supports beneficial insects, pollinators, and soil microbes, strengthening ecosystem health and resilience.

Pest and disease management: Diversified farming disturbs pest and disease cycles by reducing monoculture and promoting ecological balance. Mixed cropping and habitats for beneficial insects provide natural pest control, minimizing chemical use. Livestock integration helps manage pests and weeds through grazing and interrupting their life cycles.

Climate resilience: IFS boost resilience to climate variability through diversified cropping and agroforestry, which protect against drought, floods, and temperature extremes. Conservation agriculture and water harvesting improve soil moisture retention, reduce runoff, and lessen climate change impacts on productivity.

Environmental conservation: IFS conserves biodiversity by creating diverse habitats through agroforestry, hedgerows, and riparian buffers, supporting varied plant and animal species. Reduced pesticide and fertilizer use lowers pollution and safeguards water quality, while prioritizing ecological balance and protecting natural resources from negative farming impacts.

Economic viability: IFS improve economic sustainability by diversifying income sources and lowering production costs. Alongside crop sales, farmers earn from livestock, agroforestry products, aquaculture, and value-added ventures like agro-tourism and farm-to-table sales. Reduced reliance on external inputs and efficient resource use increase returns and buffer against market and price volatility. Enterprise integration—crops, milk, eggs, mushrooms, honey, silkworm cocoons—ensures year-round cash flow.

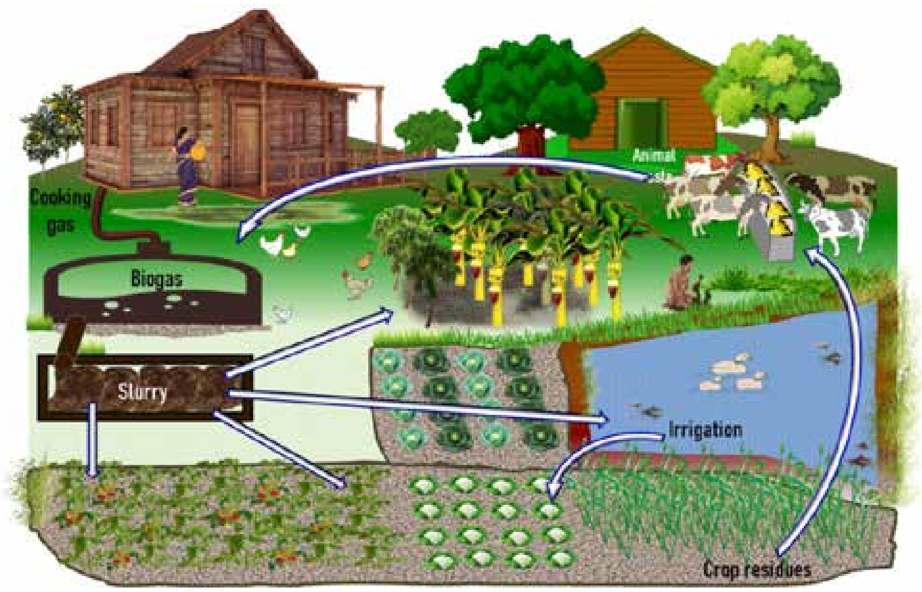
Community engagement and social benefits: IFS encourage community participation, fostering social cohesion and rural growth. Shared knowledge, resources, and labour help communities tackle challenges and improve livelihoods. Combining crops with livestock increases labor demand, reducing underemployment in rural areas.

Objectives of integrated farming systems

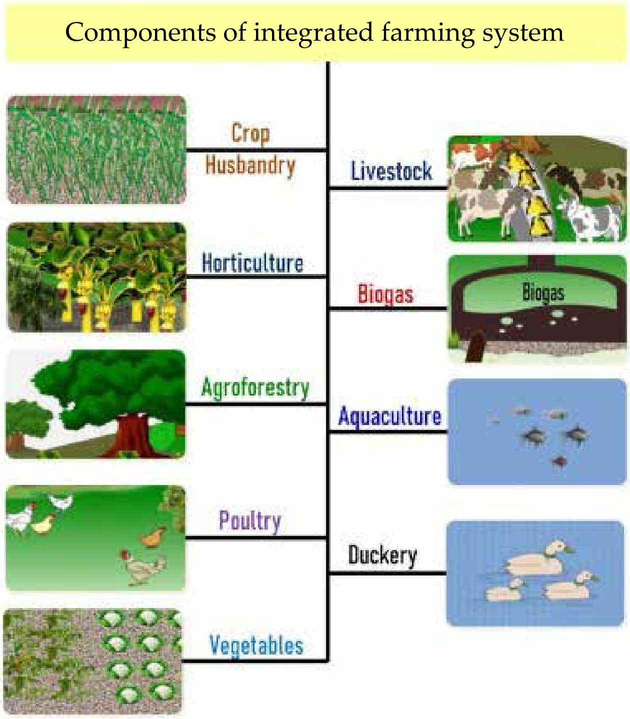
- To recognize the current farming systems, present in a particular area and evaluate their comparative viability.
- To develop farming system models that integrate primary and supplementary enterprises tailored to various farming conditions.
- To promote the optimal use and conservation of available resources while ensuring efficient recycling of farm residues within the system.
- To sustain production systems in a way that does not harm the resource base or the environment
- To enhance the overall profitability of farm households by harmonizing main and allied enterprises to complement one another.

Ideal situations for introduction of IFS

- When the farmer aims to enhance the quality of farm production.
- When the farmer's household is facing difficulties in affording sufficient food.
- When there is water storage available on the farm, such as ponds.



IFS model for smallholder farmers with around two-hectare land area



- When the farmer intends to maximize profits from the current landholding.
- When the farmer is motivated to minimize environmental pollution.

Table 1. Enterprises linked in different agro-ecosystem

Dry land	Dairy	Poultry	Goat/sheep	Agro-forestry	Farm pond	
Garden land	Dairy	Poultry	Mushroom	Bee Keeping	Piggery	Sericulture
Wet land	Dairy	Poultry	Mushroom	Fishery	Duckery	

Types of IFS

Crop-based IFS: Crop production is the main activity, complemented by livestock, agroforestry, or aquaculture to recycle organic waste, improve resource use, and boost productivity.

Livestock-based IFS: Livestock rearing is primary, with crops planned to meet fodder needs. Livestock improve soil fertility through manure recycling, provide meat, milk, eggs, and offer climate resilience, biodiversity enhancement, and income security. Examples: fish + crop, sheep/cattle + crop.

Tree-based IFS: Multipurpose trees are integrated with crops, livestock, or aquaculture to supply fuel, fodder, timber, and non-timber products. Trees support soil conservation, nutrient cycling, carbon sequestration, biodiversity, and diversified income, while enhancing environmental and social resilience.

Horticulture-based IFS: Incorporates fruits, vegetables, herbs, and ornamentals with livestock, poultry, aquaculture, or agroforestry. Offers higher yields, income diversification, biodiversity conservation, climate resilience, and improved rural livelihoods.

Principles of IFS

1. ***Diversification of crops***: Crop diversification, as opposed to monocropping, involves cultivating multiple species with varied nutrient needs and growth characteristics to maintain soil health. This approach breaks pest and disease cycles, improves soil structure, and strengthens farming system resilience to stresses such as salinity and sodicity. For instance, integrating salt-tolerant crops like quinoa, barley, or specific rice and wheat varieties alongside traditional crops can enhance soil management in saline or sodic areas.
2. ***Efficient water management:*** Efficient water management techniques in farming focus on optimizing water use, minimizing wastage, and preventing waterlogging that worsens soil salinity and sodicity. Methods such as drip irrigation deliver water directly to plant roots, reducing evaporation and salt buildup, while precision farming applies water only where and when needed to conserve resources. Proper water management helps mitigate salinity/sodicity effects, enhances crop productivity, and lowers agriculture's environmental impact. Techniques like rainwater harvesting and recycling supplement irrigation, reducing reliance on groundwater in saline and sodic regions.
3. ***Soil health improvement:*** Soil health improvement aims to enhance fertility, structure, and biological activity, which are vital for sustainable crop production. Techniques like composting, green manuring, and vermiculture increase soil organic matter, boosting nutrient and water retention. Healthy soils are more resilient to salinity and sodicity stresses and support diverse microbial communities that aid nutrient cycling and plant health. For example, incorporating cover crops and legumes in rotations fixes nitrogen, improves soil structure, and reduces erosion in saline/sodic conditions.
4. ***Integration of livestock:*** Integrating livestock into farming systems creates synergies between crop and animal production, enhancing nutrient cycling and soil fertility. Livestock supply manure that serves as organic fertilizer, improving soil structure and reducing dependence on chemical inputs. This integration not only boosts soil health but also diversifies farm income. Practices like rotational grazing on cover crops or fallow fields help evenly distribute manure while minimizing soil compaction, further supporting sustainable and productive farming.
5. ***Agroforestry practices:*** Integrating agroforestry into farming systems offers multiple benefits such as soil improvement, biodiversity conservation, and additional income sources. In saline and sodic areas, planting salt-tolerant tree species like *Tamarix* and *Populus* helps lower water tables, reduce soil salinity, and stabilize soil structure. For example, windbreaks or shelterbelts made of these trees can mitigate wind erosion, decrease soil salinity and

sodicity, and provide extra income through timber or fruit production. Overall, agroforestry contributes to long-term soil health, enhances climate resilience, and promotes sustainable land use practices in challenging saline/sodic environments.

Case study: Coastal farming community, Gujarat, India

This case study focused on a coastal farming community in Gujarat, India, facing challenges of high soil salinity due to proximity to seawater.The community adopted a multi-faceted approach involving crop diversification, efficient water management, and soil health improvement. Over a span of three years, the implementation of salt-tolerant crops such as quinoa and halophytes led to a noteworthy increase in overall crop yield. Drip irrigation systems and rainwater harvesting techniques were implemented, resulting in a 30% reduction in water usage while maintaining or increasing crop productivity. Additionally, the integration of agroforestry and livestock helped enhance soil fertility and biodiversity.

The implementation of integrated sustainable farming practices improved soil health as well as increased crop yield. Furthermore, it also increased the resilience of the farming community to climate change and market fluctuations.

Table 2. Enterprise mix diversification: An option for ecologically sustainable food and nutritional security of small holders in Indo-Gangetic plains

Crop components		Horticulture	subsidiary components		
Grain production	Fodder	Vegetables	Fruit trees	Livestocks/Poultrr	Fisheries
(1.0 ha) Rice *(Oryza sativa)* - Wheat *(Triticum aestivum)* (0.2) Rice-Wheat-Moong *(Vigna radiate)* Maize (*Zea mays*)- Wheat-Moong (0.2) Soybean (*Glycine max*)-Winter Maize (0.2) Pigeon pea (*Cajanus Cajan*)-Mustard (*Brassica spp.*)/Fodder maize (0.2)	(0.2) *Sorghum (Sorghum bicolour) - Berseem* (Trifolium alexandrinu (0.2)	(0.2) Cabbage *(Brassica oleracea var. capitata) - Tomato (Solanum lycopersicum)- Khira (Cucumis sativus)* (0.1) Bottlegourd (Lagenaria sicerarial)- Cauliflower (Brassica oleracea var. botrytis) (0.1) Potato *(Solanum tuberosum)- Onion (Allium cepa)-Okra (Abelmoschus esculentus)*	(0.2) Guava *(Psidium guajava)* + Papaya (Carica papaya) + Banana (Musa paradisiaca)	(0.2) 3 Buffaloes +2 Cows 120 Birds	(0.2) Catla Rohu Mirgal Common carp Grass carp

Source: Yadav *et al.* 2021

Table 3. Diversification of enterprise mix: An alternate for ecologically sustainable food and nutritional security for smallholder farmersof Indo-Gangetic plains

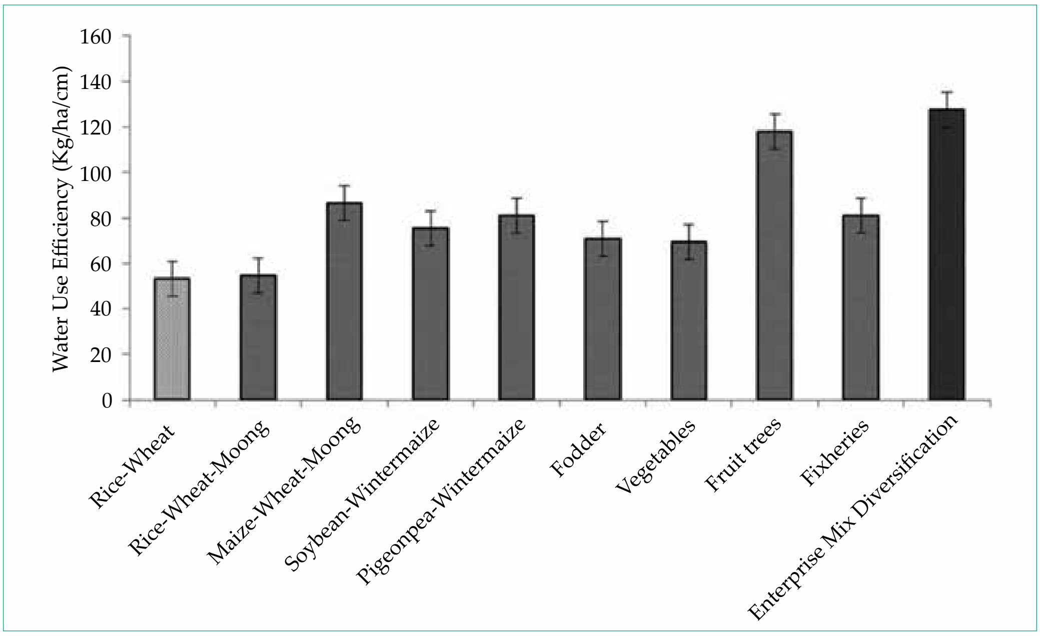
Component	Area (Ha)	Rice equivalent yield (t/ha)	Gross Income USS	Expenditure USS	Net Income USS	B.C. Ratio
Rice-Wheat	0.2	11.1	755	290	465	2.6
Rice-Wheat-Moong	0.2	12.2	833	302	531	2.8
Maizd-Wheat-Moong	0.2	*7.0*	479	180	299	2.7
Winter Maize-Soybean	0.2	*3.7*	250	99	151	2.5
Pigeon pea-Mustard-maize	0.2	*4.3*	295	134	161	2.2
Fodder	0.2	*4.4*	297	103	194	2.9
Vegetables	0.2	*6.4*	434	225	209	1.9
Fruit trees	0.2	*6.6*	451	108	343	4.2
Livestocks	0.2	*67.7*	4602	2070	2532	2.2
Fisheries	0.2	*9.3*	631	153	478	4.1
Enterprise mix diversification	2	*13.3*	9027	3664	5363	2.5

Source: Yadav *et al.* 2021

Table 4. Alterations in chemical and physical properties of soil underdifferent production systems after eight years of research

