Journal of Soil Salinity and Water Quality

Volume: 16 No. 2 2024 ISSN 0976 – 0806

SPECIAL ISSUE
on Restoring Salt–affected Ecologies in Changing Climate
in commemoration of Global Soils Conference 2024

Editors
JC Dagar
Jitendra Kumar
Gajender Yadav

Indian Society of Soil Salinity and Water Quality

Central Soil Salinity Research Institute

Karnal-132 001 (India)

Indian Society of Soil Salinity and Water Quality

(Registration No: ROS-088, Dated 6th August 2008)

Website: www.issswq.in

For online submission of articles (https://epubs.icar.org.in/index.php/JoSSWQ). For subscription, editorial enquiry and advertisements, please contact: isswq2008@gmail.com, dagarjc@gmail.com, dsbundela@gmail.com.

Membership Subscription

SNo.	Category of Membership	Subscription charges	
		Inland (₹)	Foreign ($)
1.	Life Member	4,000	250
2.	Annual Member	450	50
3.	Student Member (One year)	250	25
4.	Institutional Member (Lump sum for 30 years)	25,000	-
5.	Institutional Member (Annual)	3,500	-

Membership fee may be sent through Multicity cheque only in favour of Indian Society of Soil Salinity and Water Quality, payable at Kamal. The payments can also be deposited online into Society account (Through NEFT) with intimation to society office (Secretary/Treasurer).

Name of account holder: **Indian Society of Soil Salinity and Water Quality**; **Account number: 30451467955** (Saving Bank account); **IFS Code: SBIN0000665**; Bank and Branch: **State Bank of India, Main Branch, Karnal**

Journal of Soil Salinity and Water Quality

Journal of Soil Salinity and Water Quality (JSSWQ) serves as an official organ of the Indian Society of Soil Salinity and Water Quality (ISSSWQ) for the publication of reviews, research papers and short communications as per constitution and by-laws of the society. Soft and hard copy of the journal are sent free to all its members. All disputes are subject to the exclusive jurisdiction of competent court and forums in Kamal only. The society does not assume any responsibility for opinion by the authors in the articles and no-material in any form can be reproduced without the prior permission of the society. The society is not responsible for any delay, whatsoever, in publication/ delivery of the periodicals to the subscribers due to unforeseen circumstances or postal delay. The society does not vouch for any claims made by the advertisers of products and services. The publishers and the editors shall not be held liable for any consequences in the event of such claim not being honoured by the advertisers.

ISSN 0976-0806

Journal of Soil Salinity and Water Quality

Volume 16 **2024** **Number 2**

CONTENTS

Acknowledgement

Indian Society of Soil Salinity and Water Quality, ICAR-Central Soil Salinity Research Institute, Karnal, is Thankful to the Indian Council of Agricultural Research, New Delhi for Financial Assistance to Support the Publication of the Journal.

Editorial

The impacts of soil salinity and sodicity are profound, affecting millions of hectares of land globally and presenting significant challenges to agricultural productivity, ecosystem health, and local livelihoods. As the effects of climate change intensify, the need for effective and sustainable management strategies for salt-affected landscapes has never been more urgent. This special issue of the Journal of Soil Salinity and Water Quality "Restoring Salt-affected Ecologies in Changing Climate" aims to address these challenges by presenting cutting-edge research and solutions from leading experts in the field.

This special issue is published under the aegis of the Global Soils Conference-2024, themed "Caring Soils Beyond Food Security: Climate Change Mitigation & Ecosystem Services", organized by the Indian Society of Soil Science in collaboration with the International Union of Soil Sciences, Italy. The conference and this publication serve as platforms for disseminating knowledge, innovative practices, and integrated solutions for managing soil and water quality under changing environmental conditions.

The timely contribution by different authors is also acknowledged.