Cropping Systems	Year	pH2	EC(dS/m)	OC(%)	N (kg/ha)	P (kg/ha)	K	Sat. Hydr.	Cond. (cm/h)
Grain production	Initial	8.3	0.28	0.14	106.0	24.8	300.0		1.5
	Final	8.3	0.48	0.35	138.5	36.4	188.1		1.8
Fodder production	Initial	8.2	0.35	0.14	103.5	26.8	301.5		1.7
	Final	8.1	0.33	0.58	133.3	20.8	214.3		1.8
Horticulture production	Initial	7.9	0.41	0.14	121.0	24.2	379.9		1.8
	Final	8.1	0.30	0.98	128.1	39.8	253.1		2.0
Vegetable production	Initial	7.7	0.46	0.14	123.0	28.1	409.0		1.6
	Final	*7.7*	0.49	0.23	135.9	49.1	324.0		1.8
Pond dykes	Initial	*10.3*	4.00	0.14	55.3	15.0	213.5		1.8
	Final	*9.0*	0.93	0.35	120.2	18.9	294.8		2.0

Source: Yadav *et al.* 2021



Water use efficiency (Kg/ha/cm) of various components under enterprise mix diversification

Source: Yadav *et al.* 2021

Table 5. Credit worthiness of different components of IFS

Cropping systems	Cost of cultivation (Kg)	Total income (₹)	Net return (₹)	BC Ratio
Rice-wheat	5235	10103	4868	1.93
Forage	1198	2228	1030	1.85
Vegetables	2989	7472	4483	2.50
Fruit	3600	2100	-	1.70
Fish	16254	42840	26586	2.63
Total	29276	64743	36967	2.21

Source: Technical bulletin, CSSRI, Lucknow

Table 6. Yield and benefit cost ratio of different crop

Crop	Yield (Kg)	Expenses (₹)	Income (₹)	BC Ratio
Fish	1820	66000	163800	2.5
Potato	1000	3000	10000	3.3
Onion	400	1000	6000	6
Garlic	100	500	2000	4
Turmeric	100	500	2000	4
Maize	200	500	2000	4
Pigeon pea	40	500	2000	4
Total		72000	187800	

Source: Singh *et al.* 2014

Constraints in IFS

- Inadequate funds.
- Unavailability of animal supplements round the year
- Unavailability of labour.
- Lack of procurement of high yielding breeds of livestock.
- Non-availability of fish seed and feed timely.
- Low-cost energy efficient pumping machine.
- Lack of awareness to government schemes and credit support from financial institutions.

SUMMARY

Diversifying existing farming systems through changes in crops and cropping patterns, integrating and improving livestock, adding horticulture, introducing processing activities, and establishing boundary plantations can significantly improve the income of small and marginal farmers in India. Various IFS models have shown 2–3 times higher productivity and 3–5 times greater net returns, along with 40–50% resource savings, daily household incomes of ₹400–500, and 70–80% higher employment generation, while ensuring nutritional security. IFS offers progressive economic growth, employment, optimal resource use, and family nutrition, enhancing farmers' confidence by increasing productivity, profitability, and sustainability, especially for those with small holdings. Although numerous IFS models exist across the country, they remain insufficiently documented, highlighting the need for systematic recording and wider dissemination to benefit more farmers.

*Corresponding author email: nirmalsingh@hau.ac.in

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Improving crop resilience to salinity

stress using growth regulators

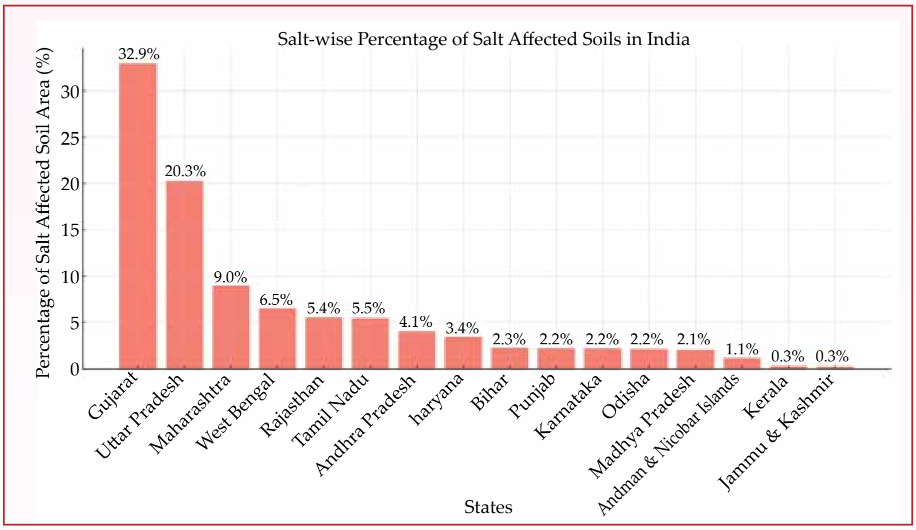
Pooja Gupta Soni[1]*, Roohi[1], Kannoj[1], Paras kamboj[1], Sarita Rani[1], Satpal[1] and Krishan Kumar[2]

[1]*Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana 125 001*
[2]*Krishi Vigyan Kendra (ICAR-Indian Agricultural Research Institute, New Delhi), Shikohpur, Gurugram, Haryana 122 004*

Worldwide climate change and declining availability of high-quality water lead to an increase in the salinization of agricultural lands. One of the major abiotic factors limiting plant growth and development is soil salinity. High salts concentrations in soil and water interfere plant physiological and metabolic processes, ultimately resulting in reduced growth, quality, and yield. In recent years, the application of plant growth regulators (Exogenous application or seed priming) can enhance plant tolerance to stress by modifying ionic and redox homeostasis, enhancing antioxidant activity, and affecting stress-responsive gene expression. Growth regulators such as abscisic acid, salicylic acid, jasmonic acid, gibberellins, cytokinins, and ethylene play an important role in reducing the harmful effects of salinity on plant growth and yield.

Keywords: Abscisic acid, Cytokinins, Growth regulators, Gibberellins, Salinity, Salicylic acid

SOIL salinity is a significant abiotic factor that impacts crop plants and restricts global production.In India, around 6.73 million hectares of land are impacted by soil salinity, constituting roughly 2.1% of the nation's entire geographical area Gujarat, Uttar Pradesh and Maharashtra shares more than 60% salt affected area on the country. Estimates indicate that approximately 10% of land becomes salinized annually, and by 2050, about 50% of arable land would be damaged by salt. Salinization can be occurred by two ways: primary and secondary. Primary salinization happens spontaneously as a result of wind and rain-induced sea salt deposits or rock weathering. In arid regions, excessive irrigation often leads to secondary salinization, wherein salts accumulate due to inadequate drainage and poor water management, compelling farmers to leave affected farms and intensifying land degradation. It is becoming major concern of irrigated agriculture.

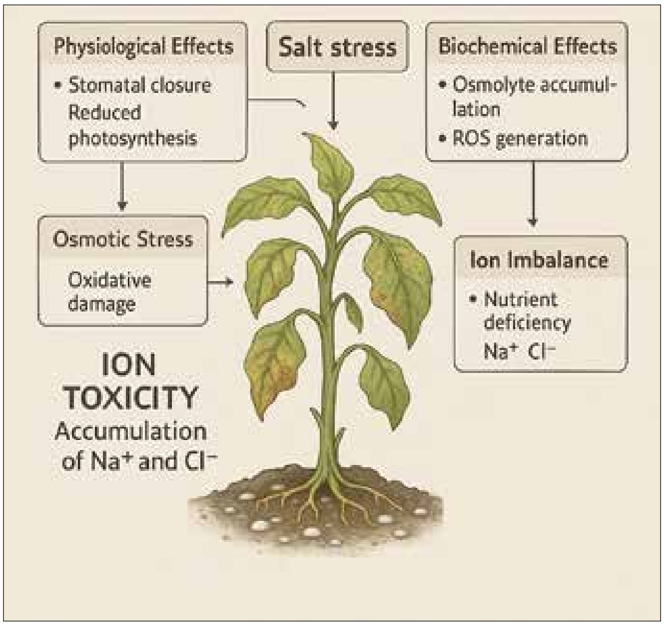


Share (%) of Salt affected soils in India

Effects of salinity stress on plants

Salt stress has detrimental effect of the plants. Salt stress resulted in physiological effects, biochemical effects, osmotic stress and ion imbalance. Due to stomatal closure, which restricts CO_2 uptake and chlorophyll breakdown during extended salt exposure, salt stress drastically alters metabolic pathways and photosynthesis. In plant tissues, hazardous levels of sodium (Na^+) and chloride (Cl^-) ions build up,

Stunt growth and poor germination of wheat under saline condition



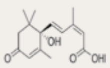
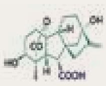
Effect of salinity stress on crop plants

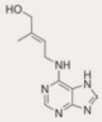
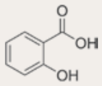
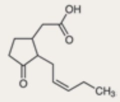
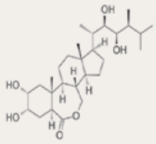
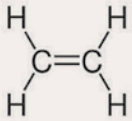
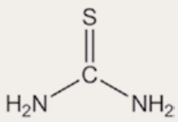
resulting in cellular toxicity and preventing enzymatic activity. Ion imbalance, osmotic stress, and oxidative damage are the causes of salt toxicity. Increased salinity causes an accumulation of Na^+ and Cl^-, which upsets the equilibrium of vital nutrients, especially potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}). Important functions including protein synthesis and enzyme activation are impacted by this ionic imbalance. Salt stress modifies biochemical pathways, which results in osmolyte buildup, reactive oxygen species (ROS) generation, and modifications to metabolic processes.

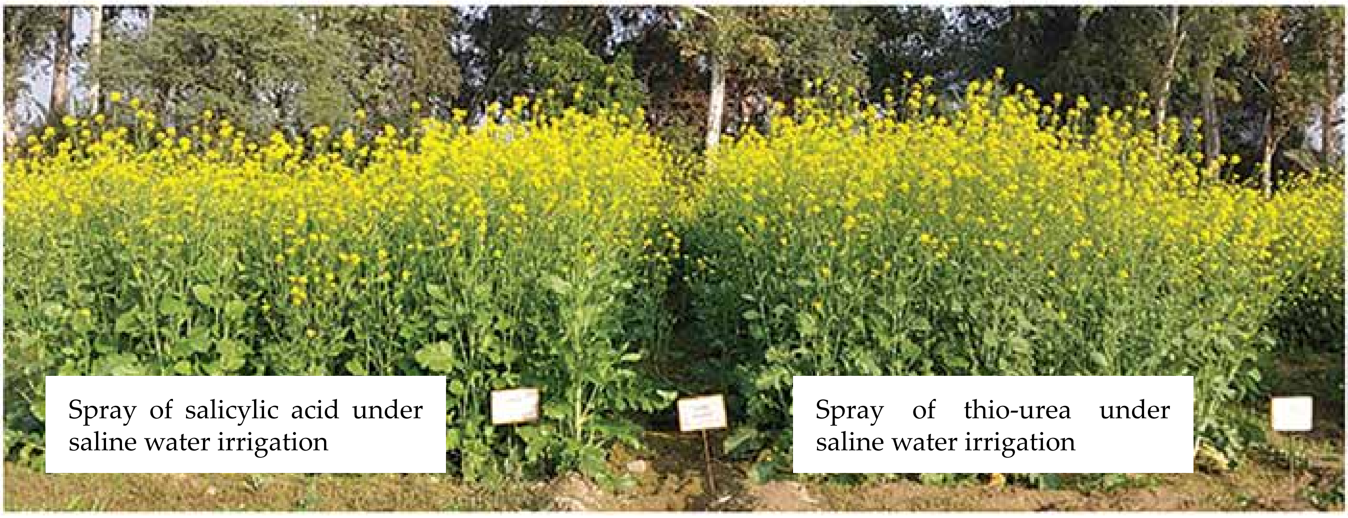
Role of specific growth regulators in mitigating salinity stress

To reduce the detrimental effects of salt stress on plant growth and yield, two distinct strategies can be adopted. The first strategy involves using molecular or traditional breeding to create cultivars that are resistant to salt. The second strategy pertains to agronomical methods and involves applying different plant growth regulators (PGRs). Synthetic or naturally occurring organic chemicals that affect higher plant biological processes at very low concentrations are known as plant growth regulators (PGRs). PGRs are widely affordable and easy to apply to crops, and they all have the same function of controlling intrinsic hormone levels in plants by modifying signaling within different hormone transduction pathways. The effectiveness of PGPRs depends on the interaction of host plant with soil environment. Certain PGRs have been demonstrated to improve plants' ability to withstand salt including ethylene, salicylic acid (SA), abscisic acid (ABA), jasmonic acid (JA), and brassinosteroids (BRs).

Table 1. Roles of specific PGRs under salinity stress with examples

PGRs	Structures	Role	Example
Abscisic Acid (ABA)		❖ Key stress hormone, regulates stomatal closure to reduce water loss under salinity stress, maintaining plant water status. ❖ Enhances the expression of stress-responsive genes and promotes the accumulation of osmolytes to improve osmotic adjustment.	Improves salt tolerance in crops like wheat and maize by enhancing root growth and reducing Na^+ accumulation
Gibberellins		❖ Promote cell elongation, seed germination, and overall growth ❖ Counteract growth inhibition caused by high salt levels	Improve salt tolerance in tomato and barley by promoting shoot and root growth
Auxins (e.g., Indole-3-Acetic Acid)		❖ Regulate root development, critical for water and nutrient uptake	Mitigates salinity stress in soybean by improving root growth and reducing oxidative damage

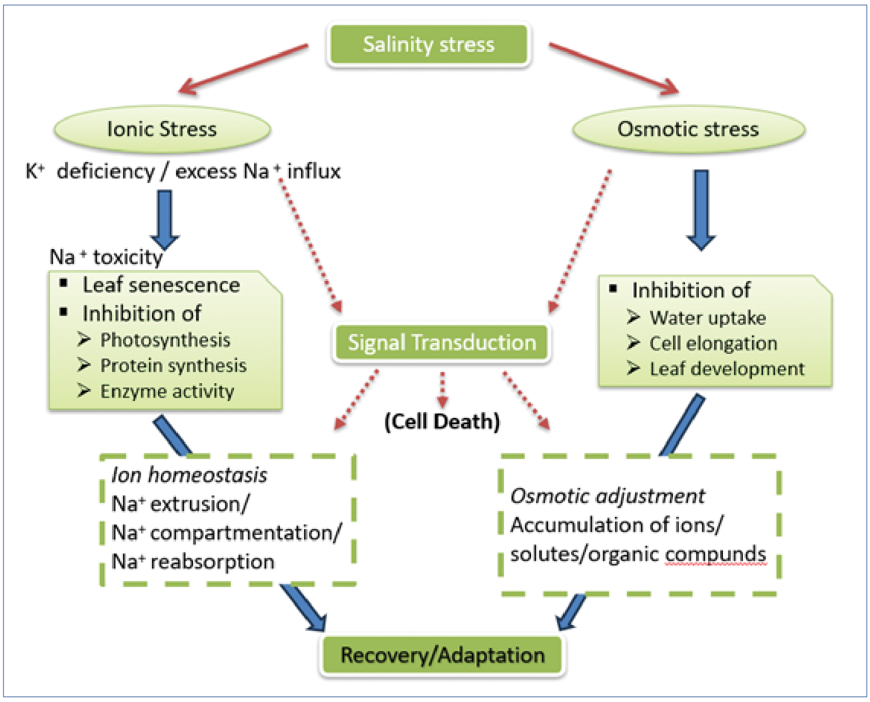
PGRs	Structures	Role	Example
Cytokinins		❖ Delay senescence, maintain chlorophyll content, and promote cell division	Kinetin application improves salt tolerance in wheat by enhancing chlorophyll stability and antioxidant activity
Salicylic Acid (SA)		❖ Enhances plant defense against salinity-induced oxidative stress and improves photosynthetic efficiency	Salt tolerance in mung bean and rice by enhancing antioxidant capacity and maintaining membrane stability
Jasmonic Acid (JA)		❖ Enhances stress signaling and improves plant resilience to salinity by activating defense mechanisms	Methyl jasmonate application alleviates salinity stress in pepper by improving photosynthetic rates and reducing Na^+ toxicity
Brassinosteroids		❖ Improve plant growth and stress tolerance by enhancing photosynthetic efficiency and membrane stability	24-epibrassinolide application enhances salt tolerance in cucumber and rice by improving photosynthesis and antioxidant defenses
Ethylene		❖ Modulates stress responses, effects varying based on concentration and plant species ❖ At low levels, it can promote stress tolerance	Application of ethylene precursors (e.g. ethephon) can enhance salt tolerance in certain crops like maize by improving root growth and ion balance
Thio-urea		❖ Cope with drought, heat and heavy metal toxicity by improving antioxidant defense mechanism ❖ Potent antioxidant, scavenging harmful ROS, Protect oxidative damage	Improve grain yield by influencing gas exchange, nutrient uptake and sugar mechanism in various crops



Effect of foliar spray of thio-urea and salicylic acid on the mustard crop under saline water irrigation

Mechanisms: One of the key mechanisms through which PGRs induce salt tolerance is the regulation of ion homeostasis and compartmentalization. ABA promotes selective accumulation and intracellular sequestration of Na^+ ions in vacuoles, lessening cytoplasmic toxicity and enzyme activity. At the same time, PGRs like SA and JA enhance the accumulation of osmolytes proline, glycine betaine and soluble sugars, which account for osmotic adjustment and cell turgor maintenance. Oxidative stress, a significant salinity impact, is tempered by PGR-augmented activity of the antioxidant defense system. Exogenously applied PGRs augment the activity of some key enzymic antioxidants like superoxide dismutase (SOD), catalase (CAT), peroxidase (POD) and ascorbate peroxidase (APX), thus scavenging reactive oxygen species (ROS) and safeguarding cellular structures from oxidative damage.

Furthermore, PGRs are also crucial for maintaining photosynthesis under salinity stress. Brassinosteroids and cytokinins have been found to preserve chloroplast ultrastructure, maintain chlorophyll content and keep photochemical activity intact, leading to enhanced carbon assimilation. The regulators also affect root architecture, with auxins and cytokinins promoting



Effect of salinity on the plant and recovery through different mechanisms

lateral root growth and augmenting the surface area of roots for water and nutrient uptake. Furthermore, ABA-mediated regulation of stomata reduces transpirational water loss, thus enhancing water-use efficiency under salt stress. Importantly, functional coordination between various PGRs enables plants to coordinate a highly integrated response to salinity. ABA, SA, JA and ethylene crosstalk regulates stress-responsive gene expression, ion transport and hormonal signaling pathways, leading to enhanced and integrated defense.

Practical approaches and application techniques

The practical application of PGRs in saline agriculture requires strategic timing, appropriate formulation and integration with complementary agronomic practices. Seed priming with low concentrations of SA, GA_3, or BRs has been shown to enhance germination, seedling vigour and stress preparedness by inducing a primed physiological state. Foliar application is a widely adopted approach, offering rapid uptake and systemic effects; multiple sprays at critical phenological stages such as tillering and flowering can effectively alleviate salt-induced damage. In salt-affected irrigated systems, soil or fertigation-based delivery of PGRs particularly ABA analogs and polyamines enables direct targeting of the root zone, enhancing ion regulation and root metabolic activity. The efficacy of PGRs is further amplified when combined with salt-tolerant genotypes and soil amendments. For instance, integrated use of SA and halophilic plant growth-promoting rhizobacteria (PGPR) has demonstrated synergistic effects on nutrient uptake, antioxidative capacity and biomass accumulation in salt-stressed wheat.

Given the projected expansion of salt-affected arable land, especially in arid and semi-arid agro-ecosystems, the use of PGRs represents a promising strategy for enhancing crop performance under salinity stress. However, successful field-level implementation necessitates crop-specific standardization of dosages, delivery methods and timing schedules. Advances in nano-formulation technologies offer new avenues for improving the stability, bioavailability and targeted delivery of PGRs. Future research should focus on elucidating the molecular networks underpinning PGR-mediated salinity tolerance and on integrating these compounds with genomics-assisted breeding, microbial bio stimulants and precision agriculture tools to develop resilient and sustainable crop production systems for salt-affected regions.

SUMMARY

High salts concentrations in soil and water interfere plant physiological and metabolic processes, ultimately resulting in reduced growth, quality, and yield. The application of plant growth regulators is a key strategy for enhancing crop tolerance to salinity stress. These regulators help plant survival and productivity under salt-affected conditions by regulating hormonal signaling, increasing antioxidant activity, and maintaining ionic and osmotic balance.

*Corresponding author email: poojagupta.agri@gmail.com

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Combined effects of heavy metal toxicity

and salinity on wheat: Challenges and mitigation strategies

Deodate Jose George[1], Vanita Pandey[1], Rinki[1]*, Mamrutha H M[1], Mahendra Firoda[1], Preety Rani[1], Zeenat Wadhwa[1], Yogesh Kumar[1], Mukesh Kumar Singh[2], Gopalareddy K[3] and Vanishree Girimalla[3]

[1]*ICAR-Indian Institute of Wheat and Barley Research, Karnal, Haryana 132 001*
[2]*ICAR-Indian Agricultural Research Institute, Research Station, Karnal, Haryana 132 001*
[3]*ICAR-Indian Institute of Seed Science, Research Station, Gandhi Krishi Vigyana Kendra Campus, Bengaluru, Karnataka 560 065*

Wheat (Triticum aestivum)*, a staple crop nourish nearly 40% of the global population, is increasingly threatened by soil salinity and heavy metal contamination. These stresses, often occurring together, impair photosynthesis, disrupt nutrient uptake, and enhance oxidative damage, leading to reduced yield and grain quality. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and chromium (Cr) accumulate in plant tissues and pose serious food safety concerns. Salinity further aggravates the problem by inducing osmotic stress. This article summarizes the combined effects of salinity and heavy metal toxicity on wheat growth and phenology, and outlines detoxification mechanisms including sequestration, chelation, and antioxidant defense. Sustainable mitigation strategies, such as plant growth-promoting rhizobacteria (PGPR), phytoremediation, bioremediation, organic amendments, and salt/metal-tolerant varieties offer effective solutions. Integrating agronomic, biological, and molecular approaches is essential to sustain wheat productivity and ensure food security under these dual stresses.*

Keywords: Bioremediation, Detoxification, Heavy metal, Plant growth-promoting rhizobacteria, Salinity stress, Wheat

WHEAT (*Triticum spp.*), a staple cereal crop from the Poaceae family, provides food and nutrition to nearly 40% of the global population and contributes approximately 20% of the world's daily calorie and protein intake. It is vital to global food security, especially in developing nations, and supports the livelihoods of over 80 million smallholder farmers. India ranks second globally in wheat production, contributing about 11.9% of global output and cultivating approximately 12% of the total wheat-growing area.

Among the growing challenges in wheat cultivation, heavy metal (HM) contamination and soil salinity pose serious threats to sustainable crop production. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), copper (Cu), and nickel (Ni) are introduced into agricultural soils through anthropogenic sources including industrial discharge, mining activities, the use of fertilizers, sewage sludge, and contaminated irrigation water. These toxic elements can accumulate in plant tissues, disrupt plant growth and metabolic functions, and pose significant risks to human and animal health via the food chain. Soil salinity, often co-occurring with HM contamination, is another major constraint to crop productivity, particularly in arid and semi-arid regions. According to FAO (2022), salinity affects up to 50% of irrigated lands in some regions and is expected to worsen due to climate change. Salt stress impairs plant functions by causing ionic and osmotic stress, oxidative damage, membrane disruption, and metabolic imbalances—ultimately reducing growth and yield. Combined exposure to heavy metals and salinity exacerbates the generation of reactive oxygen species (ROS), leading to oxidative stress, DNA damage, protein denaturation, and lipid peroxidation. The elevated uptake of toxic metals by plants not only reduces agricultural output but also compromises food safety. Essential trace metals like zinc (Zn) and copper (Cu), though vital for physiological functions, can become toxic when their concentrations exceed optimal levels.

Plants act as conduits for the transfer of heavy metals from soil to higher trophic levels, emphasizing the need for accurate monitoring of metal concentrations in soils and crops. Such assessments are critical for evaluating potential health risks and guiding mitigation strategies. Recent studies have investigated concentrations of metals like Cu, Zn, Ni, and Cr in both soils and wheat grains, underlining the urgent need for integrated approaches to manage these dual stresses.

Defence strategies against heavy metal toxicity: Detoxification mechanisms and adaptation strategies

Heavy metal toxicity poses significant environmental and health challenges, affecting ecosystems, wildlife, and human populations. Metals such as lead (Pb), mercury (Hg), arsenic (As), and cadmium (Cd) can cause severe health problems, including organ damage, neurological disorders, and cancer. To mitigate these harmful effects, both natural detoxification processes and adaptive strategies have evolved in humans and animals, including chelation, enzymatic detoxification, bioaccumulation, and environmental adaptations. Ongoing research in chelation therapy and bioremediation remains essential for managing heavy metal contamination.

Cereal crops, which are highly vulnerable to heavy metal toxicity, have developed various defense mechanisms to mitigate the harmful effects of toxic metals like Cd, Pb, and Hg, safeguarding agricultural productivity and food safety. These mechanisms include chelation, vacuolar sequestration, and the binding of metals with organic compounds, limiting metal absorption and preventing their accumulation in vital plant tissues. Additionally, root exudates play a crucial role in modifying metal availability in the soil, reducing uptake, and mitigating toxicity. Cereal crops also demonstrate adaptive responses through genetic selection and breeding for enhanced metal tolerance. Key detoxification and adaptation strategies include metal transporters, metallothioneins, cell wall binding, rhizosphere interactions, and vacuolar sequestration. These mechanisms can function independently or synergistically, enabling plants to adapt and thrive in heavy metal-contaminated environments. The specific response varies depending on the cereal species and environmental conditions.

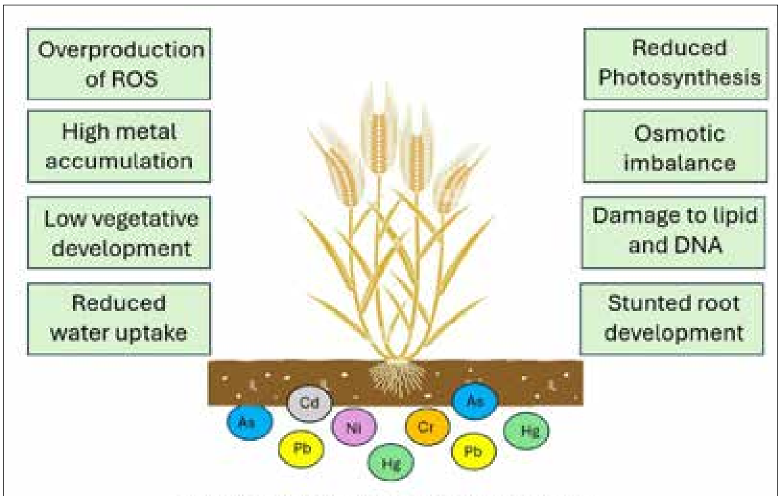

Fig : Negative impacts of heavy metal toxicity on wheat

Bioremediation of heavy metal toxicity: A general perspective

Several physical and chemical techniques such as coagulation, chemical precipitation, ion exchange, nanofiltration, reverse osmosis, soil washing, and excavation have been employed to remediate heavy metal-contaminated soils. However, these methods are often costly, labour-intensive, disruptive to the soil ecosystem, and impractical for large-scale application. In contrast, bioremediation has emerged as a sustainable and eco-friendly alternative. It involves modifying environmental conditions to enhance the activity of microorganisms that can degrade or immobilize pollutants, thereby restoring soil health. Bioremediation is broadly classified into: *In situ* bioremediation (treatment of contaminants directly at the polluted site; it is cost-effective and less invasive) and *Ex situ* bioremediation (removal of contaminated soil for treatment elsewhere; generally more expensive and environmentally taxing).

Due to lower cost and minimal environmental disruption, *in situ* bioremediation is the preferred approach for managing heavy metal-contaminated soils. Common microbiological strategies for metal remediation include bioaccumulation (uptake of metals by microbial cells), biosorption (passive binding of metals to microbial cell surfaces), biotransformation (conversion of toxic metals into less harmful forms), bioleaching (microbial mobilization of metals from solids into solution) and biovolatilization (transformation of metals into volatile forms). These biological processes offer promising potential for restoring soil productivity and ensuring environmental safety in contaminated agricultural lands.

Major heavy metals, source, symptoms and mitigation strategy

Heavy metal contamination in soil is a growing concern for wheat production, as it affects plant physiology, reduces yield, and leads to bioaccumulation in grains, posing health risks. Below is an in-depth look at major toxic heavy metals and their effects on wheat.