Editors
Special Issue

Journal of Soil Salinity and Water Quality 16(2), 143-151, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156501

Impact of Large-Scale Sodic Soils Reclamation Projects in India: Key Insights for Policy Implications

Suresh Kumar[1]*, Sanjay Arora[2], Rajkumar[1], Ram Kishor Fagodiya[1], Satyendra Kumar[1], Kailash Prajapat[1], Rohtash Kumar[1], Bhupender[1] and RK Yadav[1]

[1]ICAR-Central Soil Salinity Research Institute, Karnal-132001, Haryana
[2]ICAR-Central Soil Salinity Research Institute, Regional Research Station, Lucknow-226002, Uttar Pradesh
Corresponding author's E-mail: skdagri@gmail.com

Abstract

Uttar Pradesh state in India is vital for national food security, requiring sustainable rehabilitation of sodic soils predominant in the state. The *Uttar Pradesh Bhumi Sudhar Nigam* (UPBSN) has led sodic land reclamation programme since 1993 with World Bank support. This study aims to: (a) analyse the project design; (b) assess the impact of the Uttar Pradesh Sodic Lands Reclamation Projects (UPSLRPs); and (c) summarize lessons learnt. The reclamation efforts significantly improved crop yields and agricultural productivity, while enhancing local villagers' awareness and skills in resource management. Grassroots institutions were crucial for executing activities that aimed at poverty alleviation through sodic soil reclamation. Over three project phases, activities improved soil health, provided quality inputs, and fostered collaborative resource management. The project also promoted crop diversification, gender equity, women's empowerment, and livestock productivity. Additionally, improved infrastructure and market access, led to better price realization of produce. A key insight was the importance of engaging local communities in land reclamation projects.

Key words: Policy insights, Land reclamation projects, Sodic soils, Local communities

Introduction

With 14.98% (19.55 mha) and 17.77% (56.11 mt) share in total area under food grain (130.58 mha) and its production (315.72 million tons - mt), Uttar Pradesh (UP) state in India is a significant contributor of food security of the nation (MoAFW, 2022). The primary agricultural production system in the state is characterized by the rice-wheat cropping system (RWCS), with share of 11.72% (15.27 mt) and 31.77% (33.95 mt) of India's rice (130.29 mt) and wheat (106.84 mt) production, respectively (MoAFW, 2022).

The pressure on natural resources in the state can be realized by the fact that as per population census (2011), Uttar Pradesh (UP) is the most populous state in India with a population of about 199 million (SIP, 2022), which account for 16.5% of the total population of the country. In the State, approximately 80% of the population in UP lives in the rural areas, and about two-thirds (66%) of them are dependent on agriculture for their livelihoods. Over the years, the share of agriculture in the state domestic product (SDP) has declined from about 33% in 1999-2000 to 26.15% in 2020-21 (MoAFW, 2022). The performance of agriculture in UP is constrained by numerous issues such as low land productivity, land degradation (Nayak, 2006; Arora, 2020), small land holdings, weak dissemination of agricultural technology, and weak systems for delivering agricultural credit (Kumar *et al.*, 2020). The extent of the degraded land is around 7.45 to 3.88 mha, which is ~31% and 13.2% of the total area of the state (Nayak, 2006). Among the various states in India, Uttar Pradesh stands have the largest area under salt-affected soils, ~ 1.37 mha. This area accounts for nearly 20.5% of the total salt-affected soils in the country i.e., 6.73 mha (Yadav, 1993). Of the total salt-affected area in the state, 98.4% area is sodic (Mandal, 2010), and salinity affected area is concentrated predominately in Agra and Mathura region, this region also has issue of poor-quality groundwater (Yadav, 1993). The issue of salt-affected soils within the state was first identified in 1876 by Mr. David Robarts, who deployed to the Board of Revenue for relief (Yadav, 1993; Yadav, 2024). In Uttar Pradesh, land reclamation emerges as a critical issue, particularly given that the state ranks among the poorest in India, with a substantial percent of its inhabitants relying on agriculture as their main means of subsistence (Kuehnast, 2001). Sodic soils represent a high level of degradation, characterized by severely compromised physical conditions. The characteristics and origins of alkalinity in these soils differ significantly across various locations. Salt-affected soils are developed due to several factors, including salt accumulation from runoff, poor drainage from low hydraulic conductivity, and high sodium concentration in soils. Nearby unlined canals cause water table fluctuations that promote capillary rise, leading to alkali salt accumulation on the soil surface in summer (Tiwari *et al.,* 1983). Expanded canal network was not supported by effective soil and water management practices. Consequently, vast expanses of agricultural land in the command areas of major canals became more susceptible to waterlogging and salinity. However, the government dedicated considerable resources to the reclamation of affected area but the desired outcomes highly inconsistent (World Bank, 2004). With mounting pressure on land resources coupled with potential detrimental effects of climate change, one of the key approaches for achieving food and nutritional security involves the sustainable restoration of soils impacted by salinity, alkalinity, and other challenges (Verma *et al.*, 2021). In light of these formidable challenges and their adverse impacts on agricultural land availability and productivity, the Government of Uttar Pradesh (GoUP) has identified the reclamation of sodic soils as a critical priority area for investment. This initiative is driven by concerns regarding the degradation of natural resources and the potential social benefits it could yield. World Bank was involved with anticipation of supporting the scaling-out the sustainable production technologies along with capacity building of local institutions, playing an integral role in the reclamation process (World Bank, 2004). As a part of this strategy, *Uttar Pradesh Bhumi Sudhar Nigam* (UPBSN), a nodal agency for reclamation project, started reclaiming sodic land with the support from World Bank in 1993 (Nayak, 2006). In the Sodic Lands Reclamation Projects (SLRPs), the community participation was an integral part for ensuring the effective and efficient implementation of planned activities.