PGPR associated growth improvement in wheat under metal stress

The effectiveness of plant growth-promoting rhizobacteria (PGPR) in mitigating heavy metal stress in wheat depends on their metal tolerance, colonization ability, and functional traits. Beyond their typical plant growth-promoting functions, PGPR play a crucial role in alleviating metal-induced toxicity, thereby enhancing wheat growth and productivity in contaminated soils. In various studies, PGPR inoculation has led to notable improvements in wheat grown under heavy metal stress:

Table 1. Brief outline of heavy metals, their source, effect and mitigation strategies in wheat

Heavy Metal	Source	Effect on Wheat	Mitigation Strategies
Lead (Pb)	-Industrial emissions, mining, vehicle exhaust - Lead-containing pesticides and contaminated fertilizers - Sewage sludge and wastewater irrigation	-Inhibits root elongation and damages cell structure - Reduces chlorophyll content, causing chlorosis - Disrupts water balance, affecting metabolism - Decreases grain quality and accumulates in kernels	-Phytoremediation using Pb-accumulating plants (e.g., sunflower, mustard) - Organic amendments (e.g., manure, biochar) to immobilize Pb - Calcium and phosphorus fertilizers to reduce Pb bioavailability
Cadmium (Cd)	-Industrial waste, phosphate fertilizers, metal mining - Contaminated irrigation water, sewage sludge	-Interferes with water and nutrient uptake - Reduces chlorophyll synthesis, affecting photosynthesis - Stunts root and shoot growth - Accumulates in grains, posing health risks	-Soil amendments (biochar, organic matter, lime) to reduce Cd mobility - Growing Cd-tolerant wheat varieties - Crop rotation with Cd hyperaccumulators (e.g., Brassica species)
Arsenic (As)	-Industrial effluents, mining, contaminated groundwater - Pesticides and herbicides containing arsenic	-Alters metabolic pathways and enzyme activities - Causes root browning and stunted growth - Reduces seed germination and chlorophyll content - Increases grain arsenic concentration, making wheat unsafe	-Silicon and iron-based fertilizers to reduce uptake - Growing wheat varieties with low arsenic accumulation - Avoiding arsenic-contaminated irrigation water
Mercury (Hg)	-Industrial pollution, coal combustion, mercury-containing pesticides - Wastewater from chemical industries	-Disrupts cellular functions by binding to proteins and enzymes - Causes oxidative stress, leading to DNA damage - Reduces seed germination and plant growth - Accumulates in plant tissues, entering the food chain	-Bioaugmentation using mercury-resistant bacteria - Organic amendments to immobilize Hg in soil - Avoiding mercury-containing fertilizers and pesticides
Chromium (Cr)	-Tannery waste, textile dyes, industrial emissions - Electroplating industry waste, polluted irrigation water	-Inhibits root development and disrupts metabolism - Reduces photosynthesis by affecting chlorophyll biosynthesis - Causes oxidative stress, leading to early senescence - Affects protein and enzyme function, reducing yield	-Organic matter and biochar to reduce Cr bioavailability - Cr-resistant microbes to promote plant growth - Avoiding wastewater irrigation from tanneries
Nickel (Ni)	-Industrial activities, electroplating, mining - Sewage sludge, fertilizers, contaminated water	-Toxic at high concentrations, causing leaf chlorosis and necrosis - Interferes with iron uptake, leading to nutrient deficiencies - Inhibits seed germination and weakens plant defenses - Reduces protein synthesis and grain quality	-Organic amendments (compost, farmyard manure) to reduce Ni toxicity - Soil pH adjustment using lime to reduce Ni solubility - Crop rotation with Ni-accumulating plants (e.g. Alyssum species)

- ***Cadmium (Cd) stress**:* Inoculation with *Pseudomonas* strains SNA5 and PBB1 improved germination, root and shoot length, and overall growth.
- ***Chromium (Cr) stress**: Pseudomonas fluorescens* Q14 and *Bacillus thuringiensis* KAP5, possessing ACC deaminase and phosphate-solubilizing traits, enhance root (208%) and shoot (67%) growth, as well as dry biomass of roots (140%) and shoots (71%).
- ***Zinc (Zn) stress**: Pseudomonas aeruginosa* increased photosynthetic pigment content, improved growth parameters, and reduced oxidative stress indicators such as malondialdehyde (MDA) and antioxidant enzyme activity.
- ***Lead (Pb) stress**: Azotobacter* and *Azospirillum* strains enhanced membrane stability and grain yield while reducing MDA, proline, and hydrogen peroxide (H_2O_2) levels.
- ***Copper (Cu) stress**: Bacillus* sp. USTB-O, an IAA-producing strain, improved growth, reduced proline accumulation, and strengthened antioxidant defenses.
- ***General metal stress**:* Inoculation with *Azotobacter chroococcum* and other PGPR strains consistently reduced oxidative stress markers. *Bacillus subtilis* SU47 and *Arthrobacter* sp. SU18 were also effective in lowering antioxidant enzyme activity, indicating stress alleviation.
- ***Arsenic (As) stress**: Pseudomonas gessardii* and *Brevundimonas intermedia* increased dry biomass and reduced oxidative stress. Similarly, *Planomicrobium chinense* and *Bacillus cereus* lowered antioxidant enzyme activity under metal stress.

These findings demonstrate the potential of PGPR as a sustainable and eco-friendly strategy to enhance wheat growth and yield under heavy metal stress while simultaneously mitigating toxicity through improved physiological and biochemical responses.

Mitigation strategies for salinity in wheat

Salinity stress poses a major challenge to wheat cultivation, affecting plant growth, water uptake, and yield. Effective mitigation strategies include the development and use of salt-tolerant wheat varieties through traditional breeding and genetic engineering. Agronomic practices such as proper irrigation management, use of gypsum or organic amendments, and crop rotation help reduce salt accumulation in the root zone. The application of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi can enhance stress tolerance by improving nutrient uptake and reducing oxidative damage. Additionally, seed priming with osmoprotectants and foliar sprays of antioxidants or micronutrients can strengthen the plant's defense mechanisms, promoting better growth and yield under saline conditions.

Future prospects

Emerging strategies for combating heavy metal stress in wheat include advances in bioremediation, genetic engineering, and sustainable agronomic practices. Research is focusing on plant-microbe partnerships, including metal-tolerant rhizobacteria and mycorrhizal fungi, to enhance metal detoxification. Breeding and genetic modification aim to develop wheat varieties with enhanced tolerance and reduced metal uptake. Innovative tools such as nanotechnology, biochar, and organic soil amendments are proving effective in immobilizing metals and restoring soil health. Precision agriculture through targeted nutrient management and real-time soil monitoring further supports resilient wheat cultivation in contaminated areas. Combined with strong environmental regulations and ongoing research, these integrated approaches offer a path toward safe, productive, and sustainable wheat farming in heavy metal-affected regions.

SUMMARY

Heavy metal toxicity and salinity severely impacts wheat growth, physiology, and yield by inducing oxidative stress, impairing photosynthesis, and disrupting nutrient uptake. Toxic metals like cadmium (Cd), lead (Pb), mercury (Hg), nickel (Ni), chromium (Cr), and arsenic (As) accumulate in plant tissues, posing significant risks to human and animal health through the food chain. Mitigation strategies such as the application of plant growth-promoting rhizobacteria (PGPR), microbial bioremediation, phytoremediation, and the use of melanin-producing organisms offer effective and sustainable solutions. Additionally, the interaction between cadmium and zinc plays a critical role in determining the nutritional quality of wheat and warrants further study.

*Corresponding author email: rinkikhobra@gmail.com

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An overview of emerging trends in sodicity reclamation and enhanced food production

Parul Sundha*, Nirmalendu Basak, Arvind Kumar Rai, Priyanka Chandra, Amresh Chaudhary and Rajender Kumar Yadav

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Soil salinity and sodicity have emerged as serious environmental concerns worldwide. The poor soil structure, variability in soil chemical properties and low nutritional status restrict the crop growth with lower productivity in these soils. Around 50 % of the world's arable lands are moderately or highly affected by different levels of degradation. Sodic soils are characterized by high pH and exchangeable sodium percentage, poor hydraulic conductivity with large clay dispersion and significantly low nutrient availability. Gypsum application is the most widely adopted technology for sodic soil reclamation. However, considering the issues related to the availability and purity of mined gypsum, other alternatives are also explored. Some potential industrial by-products, organic sources, and conjunctive synthetic and organic formulations for rapid and cost-effective alternatives to degraded land reclamation are discussed in the article.

Keywords: Crop productivity, Degradation, Nutrients, Reclamation, Soil sodicity

INDIA accounts for 6.73 million hectares of land affected by salinity and sodicity, which impacts the livelihood security in arid and semi-arid regions. Out of this total salt-affected area, sodic soils account for more than 50% (3.77 m ha). The areas are expected to increase under extensive irrigation with RSC and high SAR water. Sodic soils, or alkali soils, contain higher levels of sodium (Na^+) relative to the calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil exchange sites and the soil solution. The exchangeable sodium percentage is more than 15, $pH_s > 8.2$ and variable ECe. The soils are characterized by poor physical structure with larger clay dispersion, less pore space and poor hydraulic conductivity. These soils are often low in organic matter and other nutrients. High alkaline hydrolysis, and toxic appearance of Na^+ and the precipitation of Ca^{2+} as $CaCO_3$ further exacerbate the Na-induced toxicity and nutritional deficiency. The widely used chemical ameliorants in saline – sodic soils are gypsum, elemental sulphur, phosphogypsum, FGD gypsum, silicious chalk, etc. Besides, organic sources such as farmyard manure (FYM), press mud, corn stalks, city waste compost, biogas slurry and crop residue are also used with reduced doses of gypsum to amend the salt-affected soils.

Sodic soil in Etah district of Uttar Pradesh

Sodic soil reclamation

Gypsum, chemically $CaSO_4.2H_2O$ is the most effective amendment source in sodic soils. The gypsum requirement (GR) is calculated based on the amount of salts present in the soil and other parameters like soil structure, water quality available for irrigation and crop variety opted. The reaction activity of the gypsum involves the replacement of Na^+ from the exchange complex by Ca^{2+} ions through leaching to the lower depths. Gypsum is made available to farmers through different agencies across the country, like the World Bank, European Union, and State Soil Reclamation and Development Corporations, other developmental agencies etc. It is reported that 2.10 M ha of alkali lands have been reclaimed by different technologies, with the largest area reclaimed in Punjab (0.79 M ha), then Uttar Pradesh (0.73 M ha), followed by Haryana (0.35 M ha) and a total of 0.70 M ha in other states.

Industrial waste by-products are other ameliorants having potential for reclamation of the degraded soils. Fly–ash contains nutrients like silicon (Si), aluminium (Al), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), phosphorus (P), and sulfur (S) essential for plant growth. It also contains micro-nutrients such as boron (B), copper (Cu), and zinc (Zn). Biomethanated spentwash (PBSW) is produced during the process methane gas generation from raw spent wash. It contains high organic carbon, calcium and potassium as nutrients for improved plant growth. Sugarcane processing industries produce pressmud with an estimated production of 3 tonnes of pressmud cake from 100 tonnes of crushed sugarcane. Utilization of pressmud in sodic soil amelioration is well reported.

Manures like farm yard manure (FYM) are low-cost, locally available source for application to degraded agricultural lands. It helps increase the amount of water-soluble salts, improves soil nutrients, and increases crop production. It also increases the cation exchange capacity and soluble and exchangeable K, restricting the Na^+ entry into the exchange complex and improving the soil structure, thereby supporting crop growth in sodic environment.

Innovative reclamation sources to combat soil sodicity

Sodic soil requires high Ca^{++} sources for replacing the Na^+ in the soil exchange sites and the soil solution. The mined gypsum with high purity and availability to the farmers is an issue nationwide. ICAR-CSSRI has explored some potential industrial by-products, organic sources, and conjoint synthetic and organic formulations for rapid and cost-effective alternatives to degraded land reclamation.

Flue gas desulfurization gypsum (FGDG), is the by-product of the coal-fired power generation plants produced during scrubbing of sulfur from combustion gases. Applications of FGDG in sodic soils supply Ca^{2+} ions to replace the Na^+ in the soil matrix and improve physico-chemical properties, reduce the nutritional losses and enhance the crop yield; thereby, increasing crop productivity. Co-utilization of FGDs with organic materials (manures, composts, bio-solids) is more beneficial in terms of improving soil physical and chemical properties and supply of essential nutrients. The FGD gypsum having a high purity percentage (>90%), could be a potential source of sodic soil reclamation.

Sulphuric acid (H_2SO_4) application in the calcareous sodic soils reacts with the soil calcium carbonate ($CaCO_3$) and releases calcium sulphate, neutralizing the free sodium carbonate in soils. Sulphuric acid also decreases the alkalinity of irrigation water, but the handling and transportation is an issue.

Elemental S is used to reclaim the calcareous–sodic soil. It is oxidized to H_2SO_4 by the microbial activities (*Thiobacillus thiooxidans*) under moist conditions and converts sodium carbonate and bicarbonate to sodium sulphate. Elemental sulphur-based formulation (Reliance formulated S) application increased 8–225% crop yield in low to highly sodic soils compared to unreclaimed sodic soils. The soil pH was reduced by 0.6–1.5 units with the application of sulphur after the crop harvesting in the first season with the benefit-cost ratio from 1.22 to 1.70 in different agro-ecologies.

Marine gypsum is another by-product produced in the coastal areas of Gujarat and Tamil Nadu during the production of common salt by solar evaporation. Approximately one tonne of salt production produces around 30–50 kg of marine gypsum and is expected to proportionally increase with the increased solar salt production in the nation.

Silicious chalk is the amorphous material recovered from the gypsum mines. It contains silica, calcium and other soil nutrients for sodic soil reclamation. The experiments conducted at farmers' fields have shown an increase in the yield of rice and wheat crops of sodic soils in Haryana and Punjab, and rice crop yield in acidic soils of West Bengal. Further, biological interventions for better nutrient use efficiency of silicious plants are being assessed.

The application of city waste compost (CWC) in the amelioration of high pH sodic soils improves the soil structure and aggregation, increases the

Alternate amendment sources for sodic soil reclamation

Improved crop growth in sodic soil at farmer's field in Nagawan village, Patiala, Punjab hydraulic conductivity and cation exchange capacity. The conjunctive use of the gypsum (25 GR) and CWC decreases the soil *p*H, accelerates the NaCl leaching, decreases the exchangeable sodium percentage, and increases water infiltration. The increase in the soil beneficial organisms tends to reduce the plant pathogens. It is reported that the sole application of gypsum in the sodic soils reduces the nitrogen and phosphorus availability; this can be improved with the CWC application in conjunction with gypsum. The rapid acidulation of the compost and manure with elemental S (S°) and S° oxidisers alleviates the sodicity stress by declining the soil pH within 28 days of soil incubation is an improved alternative to sodic soil reclamation.

The biogas slurry (BGS) is the by-product produced from the biogas plants as an emerging organic source for the nutrient-deficient, degraded sodic soils. BGS is a rich source of organic carbon, nitrogen, phosphorus, potassium and as well as micro elements like Ca, Zn, Mg, S, Fe, Cu, and Mn based on the type of feedstock used during the fermentation. The application of biogas slurry improves the organic content in soil, macro- and micro-nutrients in soil and reduces the N_2O emissions. The conjoint application of slurry (25% N requirement) and sub-optimal doses (75%) of NPK fertilizers has shown higher crop productivity and long-term nutrient sustainability. This fermented organic manure is reported to reduce the load of synthethic fertilizer requirement by 20%. The holistic approach works under the umbrella of government scheme 'GOBARdhan' towards integrated agri–waste management and organic feedstock digestate utilization for environmental stabilization and bio-circular economy, ensuring food safety and sustainable development.

Arbuscular Mycorrhizal Fungi (AMF) enhance the crop resilience under stress conditions, particularly in salt-affected soils (SAS). These fungi establish mutualistic associations with plant roots, forming extensive hyphal networks that significantly improve the uptake of growth-limiting nutrients such as phosphorus and micronutrients. Under salt-stressed environments, where nutrient availability and water absorption are limited, AMF maintain ionic balance by reducing sodium accumulation and promoting potassium uptake in crops, thereby protecting cellular functions. Additionally, they boost the plant's antioxidant defense system and modulate stress-related hormones, which collectively enhance tolerance to salinity. AMF produces organic acids and glomalin, which play a crucial role in chelating heavy metals, boosting carbon sequestration, preventing soil erosion, and stabilizing soil macro-aggregates ultimately contributing to improved soil health. Their mycelial hyphae aid in the formation of soil aggregates, thereby enhancing soil structure. Additionally, AMF also increases phosphorus availability in the soil through the synthesis of phosphatase enzymes. Phosphate-solubilizing bacteria (PSB) complement this process by releasing organic acids, siderophores, gluconic acid, and ketogluconic acid, which facilitate mineralization of organic phosphorus in the soil. Native AMF strains, being well-adapted to local soil and climatic conditions, offer a cost-effective and sustainable strategy for mitigating salt stress, reducing dependency on chemical inputs, and improving overall soil health through better structure and water retention.

SUMMARY

Soil sodicity deleteriously affects the soil health and crop productivity in many of the arid and semi–arid regions of the country and is aggravated with emerging secondary salinization. Gypsum application is one of the methods adopted for sodicity reclamation, but the issues of availability and purity of agricultural-grade gypsum have diverted attention towards the alternative sources. Presently, CSSRI is working on the utilization of elemental sulphur, flue gas desulfurization gypsum (FGDG), marine gypsum, silicious chalk, pressmud CWC, biogas slurry, AMF, etc. for the reclamation of sodic soils with larger stock availability. The farmers' field experiments are being conducted to assess the potential of emerging sources in refurbishing the sodic soils and boosting crop yield.

*Corresponding author email: parul34046@gmail.com

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Subsurface drainage technology for restoring crop productivity in waterlogged saline soils

Sagar D. Vibhute*, Satyendra Kumar, D. S. Bundela, Suresh Kumar, Anil R. Chinchmalatpure, Jitendra Kumar, Bhaskar Narjary, Raj Mukhopadhyay and Aslam L. Pathan

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Waterlogged saline soils are severely affecting crop production in irrigated areas of the country and appropriate technologies need to be adopted for their reclamation. Subsurface drainage (SSD) is proven technology for reclamation of such soils and about 1,10,000 ha area has been reclaimed in India using this technology. However, very high installation cost, non-availability of adequate trencher machines and need of region/soil specific design requirements has resulted in its adoption at very slow pace. The brief information of SSD technology covering its benefits, components, installation, and a few case studies of its performance in different parts of the country is presented in this article.

Keywords: Crop productivity, Food security, Sub-surface drainage technology, Waterlogged saline soils

LAND degradation poses significant threat for sustaining agricultural production in the country and climate change is further aggravating its impact on crop production. In the past, irrigation has played an important in Indian agriculture for safeguarding the nation's food security by ensuring availability of adequate irrigation water to high yielding varieties through extensive canal network. But at the same time, land drainage, an equally important aspect of integrated water resource management was simply ignored. This has resulted in severe problem of secondary soil salinization in canal command areas, mainly due to seepage from canals and over irrigation. The adoption of inefficient water management practices has also led to the waterlogging and soil salinity problems. Waterlogged saline soils occur on about 2 million hectares area in arid and semi-arid alluvial north western states of India and more than 1 million hectares each in coastal and black cotton soil (Vertisol) regions of the country. However, in India, area covered under subsurface drainage system is only about 80,000 ha; and the faster pace of adoption is required to achieve the land degradation neutrality goal by 2030. Subsurface drainage (SSD) is a successful technology for reclamation of waterlogged-saline soils and has given promising results across the soil types of the country. Apart from lowering water table to the desired level, it also removes excess soluble salts and thereby creates favourable condition for the crop growth.

Components of subsurface drainage system

However, proper design, installation and operation of drainage system is necessary to get desirable results. Further, sub surface drainage is science as well as art of removal of excess water, and thus, site-specific changes in lateral spacing should be adopted to improve the efficiency of the system and minimize cost of installation. Considering these factors, the wider adoption of this technology needs to be undertaken through advance design and installation methods, appropriate policy decisions, and financial support to the farmers.

Subsurface drainage consists of network of underground pipelines to remove excess water from agricultural fields. Depending upon the function, the pipes are classified as lateral, collector and main drains and different structures like manholes, sump and outlets are other parts of the system.

Table 1. Different components of modern-day SSD system

Component	Function	Specification
Lateral pipes	Primarily control the ground water table by intercepting water coming in root zone	Perforated single wall corrugated UPVC as per BIS 9271 80 mm most commonly used size 65 and 100 mm pipe sizes are also available
Collector pipes	Collects the water from individual lateral drains and convey it to the main drain/outlet	Double wall corrugated (DWC) HDPE pipes as per BIS 16098 Part 2: 2013 are generally preferred, size varies from 100 to 400 mm In severely waterlogged soils to avoid floating of the pipes, perforated UPVC pipes should be used, size varies from 100 to 355 mm
Pipe Main Drain	Used in large drainage projects where natural stream is far from outlet	DWC HDPE as per IS 16098 Part 2: 2013 Size can be up to 550 mm depending discharge and different dia. pipes may be used in project
Sump/ manholes	Manholes help in inspection and Sump collects water at outlet	Pre-fabricated RCC pipes are used Diameter of pipes are 0.9 and 1. 2 m Pipe lengths used are of 2.5, 3.75 and 5 m
Envelope	To trap entry of soil/foreign material in pipe to avoid its chocking and to improve hydraulic performance of drains	Non-woven poly propylene synthetic geotextiles (Thickness > 2.5 mm and O_{90}> 300 micron) for light and medium textured soils Non-woven poly propylene/ polyester fabric with needle punched geotextile for heavy textured soils Woven nylon 60 mesh socks for perforated collector pipes
Outlet	To safely dispose of highly saline effluents	Gravity outlets are used if deep surface drain is available nearby Otherwise, pumped outlets with suitable pump

Semi-mechanized installation

Fully-mechanized installation

Installation of sub surface drainage network

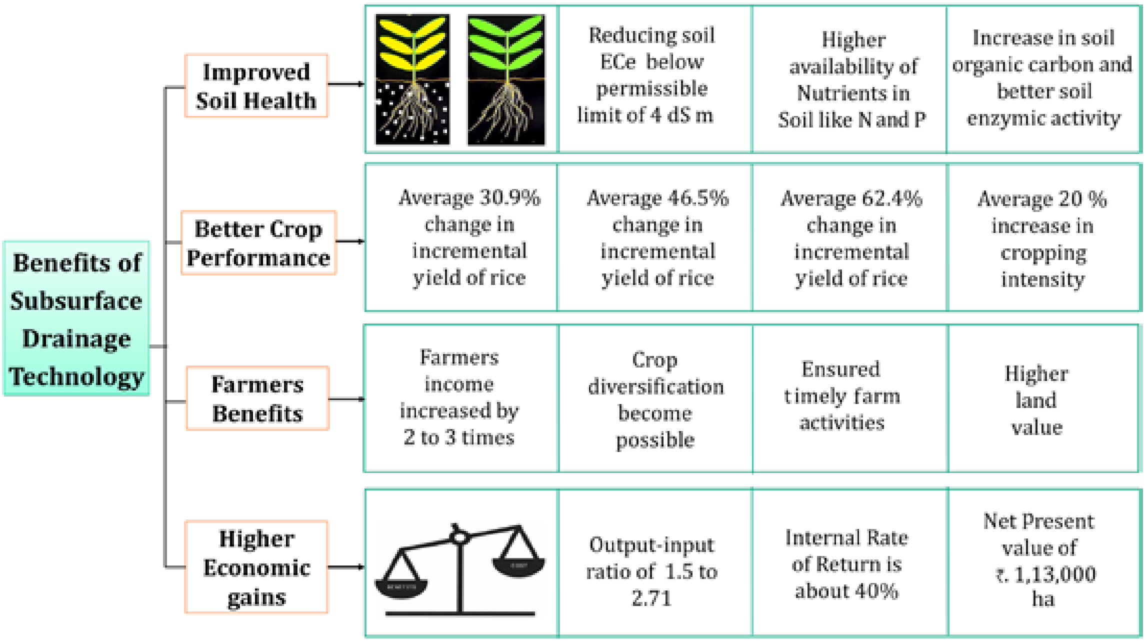
The installation of SSD system network consists of laying of perforated lateral and collector pipes, manhole and sump as per design. The installation work consists of excavation of trench, providing proper grade to the trench bottom, placement of drain pipes and backfilling of the trench. Depending upon the degree of involvement of machinery in these operations, installation procedure is classified as semi-mechanized and fully mechanized. In semi mechanized installation, trench of required dimensions is excavated using hydraulic excavator and subsequently desired grade is given manually. Backfilling is also done manually immediately after lowering the pipes. While in fully mechanized installation, grade control and pipe laying is carried out simultaneously by the drainage trencher machine which uses inbuilt laser guided grade control system. Subsequently trench is backfilled by bulldozer.

Design parameters of SSD for different regions: The drainage coefficient and drain spacing are the main design parameters of SSD system.

Table 2. Design parameters of SSD system

Drainage Coefficient (mm/d)			Drain Spacing (m)	
Climate	Range	Optimal	Soil Texture	Spacing
Arid	1–2	1	Light	100–150
Semi-Arid	1–3	2	Medium	50–100
Humid	2–5	3	Heavy	20–50

Benefits of SSD technology: The SSD system has multiple benefits in crop production such as improved soil health, enhanced crop yield, increase in farmers' income and higher economic gains.

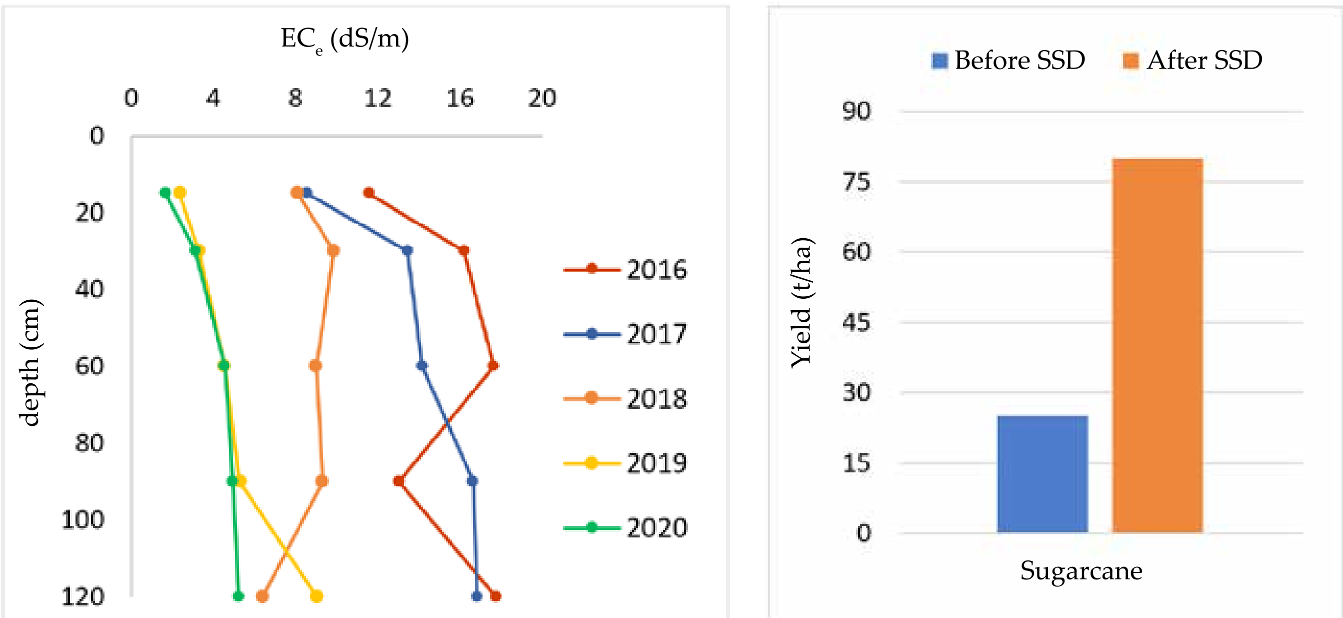


Case studies on SSD

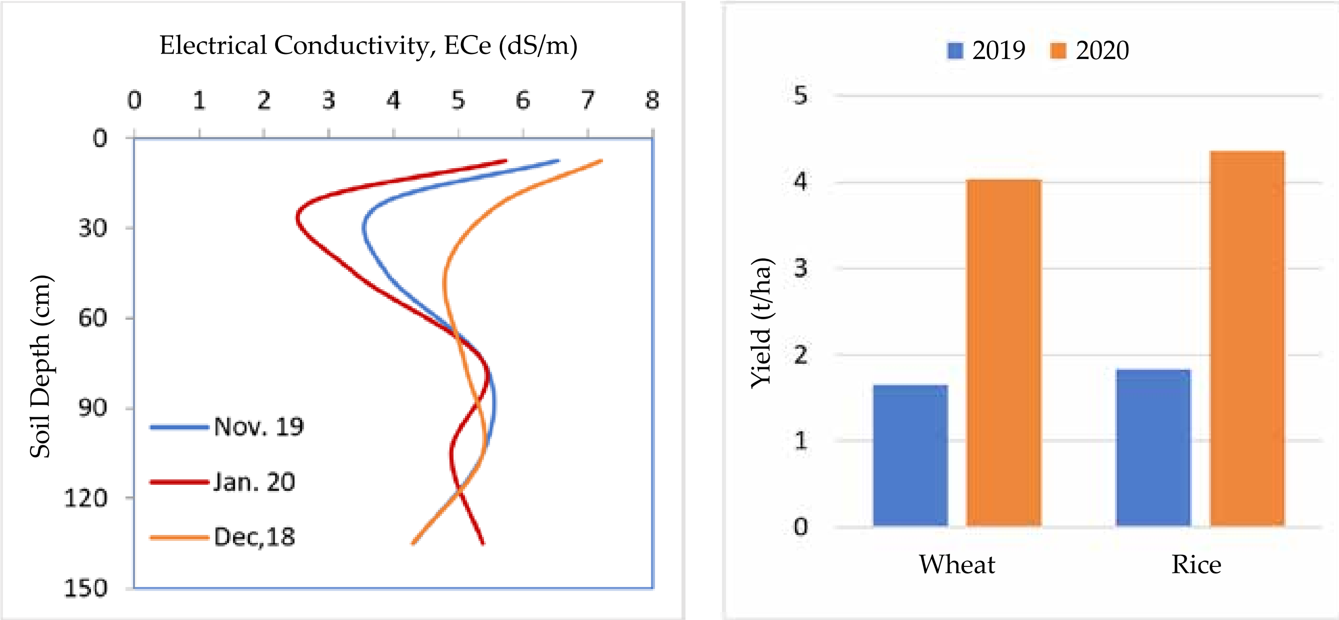
SSD in vertisols of Gujarat: Subsurface drainage system was installed in Adadara village of Bharuch district, having highly saline waterlogged black soil (ECe more than 10 dS/m in all soil layers) in order to reduce soil salinity and improve crop productivity. Prior to SSD installation, farmers of the village literally abandoned sugarcane cultivation due to highly unfavurable crop growth conditions and very low yield (~25 t/ha). SSD was installed in the month of February 2017 with a lateral spacing of 35 m and data pertaining to soil, water and crop was collected at regular intervals. Depth wise temporal variation in soil salinity is pictorially depicted, where in, drastic reduction in soil salinity (up to 86%) was observed.