With this backdrop, the objectives of the study were: (a) to understand the framework of the project design; (b) to assess the impact of the UP sodic lands reclamation projects (UPSLRPs), and (c) synthesize the lesson learned from the UPSLRPs. This study is primarily based on the project implementation completion and results report project and mid-term review (MTR) reports of UPSLRPs. This is also worth mentioning that due to non-uniformity of the parameters assessed for evaluation of different phases i.e. Phase-I (1993 to 2001), Phase-II (1997 to 2007) and Phase-III (2009-2018), we could not report the outcome in comparable terms in the study. The first section of the paper deals with framework of the project design, second section represents the impact of the projects, and third section summarises the key learnings from the projects, and finally conclusion and policy implications are presented.

Framework of sodic lands reclamation project design

With the UP Bhumi Sudhar Nigam (UPBSN) was the project implementing agency, world bank funded, the Phase-I (1993-2001) initiative was built upon the lessons learned from the state government's previous efforts to restore salt-affected soils. It became evident that prior attempts had not yielded the expected outcomes, largely due to a lack of robust mechanisms to promote farmer participation, weak institutional frameworks, and poor collaboration among stakeholders. As a result, the first phase of the Sodic Lands Reclamation Project focused on enhancing community engagement and implementing an integrated strategy for land reclamation. The involvement of farmers was crucial to the reclamation initiative; however, facilitating this participation proved to be challenging. In villages where reclamation activities took place, site implementation committees (SICS) and water user groups (WUGs) were established. The SICS functioned as the local governance entity responsible for the dissemination of information related to the project, facilitating decision-making processes, and overseeing the execution of reclamation initiatives at the village level. This committee comprised beneficiaries from the community, alongside officials from various government departments, *Mitra Kisan*, *Mahila Mitra Kisan*, representatives from non-governmental organizations, and project personnel. The *Gram Pradhan* was the president of the SIC. The activities undertaken by the SIC encompassed the distribution of essential inputs, such as gypsum for land reclamation, the assignment of tasks for the construction of link drains, land classification, the upkeep of the drainage infrastructure, and the resolution of conflicts. The WUG was an informal group of 10-15 farmers managing a 4-5 ha area cluster. UPBSN field personnel and NGO representatives encourage the formation of WUGs, where members elect a chairman and co-chairman. They utilize a borewell, either newly drilled or existing, for irrigation, with pump ownership shared or individual. WUGs ensure equitable water distribution and facilitate the construction and maintenance of irrigation systems, functioning as part of SIC. Financial transactions for on-farm development are processed through WUG bank accounts. In the beginning of the project, it was recognized that these entities were not functioning effectively prompted the organization of training sessions for UPBSN staff by NGOs, focusing on the formation and development of WUGs. Additionally, a participatory cell was established within UPBSN. Significant attention was also directed towards raising awareness and encouraging villagers. The project's strategic sequencing of activities played a vital role in fostering farmer commitment to agricultural development on the reclaimed lands (World Bank, 2004).