The average electrical conductivity of soil (ECe) was less than 4 dS/m in surface layer (0—30 cm) whereas in subsurface layers (30–120 cm), it varied from 4 to 5.2 dS/m. This improvement in soil salinity was mainly attributed to timely efforts from the farmer to ensure proper drainage outflow from the sump. Forage crop was cultivated immediately after SSD installation and subsequently decrease in soil salinity by SSD system made sugarcane cultivation possible with significantly higher yield (80 t/ha) resulting into yield enhancement of more than 200%. Moreover, waterlogged conditions improved with water table going below 1 m. Overall, successful operation of SSD system for 4 years led to effective desalinization of the soil profile and hence improved soil quality, productivity and enhanced farm income.

SSD in alluvial soils of Haryana: The study was carried out at Kahni site of Rohtak district of Haryana (India) where subsurface drainage system was installed in 2016 in 160 ha land with 4 SSD drainage blocks. The depth of collector varied from 2.25–2.6 m and spacing of



Temporal variation in soil salinity and crop performance at Adadara SSD site



Reduction in soil salinity and enhanced crop productivity at Kahni SSD site

lateral pipe was 60 m. The collector pipe was connected with sump, installed in each SSD block near to surface drain. The excess water present in sub soil collected from the entire field through installed perforated pipe network to the sump and that was pumped in to the surface drain. Hence, salts were flushed out from the soil profile and created favourable environment for plant. The drainage effluent carried away from the agricultural field through surface drainage network.

A continuous change in salinity with time was recorded in whole soil profile which reveals an effective flushing of salts from the soil profile and disposal of drainage effluent away from the affected area. The soil salinity in sub soil (20–60 cm) reduced to normal (<4 dS/m) by the end of 3rd year of SSD installation. Interestingly, this area was waterlogged and operation of SSD ensured flushing of salt out of crop root zone by controlling groundwater level and facilitating leaching process. The reduced salt load in soil translated into improved performance of rice-wheat crops. An average yield of rice was recorded as 4.36 t/ha, and corresponding surface (0–15 cm) soil salinity ranged between 3.4 to 5.70 dS/m after successful operation of SSD system of 2 consecutive years. While, before installation of SSD, average rice yield was merely 1.83 t/ha, and thus yield enhancement of 138% was achieved. In wheat, average yield was found to be 1.65 and 4.03 t/ha, respectively for before and after the introduction of SSD, resulting into yield enhancement of 144%.

SUMMARY

Properly designed and maintained subsurface drainage system helps in removal of excess water and salts from the soil profile and subsequently enhances crop yield. The adoption of optimum drain spacing as per the soil hydraulic properties and adequate pumping in case of pumped outlet are the main factors governing the speed of reclamation of waterlogged saline soils. Moreover, availability of trencher machine and integration of laser guided grade control system in semi-mechanized installation is very much essential to increase the pace of installation of SSD system in India. Also adequate financial support should be provided to the farmers through government schemes or subsidies for early and wider application of this technology in severely affected areas.

*Corresponding author email: vibhutesagar5@gmail.com

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Commercial vegetable production

under protected structures in saline environments: A promising strategy for livelihood security

R. L. Meena*, B. L. Meena, Priyanka Chandra, S. K. Sanwal and Bhaskar Narjary

ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001

Salinity and water scarcity are major constraints in arid and semi-arid regions of India, where a large share of groundwater is saline. Protected cultivation through polyhouses, shade nets and tunnels provides a viable option for vegetable production under such environments. These structures improve microclimate, enhance water and nutrient use efficiency and enable the safe utilization of saline water. Crops like tomato, capsicum and chilli perform well under drip fertigation and raised-bed systems in polyhouses. Technologies such as grafting, mulching, soilless media and saline water blending reduce salt stress and improve yield and quality. With higher profitability, employment generation and government support, protected cultivation offers a promising strategy for livelihood and nutritional security.

Key words: Climate resilience, Livelihood security, Polyhouse, Protected cultivation, Saline water irrigation, Vegetable production

IN India's arid and semi-arid regions, the problem of water scarcity is particularly acute. States like Rajasthan, Gujarat, Haryana, southwestern Punjab, and northwestern Uttar Pradesh frequently face erratic and low rainfall coupled with poor-quality groundwater. Surveys report that 32–84% of the groundwater in these regions is saline or alkaline, severely affecting sustainable crop production. However, studies suggest that saline water with EC levels up to 11 dS/m can be used successfully for certain crops when appropriate irrigation methods are adopted. Among these, drip irrigation under protected cultivation has shown considerable promise by allowing precise water application, minimizing salt stress, and protecting crop foliage. India's diverse climate ranging from freezing winters to scorching summer sposes additional challenges to open-field vegetable cultivation. Despite being the world's second-largest vegetable producer, India faces low per capita availability due to traditional practices, low yields, and susceptibility to climatic stress. To meet rising demand and ensure nutritional security, expanding vegetable production through improved varieties and scientific farming methods is essential. Protected cultivation systems such as polyhouses, shade nets, low tunnels, and plastic mulches offer a sustainable solution. These structures create favourable growing conditions, reduce water use, enable off-season production, and support the safe use of saline water, ultimately improving crop quality and profitability.

Vegetables are vital for human nutrition and farmer livelihoods. Their commercial value has grown rapidly, outpacing cereals in recent decades. In 2014–15, vegetables were grown on just 2.8% of India's cropped area, yielding 169.47 million tonnes from 9.52 million hectares. States like Haryana produced 5.5 lakh tonnes from 373.17 thousand hectares, showing considerable potential for growth (National Horticulture Board 2015). Given the twin challenges of water scarcity and climate variability, there is an urgent need to promote sustainable and innovative farming approaches. Efficient saline water use and expansion of protected vegetable cultivation can play a key role in securing food supplies, enhancing incomes, and sustaining agriculture under changing environmental conditions.

Understanding salinity and its effects on crop

Salinity refers to the accumulation of soluble salts in soil and water, mainly sodium (Na^+), chloride (Cl^-), and sulfates (SO_4^{2-}). These salts inhibit seed germination, disrupt nutrient uptake, reduce photosynthesis, and affect plant water relations. In vegetables, this leads to lower yields, poor-quality fruits, and in some cases, complete crop failure. Among vegetables, tomato exhibits moderate tolerance to salinity, while crops like cucumber and okra are more sensitive. Managing salinity requires site-specific interventions, particularly when using saline water with electrical conductivity (EC) above 2 dS/m. Additionally, prolonged exposure to high salinity reduces microbial activity in soil, negatively influencing nutrient mineralization. This leads to nutrient deficiencies and imbalances in plants. Secondary stresses, such as oxidative stress from reactive oxygen species (ROS), also accumulate, further impairing plant metabolism and growth.

Soil salinity can be classified as natural (primary) or induced (secondary), with secondary salinity often resulting from human interventions like improper irrigation practices and lack of drainage. Identifying the type of salinity and implementing appropriate agronomic and engineering solutions is essential for long-term management.

Protected cultivation: An overview

Protected cultivation or controlled-environment agriculture (CEA) uses structures such as greenhouses and polyhouses to shield crops from external stresses. These systems facilitate: Better temperature and humidity control, reduced pest and disease pressure, efficient water and nutrient use, and Enhanced crop quality and yield. CEA practices are particularly suited to India's agro-climatic zones, enabling year-round vegetable production even under extreme temperatures or degraded soils. These systems also enhance resource use efficiency critical in water-scarce, salinity-affected areas.

Types of structures

- ***Greenhouses:*** Fully controlled environments for high-end production with temperature, humidity, and CO_2 regulation.
- ***Polyhouses:*** Semi-controlled and cost-effective structures ideal for smallholders using locally available materials.
- ***Shade net houses:*** Simple and economical, reducing light intensity and preventing heat stress. Ideal for nursery production.
- ***Low tunnels:*** Temporary mini-structures that protect seedlings and early-stage crops from salinity and temperature extremes.
- ***Walk-in tunnels:*** Intermediate structures offering partial climate control with lower cost than full greenhouses.

Each structure type has unique advantages, and selection depends on crop type, location, economic feasibility, and farmer experience.

Suitable vegetable crops for saline protected cultivation

Many vegetables exhibit differential tolerance to salinity. Those with moderate tolerance, short duration, and high value are preferred under protected cultivation in saline condition. Other crops like spinach, lettuce, broccoli, coriander, and fenugreek also show promise under regulated environments with optimal nutrient and water management.

Table 1. Salinity tolerance limits (ECiw) of selected vegetable crops and recommended adaptation strategies for cultivation under saline irrigation conditions

Crop	Salinity tolerance (ECiw)	Adaptation strategies
Tomato	Up to 10 dS/m	Grafting, drip irrigation
Capsicum	Up to 6 dS/m	Mulching, soilless media
Green Chilli	Up to 6 dS/m	Raised beds, saline water blending
Eggplant	Up to 3.5 dS/m	Salt-tolerant rootstocks
Okra, Cucumber	Up to 2.5 dS/m	Shade net, frequent leaching
Leafy Greens	Up to 2.0 dS/m	Soilless cultivation, misting systems

Pest and disease management

Protected cultivation environments often create favourable conditions for the rapid build-up of pests and diseases, primarily due to high humidity levels. Effective management requires an integrated approach. Integrated Pest Management (IPM) combines cultural, biological, and chemical control methods to ensure

Drip-irrigated tomato seedlings planted in raised beds inside a naturally ventilated polyhouse

Performance of capsicum and tomato under 10 dS/m saline water irrigation

Performance of chilli under 10 dS/m saline water irrigation

sustainable crop protection. The use of bioagents such as *Trichoderma*, *Pseudomonas*, and neem-based biopesticides helps in reducing the dependence on synthetic chemicals. Preventive measures like insect-proof netting and yellow sticky traps are useful in controlling insect vectors. Maintaining proper sanitation and practicing crop rotation help minimize the carryover of pathogens between crop cycles. Additionally, advanced monitoring tools including pheromone traps, thermal foggers, and decision-support system said in early detection and timely intervention, thereby reducing crop losses and enhancing productivity.

Table 2. Key challenges in protected cultivation under saline environments and corresponding mitigation strategies

Challenge	Solution
High capital cost	Government subsidies; FPO or SHG-based ownership
Salinity build-up	Drainage, gypsum use, rotation with salt-tolerant crops
Skill gap	Training by ICAR/KVKs, demo units, mobile apps
Pest/disease outbreak	IPM practices, regular monitoring
Climate stress	Thermally insulated covers, side vents, misting
Market access	Linking with FPOs, digital platforms, cooperative models
Input availability	Localized production of seedlings, nutrient kits

Techniques for salinity management in protected cultivation

To maximize vegetable performance under saline conditions, specific practices and technologies are adopted in protected cultivation systems. These reduce salt accumulation in the root zone and improve crop resilience.

- ***Soilless media:*** Substrates like cocopeat, perlite, and vermiculite offer excellent drainage and aeration, which dilute salt effects and promote root health.
- ***Leaching salts through controlled irrigation:*** Excess salts can be leached below the root zone by applying controlled volumes of low-salinity water through drip irrigation or during off-season flushing. Periodic leaching maintains the root zone EC within acceptable limits.
- ***Use of grafted plants for improved salt resistance:*** Grafting salt-sensitive scions onto salt-tolerant rootstocks improves the plant's physiological tolerance to salinity. Grafted tomatoes and melons exhibit improved water uptake, nutrient absorption, and reduced sodium translocation to shoots. This technique is gaining popularity in saline-prone regions under protected farming.
- ***Salt-tolerant cultivars and hybrids:*** Selecting salt-tolerant vegetable varieties or hybrids is the most sustainable long-term approach. Examples include

salt-tolerant cultivars of tomato (e.g. 'PusaRohini'), chilli (e.g. 'Pusa Sadabahar'), and brinjal (e.g., 'Arka Neelkanth'). Protected environments further buffer these cultivars from abiotic stress, enhancing yields.

- ***Mulching to reduce evaporation and surface salt accumulation:*** Mulching with plastic films or organic materials (e.g. straw, compost) minimizes soil evaporation, thereby reducing upward salt movement. Helps maintain stable soil temperature and moisture. Reduces weed pressure and promotes beneficial microbial activity in the root zone.

Water management in protected cultivation

Efficient water management is essential for successful crop production under protected cultivation, especially in saline environments. Drip irrigation delivers water directly to the root zone, minimizing evaporation losses and ensuring efficient use. Fertigation, which combines irrigation with fertilizers, allows for precise nutrient application while maintaining salt balance in the root zone. Rainwater harvesting systems are useful for collecting and storing quality water, helping to dilute salts and reduce long-term salinity buildup. Blending saline water with fresh water ensures that the electrical conductivity (EC) of irrigation water stays within crop-specific safe limits. Subsurface drainage systems aid in leaching accumulated salts and maintaining overall soil health. Additionally, automated irrigation systems equipped with soil moisture sensors help regulate water flow accurately, ensuring crops receive the right amount of water at the right time.

Nutrient managementin protected cultivation

Proper nutrient management is critical for maintaining soil fertility and crop productivity under protected and saline conditions. Balanced application of macronutrients (NPK) and micronutrients, tailored to the specific crop and growth stage, ensures optimal plant development. In sodic soils, gypsum (calcium sulfate) is applied to replace sodium ions and improve soil structure. Foliar sprays of micronutrients like iron (Fe), zinc (Zn), and manganese (Mn) help correct deficiencies often caused by high soil pH. Regular monitoring of parameters such as EC, sodium adsorption ratio (SAR), and *p*H is essential to prevent salt accumulation and nutrient toxicity. The use of organic fertilizers and microbial inoculants further enhances nutrient availability, improves soil health, and increases crop resilience to environmental stress.

Economic feasibility and farmer benefits

Protected cultivation offers substantial returns, especially when market demand and quality premiums are considered. Polyhouse production ensures round-the-year employment and income, especially for women and youth. Surplus production may be marketed directly or through FPOs. Additional benefits include:

- Promotion of women entrepreneurship through nursery and value-addition units

Table 3. Yield and gross returns of selected vegetable crops under protected cultivation in an area of 300 m^2

Vegetable Crop	Yield ($q/300m^2$)	Gross Returns (₹)
Tomato	31.75	1,98,099
Capsicum	12.89	1,38,052
Green Chilli	10.78	1,15,525

- Total Production Cost: ₹2,15,623
- Net Present Value (NPV): ₹6,25,711
- Benefit-Cost Ratio (BCR): 1.41
- Payback Period: 2 years

- Climate resilience through protected structures against extreme weather
- Higher employment due to labour-intensive nature of precision farming

Policy support and future prospects

The Government of India has taken several initiatives to promote protected cultivation, recognizing its potential to enhance productivity, improve resource use efficiency, and ensure year-round vegetable supply. Key schemes such as Mission for Integrated Development of Horticulture (MIDH), Rashtriya Krishi Vikas Yojana (RKVY), National Horticulture Board (NHB), and National Mission for Sustainable Agriculture (NMSA) provide strong policy backing. Farmers can benefit from various forms of assistance including capital subsidies of up to 75%, credit-linked back-ended subsidies, and technical guidance through ICAR institutes. Moreover, protected cultivation is now recognized under priority sector lending through the Agri-Infrastructure Fund, encouraging investment in climate-resilient technologies. Looking ahead, future prospects for protected cultivation are promising with the integration of digital tools for precision fertigation, adoption of solar-powered irrigation systems, and the development of carbon credit models that reward climate-smart practices. Technologies like blockchain can enhance traceability and help farmers achieve premium prices, while e-commerce platforms offer new avenues for direct-to-consumer vegetable sales, strengthening market linkages and farmer profitability.

SUMMARY

Protected cultivation under saline environments offers a viable pathway for sustainable vegetable production. It helps utilize degraded lands and brackish water efficiently, generating high income from small holdings. With suitable policy, institutional, and technical support, it can transform rural economies by ensuring food, income, and nutritional security in salt-affected areas. Farmers must be empowered through capacity-building, public-private partnerships, and inclusive market linkages. Scaling these systems across India's saline zones could play a pivotal role in achieving rural prosperity and climate-resilient agriculture.

*Corresponding author email: rlmeena69@gmail.com

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Use of modern digital techniques for mapping and assessment of salt-affected soils

Amresh Chaudhary[1]*, Sandeep Kumar[2], Nirmalendu Basak[3], Parul Sundha[1], Priyanka Chandra[1] and A. K. Rai[1]

[1]*ICAR-Central Soil Salinity Research Institute, Karnal, Haryana 132 001*
[2]*ICAR-National Bureau of Soil Survey and Land Use Planning, Regional Centre, Jorhat, Assam 785 004*
[3]*ICAR-National Bureau of Soil Survey and Land Use Planning, Regional Centre, Kolkata 700 091*

Soil salinity is a growing global challenge, threatening agricultural productivity and food security. Conventional methods for diagnosing salt-affected soils such as visual inspection, field sampling, and laboratory testing have long provided essential insights but remain time-consuming, costly, and limited in spatial coverage. Recent advances in geospatial technologies, particularly remote sensing, geographic information systems (GIS), and machine learning (ML), are transforming how soil salinity is detected, mapped, and managed. Optical remote sensing now enables large-scale monitoring by capturing spectral signals linked to salinity stress, while predictive algorithms such as random forests, support vector machines, and neural networks enhance mapping accuracy across diverse landscapes. Digital Soil Mapping (DSM) builds on these innovations by integrating multi-source environmental data with advanced models to generate high-resolution, continuous maps of soil salinity, offering actionable intelligence for precision agriculture. In India, pioneering applications of DSM have shown promising results, from improving fertilizer efficiency and water use in Maharashtra to large-scale initiatives like the Soil Intelligence System in Andhra Pradesh, Bihar, and Odisha. The ICAR-Central Soil Salinity Research Institute (CSSRI) has also advanced national-level salinity mapping efforts, combining legacy soil data with remote sensing and ML approaches. Emerging tools such as UAVs further add local-scale precision, enabling dynamic monitoring of soil health. Together, these developments illustrate how DSM is reshaping salinity diagnostics, bridging science and practice, and paving the way for more sustainable land management strategies in the face of climate change and increasing soil degradation.

Keywords: Digital soil mapping, Machine learning, Remote sensing, Soil salinity

SOIL salinity, the accumulation of excessive salts in the soil, is one of the primary causes of soil degradation globally. According to the Food and Agriculture Organization (FAO), salt-affected soils (SAS) cover 1381 million hectares or 10.7 % of total land area globally, with the extent increasing in regions that depend heavily on irrigation. The spread of SAS is expected to worsen due to the dual impacts of climate change and unsustainable agricultural practices (FAO 2024).

Classification and diagnostic methods for salt-affected soils

SAS can be classified into saline and sodic soils based on their composition and properties. Saline soils have high concentrations of soluble salts, while sodic soils are characterized by excess sodium. Diagnosing the presence of these soils traditionally involves measuring the electrical conductivity (EC) and sodium adsorption ratio (SAR) of the soil.

While traditional diagnostic methods are critical for soil health assessments, they face significant challenges, including being labour-intensive and spatially limited. Furthermore, such methods often lack the ability to provide high-resolution spatial data on soil salinity, especially across large areas.

Advancements in geospatial technologies for salt-affected soil diagnostics

Recent advancements in geospatial technologies have revolutionized the monitoring and mapping of SAS. Remote sensing (RS), geographic information systems

(GIS), and machine learning (ML) techniques have enabled the large-scale, high-resolution mapping of salt-affected areas. The integration of these technologies allows for the creation of digital soil maps that provide predictive, continuous data on soil salinity across vast regions.

Remote sensing and soil salinity detection

Salt-affected soils (SAS) are a major challenge for farmers, especially in arid and semi-arid regions where white crusts of salt often appear on the surface, stunting crops and reducing yields. Traditionally, diagnosing and mapping these soils relied on physical inspections, soil testing, and expert judgment. For instance, farmers and soil scientists would look for visible salt crusts, poor vegetation cover, or stressed plants as warning signs. Field surveys and sampling at different depths then helped determine the extent and severity of salt accumulation. In the 1990s, researchers even started using satellite images in "false colour" mode, where experts drew boundaries around areas that looked similar in colour, brightness, or texture—essentially hand-mapping salinity based on experience. While these conventional methods have played a crucial role, they are far from perfect: They are time-consuming, labour-intensive, and limited to discrete sampling points that cannot capture the full variation of salinity across large landscapes.

This is where modern geospatial technologies have changed the game. By combining remote sensing, GIS, and machine learning, scientists can now map salinity with much greater accuracy and efficiency. Instead of collecting hundreds of soil samples, satellite data can be fed into predictive models to estimate soil salinity over entire districts or regions. This approach provides a continuous picture of salt distribution and allows for large-scale monitoring something that was impossible with traditional methods.

RS in particular has become a powerful ally in the fight against soil salinity. Satellites can capture information from areas that are difficult to reach, track changes over time, and even distinguish subtle differences in soil or vegetation health. Optical remote sensing uses spectral reflectance—how soils and plants reflect light at different wavelengths to infer salinity levels. For example, stressed plants or bare salty patches reflect light differently from healthy vegetation, providing clues about underlying soil conditions. With frequent satellite passes, scientists can monitor how salinity changes over months or years, offering valuable insights for land management.

Studies have shown that newer satellites like Sentinel-2 perform better than older ones like Landsat, largely due to their higher resolution (10 meters vs. 30 meters) and more frequent coverage (every 5 days instead of 16). Sentinel data has been found to predict soil salinity with about 70% accuracy, compared to 66% for Landsat. But satellites alone are not enough—scientists also use algorithms ranging from simple regression models to advanced machine learning techniques like Random Forest (RF), Support Vector Machines (SVM), and neural networks offering superior predictive performance compared to traditional geostatistical methods like Kriging. Each has its strengths: Neural networks can capture complex non-linear relationships, while RF reduces the risk of overfitting. Although no universal algorithm has emerged as the global "best fit," machine learning consistently outperforms traditional methods for salinity prediction.

However, challenges remain. For example, in agricultural areas, spectral signatures of saline soils can be confused with other bright surfaces like roads, buildings, or even nearby salt ponds. Vegetation-based indices such as NDVI (Normalized Difference Vegetation Index), EVI (Enhanced Vegetation Index), or the Canopy Responsive Salinity Index (CRSI) are often used as indirect measures, since salinity affects crop growth and canopy temperature. Yet no single index works equally well across all regions. The Vegetation Soil Salinity Index (VSSI), for instance, is effective in coastal zones but often misclassifies dry, bare soils as saline in arid regions.

To overcome these hurdles, scientists are increasingly turning to Digital Soil Mapping (DSM). DSM combines remote sensing data with environmental variables such as climate, topography, and land use, and uses predictive models to generate continuous maps of soil salinity. Unlike conventional mapping or simple index-based methods, DSM can capture spatial variability more accurately and is adaptable to diverse landscapes. In effect, DSM is helping move soil salinity studies from isolated observations toward dynamic, data-driven solutions that support precision agriculture and sustainable land management.

Digital soil mapping (DSM)

DSM is a powerful approach for predicting soil properties over large areas using geospatial data and advanced modeling techniques. The SCORPAN model is often used in DSM to predict soil properties by integrating spatial and environmental covariates such as climate, topography, parent material, and vegetation. The equation for DSM is typically represented as SCORPAN model given below:

$$S= f\,(S, C, O, R, P, A, N) + \varepsilon$$

Where S, Soil attributes at an unvisited location; f, Numerical model (e.g. decision tree, random forest, deep learning); C, Climatic properties; O, Organisms, vegetation, or human activity; R, Relief or slope; P, Parent material, lithology; A, Time factor (age); N, Location or relative spatial information; ε, Auto-correlated random spatial variation.

So, DSM can be defined as computer-assisted production of digital interpolated maps of soil properties using machine learning, deep learning, ensemble models or other statistical models that pool information from soil observations with information contained in correlated environmental variables as mentioned earlier in the previous paragraph as climate, organisms (presented through various remote sensing based indices), relief and parent material.

The application of DSM for salt-affected soils helps in producing high-resolution, continuous maps that overcome the limitations of traditional polygon-based mapping. DSM also benefits from the integration of remote sensing data, GIS, and other environmental data sources, allowing for real-time updates and dynamic monitoring of soil salinity.

Case studies related to use of DSM in India

DSM is quietly transforming Indian agriculture, with several success stories showing how data and technology can reshape the way farmers manage their soils. In Maharashtra's Vidarbha region, often associated with low productivity and farmer distress, digital soil health mapping using IoT sensors and geospatial tools has helped cotton and soybean growers cut fertilizer use by nearly 15%, save 20% water, and still boost yields by 25–30%. In Odisha's Khordha district, GIS-based nutrient maps revealed that more than 70% of farmland was acidic and nitrogen-deficient, giving farmers and policymakers the evidence they needed for targeted soil amendments. Further east, in Assam's Upper Brahmaputra Valley, researchers applied machine learning to predict soil organic carbon across silk-producing landscapes, providing vital insights into carbon storage and sustainable land management. In Tamil Nadu, scientists used legacy soil data with advanced models like Random Forest to generate 250-meter resolution maps of soil depth, texture, and coarse fragments, producing invaluable tools for precision farming and environmental planning. Large-scale initiatives are also underway: Soil Intelligence System (SIS) in Andhra Pradesh, Bihar, and Odisha is combining soil health card data, geo-statistics, and digital dashboards to create user-friendly soil maps built on FAIR data principles, while Bihar Agricultural University has embarked on a state-wide digital soil mapping programme aiming to cover all 38 districts by 2028. Together, these efforts demonstrate how DSM can empower farmers with actionable knowledge, reduce costs, improve soil health, and set Indian agriculture on a more sustainable and resilient path.

CSSRI's initiatives in digital soil mapping of salt-affected soils

The ICAR-Central Soil Salinity Research Institute (CSSRI) had developed a computerized database and visual interpretation-based maps of salt-affected soils, including saline, sodic, and saline-sodic categories, covering the entire country. Over time, significant advancements have been made in the tools and methodologies used for soil salinity mapping. Recently, Mandal *et al.* (2023) generated a coastal salinity map using linear regression models, integrating laboratory-measured electrical conductivity of saturation paste extract (ECe) data from various coastal locations with remote sensing indices. Their study estimated that approximately 1.294 million hectares of coastal land are affected by salinity. However, a comprehensive and high-resolution map of salt-affected soils across the entire country is still lacking.

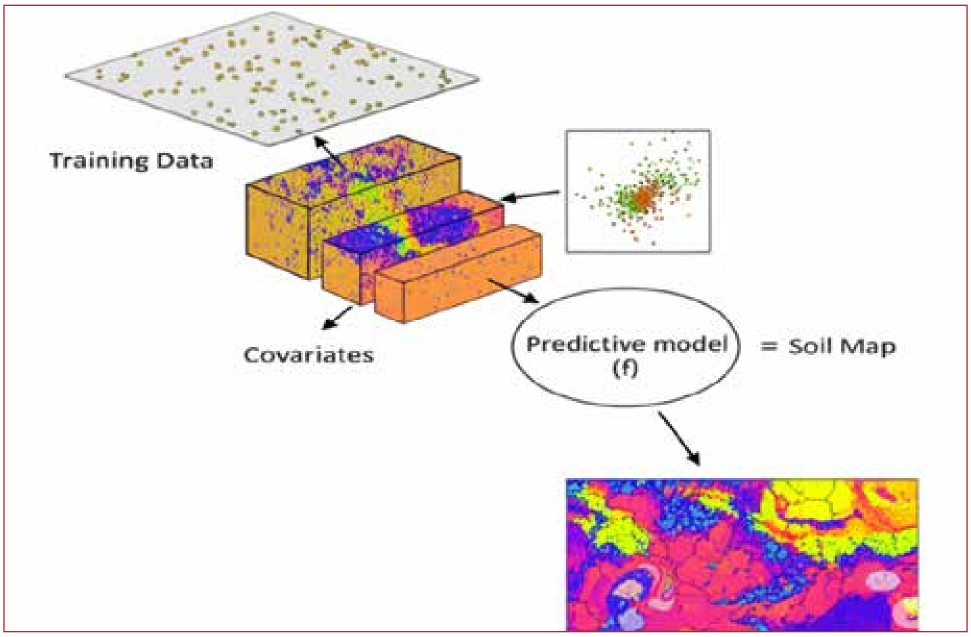
To address this gap, CSSRI has initiated the development DSM of salt-affected soils at the national level using advanced machine learning algorithms. These models integrate field observations with multi-source remote sensing datasets to generate predictive maps of salt-affected areas across India, offering improved spatial accuracy and aiding in evidence-based management and reclamation strategies.

Integration of UAVs in DSM for salt-affected soils

Unmanned Aerial Vehicles (UAVs) have emerged as an important tool in DSM, particularly for local-scale soil mapping. UAVs offer high-resolution data acquisition, flexibility in data collection, and the ability to operate in inaccessible areas. Studies have demonstrated their potential for mapping soil organic carbon (SOC) and other soil properties, which are essential for assessing soil salinity.

Future perspectives and challenges

The future of DSM in salt-affected soils will rely on further integration of machine learning, remote sensing, and environmental covariates to enhance predictive accuracy. Challenges remain in handling large-scale datasets, overcoming the impact of cloud cover, and improving sensor fusion techniques for better salinity detection across diverse land uses. The development of



Flow chart of digital soil mapping technique (AI-generated image) hybrid models and the incorporation of more remote sensing variables, such as land management practices and climate variability, will help improve the accuracy and reliability of DSM.