The sodic lands reclamation project in Uttar Pradesh, India had two main goals. The first goal was to reverse the decline in agricultural productivity through the sustainable reclamation of sodic lands. The second goal was to mitigate

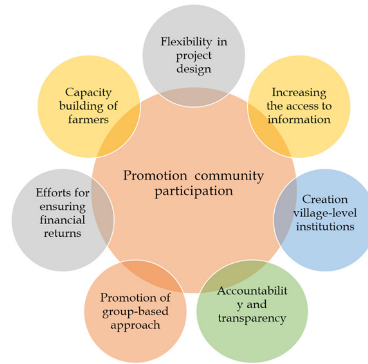

Fig. 1 Measures taken-up for promoting the community participation in the reclamation efforts

further increases in sodicity by fortifying local institutions and promoting effective management of reclamation programs, ensuring strong involvement from beneficiaries and support from non-governmental organizations (NGOs). This initiative was instrumental in reducing poverty for families engaged in the management of sodic lands (Kuehnast, 2001). For promoting a host of the measures were taken up (Fig. 1). Collective efforts are key to success to management of salt-affected soils as even economically viable may fail to yield the desired outcome with a proper institutional setting (Datta and Joshi, 1993). Therefore, efforts were made to improve the access to information thereby develop an understanding among the affected community about the adverse implication of the sodicity on the production and farm income. Additionally, efforts were made to taken up collective action for reclamation for productive use of the affected land.

To this end, group-based approach was followed along with of local institutions (Water user group) were created within villages that enable residents to exchange information, engage in discussions, and collaboratively address significant reclamation challenges. Water user groups were formed to share resources (e.g., water) and manage field drains, link drains, and irrigation channels. The focus was laid on the capacity building by imparting the technical guidance of the so as to participate effectively in reclamation activities. Project was designing with an emphasis on flexibility to enable a higher level of farmer participation in activities whenever possible.

Key components of the sodic lands reclamation project

The sodic lands reclamation project (1993-2001) was the first World Bank support for reclamation of sodic soils in India. During the initial phase-1, UPBSN was reinforced in its operational capacity concerning land reclamation, participatory management, and the dissemination of technology. This involved a comprehensive restructuring of the organization, where essential functions were assigned to full-time managers, and new offices were set up at the district level (World Bank, 2004). The details of the objectives and components are presented in Table 1. In the phase-I major components were relating to: First, strengthening of the UPBSN and the Remote Sensing Application Centre (RSAC). UPBSN, a government undertaking of Uttar Pradesh, is registered under the Companies Act and operates under the department of agriculture. Since its inception in 1978, the organization has aimed to safeguard the health and productivity of land resources. UPBSN was strengthened for ensuring the better co-ordination among the line-departments and stakeholders for implementation of the planned activities of the project. RSAC was expected to identify and monitoring of changes in soil and groundwater environment. Second, to achieve successful land reclamation, efforts were made to develop an efficient drainage infrastructure, apply gypsum, improve irrigation techniques, and assist in the cultivation of food and tree crops on privately held land, while also fostering the growth of forest tree species on communal lands. Third, the component i.e., agricultural development and technology dissemination included demonstrating reclamation techniques for cultivating crops, fruit trees, and forestry on sodic soils, establishing nurseries for fruit tree seedlings, and providing extension services with motivational campaigns and promotional materials through mass communication. In the fourth component, an adaptive research methodology was employed to