SUMMARY

Digital Soil Mapping (DSM) represents the future of soil salinity diagnostics. By integrating advanced remote sensing, geospatial technologies, and machine learning techniques, DSM offers a more efficient, cost-effective, and precise way to monitor salt-affected soils. The continued advancement of these technologies, along with the development of more refined modelling approaches, will enable better soil management and land use planning, contributing to sustainable agricultural practices and land conservation efforts.

*Corresponding author email: amu8805@gmail.com

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Waste wool technology in arid horticulture: Promoting sustainability and circular economy

Anita Meena*, M. K. Jatav, Manpreet Kaur and R. P. Meena

ICAR-Central Institute for Arid Horticulture, Bikaner, Rajasthan 334 006

Arid and semi-arid regions face significant agricultural limitations due to environmental and soil-related challenges such as erratic rainfall, poor soil fertility, and extreme temperatures. These constraints hinder horticultural productivity, which relies on stable soil moisture and nutrient availability. To promote sustainability and productivity in these regions, attention has shifted toward using locally available resources. One such resource is waste wool, a by-product of sheep rearing is an important livelihood in arid zones. Though unsuitable for textiles, waste wool is rich in organic carbon and nutrients, making it an effective soil amendment. When applied to horticultural systems, it improves soil structure by increasing porosity, moisture retention, and organic content. This not only enhances plant growth in harsh climates but also promotes ecological sustainability. Moreover, utilizing waste wool reduces agricultural input costs, turning a low-value by-product into a valuable resource. This practice strengthens the resilience of arid-zone horticulture and supports rural economies by aligning with circular economy principles. Overall, use of waste wool offers a practical and sustainable solution to improve soil health, increase productivity, and support environmental stewardship in arid and semi-arid regions.

Keywords: Ecological, Rural economies, Soil health

A substantial quantity of organic waste and by-products is generated globally each year, much of which holds significant potential for reuse within agricultural and horticultural systems. Among these by-products, waste generated by the wool industry represents an underutilized resource with considerable value for sustainable farming. The global wool industry produces millions of tonnes of wool annually, but a large fraction of this yield is categorized as waste, as well as due to fiber irregularities or poor quality unsuitable for textile applications. Traditionally, much of this wool waste has been discarded in landfills or incinerated, leading not only to environmental degradation but also to a significant loss of potential organic resources. The growing recognition of the circular economy framework has emphasized the need to reintegrate such waste streams into productive cycles. Within this paradigm, agricultural and horticultural systems are seen as key sectors for integrating organic by-products, since soils can act as natural sinks for biodegradable residues.

The reutilization of waste wool in horticultural production thus fits seamlessly into this approach, providing a sustainable alternative to conventional practices that rely heavily on chemical inputs and non-renewable resources. The urgency of such innovations has been amplified by the increasing challenges facing global agriculture. Climate change has intensified the frequency of droughts, heatwaves, and erratic rainfall, particularly in arid and semi-arid regions where water scarcity severely constraints crop production. Additionally, continuous land use, overreliance on chemical fertilizers, and unsustainable cultivation practices have accelerated soil degradation, reducing fertility and organic matter content while increasing susceptibility to erosion and salinization. These challenges necessitate the adoption of ecologically sound and resource efficient methods that not only maintain productivity but also enhance the resilience of cropping systems. Against this backdrop, wool waste offers unique advantages as a renewable, biodegradable, and nutrient-rich material that can be harnessed to improve soil quality and plant growth.

Chemically, wool is primarily composed of keratin proteins, along with other fibrous proteins such as collagen and elastin. These proteins are rich in nitrogen, sulfur, and carbon, which are essential elements for

Waste wool application under drip irrigation in arid region

plant growth. During decomposition, wool fibers release these nutrients slowly, making them available over extended periods and reducing the risk of leaching losses that are often associated with synthetic fertilizers. This controlled nutrient release contributes to long-term soil fertility and supports sustainable crop production. In addition to its nutrient profile, the fibrous structure of wool improves the physical properties of soil. When applied as a soil amendment, wool enhances porosity, aeration, and water infiltration, thereby facilitating better root penetration and nutrient uptake by plants. Another important attribute of wool waste is its exceptional capacity for water retention. Wool fibers can absorb moisture up to several times their own weight, gradually releasing it into the soil and maintaining a more stable micro-environment around the plant roots. This feature is especially beneficial in arid and semi-arid regions where water availability is the most limiting factor for horticultural production. By conserving soil moisture and reducing the frequency of irrigation, wool mulch or amendments can help farmers adapt to water scarcity and improve water-use efficiency. Furthermore, when used as mulch, wool suppresses weed growth by limiting light penetration to the soil surface, reducing competition for water and nutrients. It also buffers soil temperature fluctuations, protecting delicate root systems from extreme heat in summer and cold in winter.

In summary, the utilization of waste wool in horticultural systems offers a compelling example of how agricultural by-products can be reimagined as valuable resources. Its rich nutrient composition, water-holding capacity, biodegradability, and soil-improving properties make it a promising input for sustainable horticulture. At the same time, it addresses pressing challenges related to waste management, soil degradation, and water scarcity. By aligning with the principles of the circular economy, adoption of wool waste technology contributes not only to enhancing productivity and resilience in arid regions but also to reducing the environmental footprint of agriculture. As research and innovation in this field continue, waste wool has the potential to play a significant role in shaping future strategies for sustainable and climate-resilient horticulture.The utilization of wool waste as a soil amendment offers numerous benefits, primarily due to its inherent properties that enhance soil health and support sustainable agricultural practices.

- ***Moisture conservation:*** Waste wool, rich in nitrogen and protein, acts as an effective mulching material. It significantly conserves water by reducing evaporation from the soil surface, making it particularly valuable in arid and semi-arid regions. This property can partially or fully replace conventional chemical fertilizers, promoting resource-efficient farming.
- ***Organic mulch:*** When applied as an organic mulch, waste wool enhances the soil's water-holding capacity and creates a more favourable environment for soil microflora, boosting microbial activity and biodiversity. It also stabilizes soil temperatures, protecting plant roots from extreme thermal stress. This leads to improved soil health and better plant performance.
- ***Soil amendment:*** Incorporated into the soil, waste wool fibers improve soil structure by increasing porosity, which enhances air circulation and water infiltration. This is especially beneficial for sandy or degraded soils, improving their water retention and supporting better plant growth and drought resilience.
- ***Organic fertilizer:*** Waste wool is a valuable organic source of essential plant nutrients, typically containing about 50% carbon, 16–17% nitrogen, and 3–4% sulfur. It functions as a slow-release fertilizer due to its complex chemical structure, which resists rapid microbial degradation. While pre-treatment methods like hydrolysis can accelerate nutrient availability, its application demonstrably improves soil organic carbon and nitrogen, enhancing long-term soil fertility and productivity.

Waste wool: A sustainable solution for horticulture in hot arid zones

Hot arid zones globally grapple with agricultural challenges like low and erratic rainfall, extreme temperatures, poor soil fertility, and limited organic matter. These factors restrict crop productivity and

Crop performance under waste wool application

threaten the livelihoods of farming communities. Interestingly, these very regions are also home to significant sheep-rearing activities, which generate large quantities of waste wool that is unsuitable for textile industries due to its coarse texture, contamination, or low quality. This waste wool presents a remarkable opportunity for horticulture in arid ecosystems. When applied to barren or degraded soils, waste wool helps create a favourable micro-environment for plant growth. Its fibrous structure captures and retains atmospheric moisture, fostering a localized humid microclimate that stimulates microbial activity. This microbial proliferation enhances nutrient cycling, improves soil structure, and gradually increases organic matter, making the soil more fertile and conducive to crop production. Waste wool also functions as a natural mulch, conserving soil moisture, regulating temperature fluctuations, and suppressing weeds critical benefits under arid conditions.

Crops grown with wool based amendments can serve as fodder for sheep, reintegrating livestock and horticultural systems while closing nutrient loops. This innovative recycling model minimizes waste, enhances resource efficiency, and reduces reliance on external synthetic inputs. Environmentally, it promotes soil rehabilitation, combats land degradation, and supports the establishment of vegetative cover in fragile landscapes. Economically, it lowers input costs, increases sustainability, and provides added value to otherwise discarded wool, benefiting resource-constrained farming communities.Thus, waste wool emerges as a low-cost, eco-friendly, and sustainable solution for improving horticulture in hot arid zones while simultaneously strengthening livestock-crop integration.

SUMMARY

Integration of waste wool into arid horticulture provides a sustainable resource efficient approach to address the challenges of arid zone. The waste wool has the potential of being used as a mulch, soil amendment and organic fertilizer owing to its fibrous structure, nutrient content and moisture retention capacity. Owing to resource poor structure of arid zones, use of waste wool as a horticultural or horticultural input contributes to circular economy and prevents environmental biodegradation. The environmental benefits of waste wool use along with its economic advantage makes it a suitable option for promotion of sustainable horticulture in arid zone.

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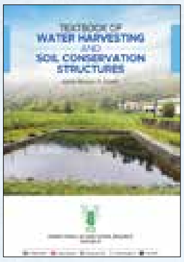

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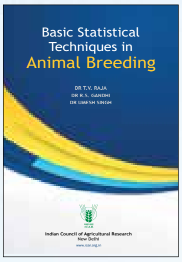

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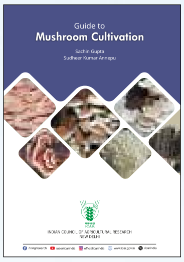

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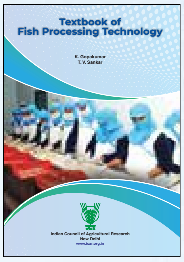

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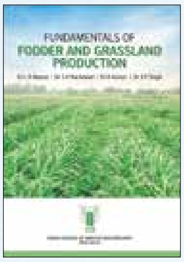

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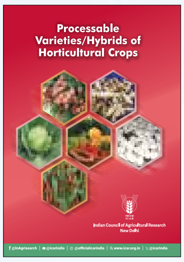

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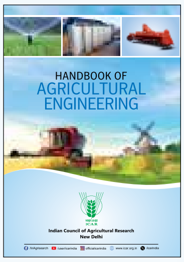

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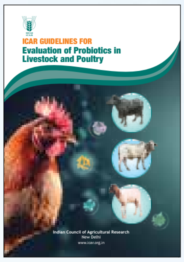

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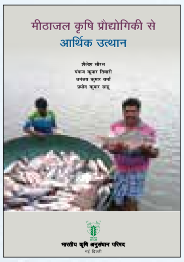

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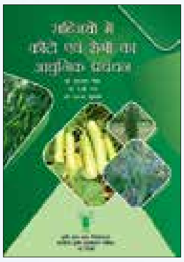

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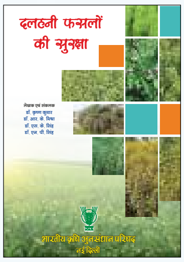

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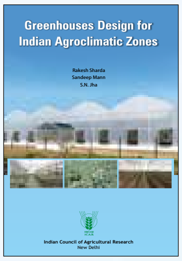

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   - Advancements in understanding of physiological mechanisms of salt tolerance in plants
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   - Impact of climate change on salinization processes and carbon sequestration
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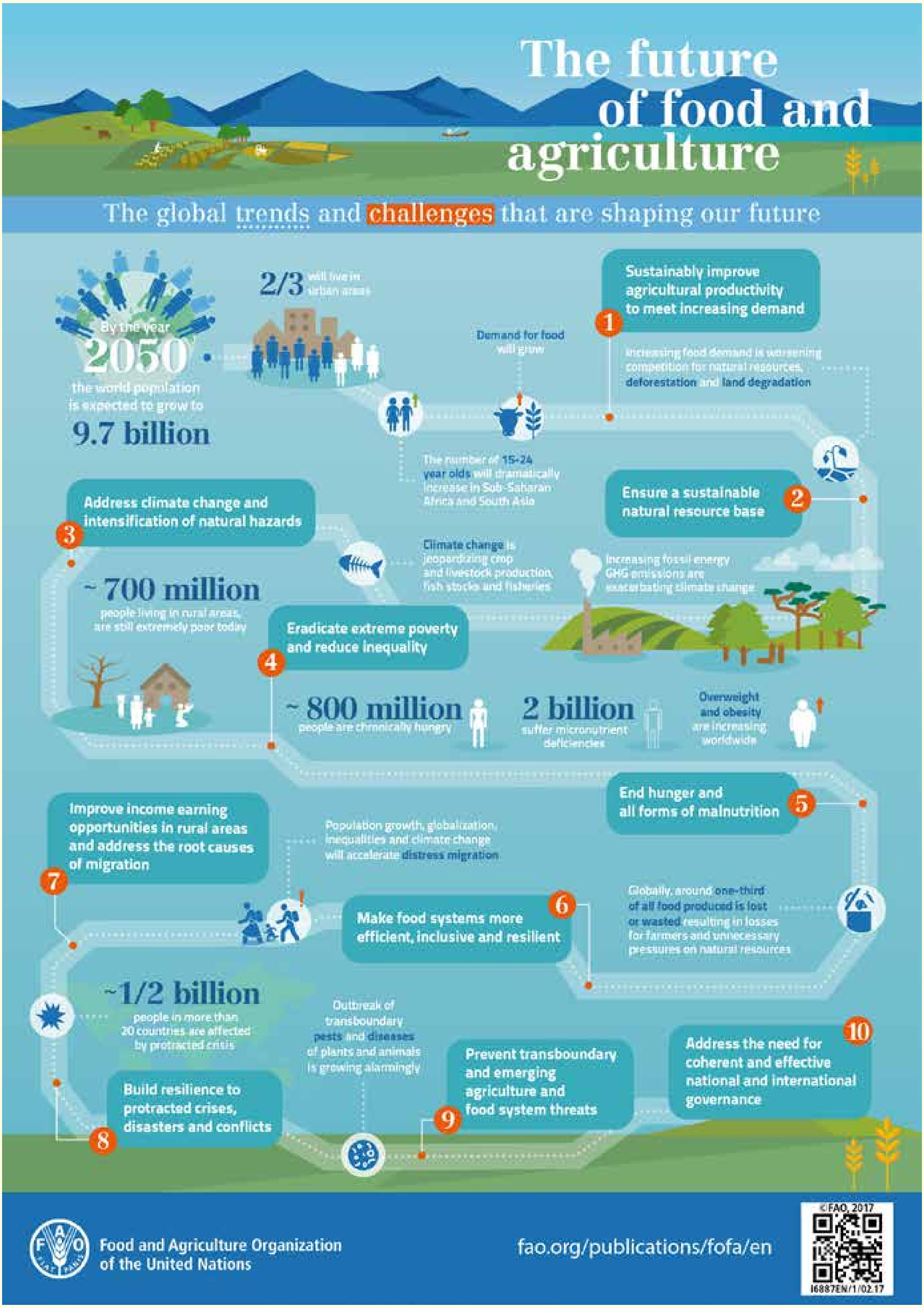

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