Table 1. Phase-wise objective and components of Sodic Lands Reclamation Project

Phase-1 (1993 to 2001)	Phase-II (1997 to 2007)	Phase-III (2009-2018)
Objectives		
To improve agricultural productivity in areas with a high concentration of sodic lands and was to be implemented over a 7-year period in 10 districts of the Uttar Pradesh state. 1. To develop models for environmental protection and improved agricultural production through large-scale reclamation of sodic lands; 2. To strengthen local institutions to manage such schemes; and 3. To contribute to poverty alleviation of the families concerned.	To ensure sustainable reclamation of sodic lands and prevention of further increases in sodicity in selected districts with the highest concentration of sodic areas in UP, which would contribute significantly to poverty alleviation in these areas	To increase agricultural productivity on degradedlands in selected areas of Uttar Pradesh by: 1. Reversing water-induced land degradation; 2. Enhancing soil fertility; and 3. Improving the provision of agricultural support services
Key Components		
1. Institutional development 2. Land reclamation 3. Agriculture development and technology dissemination 4. Reclamation technology development and special studies	1. Land reclamation and on-farm development 2. Main drain remodelling and maintenance: 3. Technology dissemination 4. Upgrading farm to market roads 5. Human resource development and institutional capacity building 6. Adaptive research 7. Project management	1. On-farm development and land treatment 2. Improvement of drainage systems 3. Agriculture support services 4. Institutional strengthening and capacity building for market access 5. Project management

enhance the then prevailing reclamation technologies, diversify cropping systems, and establish strategies aimed at preventing the further spread of sodicity. ICAR-Central Soil Salinity Research Institute (CSSRI) gypsum technology and other technical inputs for sodic soil reclamation including salt tolerant varieties of paddy and wheat were extended through RRS, Lucknow. Synergy of reduced gypsum @ 50GR and the salt tolerant varieties as low-cost sodic soil reclamation technology of ICAR-CSSRI that suits the resource poor small and marginal farmers of the state was adopted by UPBSNL in the 3rd phase of reclamation project.

The total investment was in three phases, namely, the phase-I, II and III of the sodic lands reclamation project was 103.7, 311.6 and $ 617.35 million, respectively. At the 2024 prices using the exchange rate @83.85, the value of the total investment was INR 51765 million, of which the highest share was from international development association (IDA)(~69.2%), followed by local community (beneficiaries) with ~21.1$ and ~9.7% from government of Uttar Pradesh. During the Phase-I, of the total investment ($ 103.71M), roughly, 10.45, 64.52, 22.57 and 2.46% was allocated for the institutional development, land reclamation, agriculture development and technology dissemination, and reclamation technology development and special studies, respectively. Similarly, in the phase-II of the total investment ($ 311.60 M), which was implemented with seven components, as shown in the Table 1, around 58.38, 12.96, 1.12, 12.13, 3.53, 0.19 and 11.71% of the total fund was allocated for component-1, 2, 3, 4, 5, 6 and 7, respectively. We could analyse the similar distribution pattern for Phase-III due to non-availability of the data. From this distribution pattern it is evident that around 58-64% of the funds were used for the reclamation of the sodic soils in the state (Table 2).

Coverage of the sodic lands reclamation project

For effective implementation of the soil rehabilitation works, ~88 thousands WUGs (water user group) were formed. Total area reclaimed was 68,414 ha, 1,89,700 ha and 1,42,677 ha in phase-I, II and III, respectively. Thus, ~4,00,971 ha was treated from 1993-2018 under the sodic lands reclamation project funded by world bank. Another important activity was related to rehabilitating the main-drains to manage the water-logging conditions, under this nearly 13847 km length equivalent drains were rehabilitated (Table 3).

Impact of the sodic lands reclamation project

During the Phase-I, the paddy and wheat yield increased by 101 and 56% over the pre-intervention levels of the yields, more specifically paddy yield increased to 2.99 Mg ha^{-1} from the 1.49 Mg ha^{-1}, and wheat productivity increased to the level of 2.61 Mg ha^{-1} from its 1.67 Mg ha^{-1} from its pre-project levels. Similarly, during the phase-II, paddy and wheat yields increased by ~278% (0.90 Mg ha^{-1} to 3.40 Mg ha^{-1}) and ~650% (0.40 Mg ha^{-1} to 3.00 Mg ha^{-1}), respectively. The relatively higher increase in yields can be attributed to weak base effect as this phase ~67% of the lands were of class C (almost barren lands), the same was ~50% in case of phase-II. For the phase-III, segregated data on paddy and wheat yields were available but the change in productivity was reported in terms of the food grain (paddy + wheat), and the productivity increased from 4.06

Table 2. Cost of Sodic Lands Reclamation Projects

Particular	Phase-1 (1993 to 2001)	Phase-II (1997 to 2007)	Phase-III (2009-2018)	Total (M US$))	Total (M INR@)
IDA share (M US$)	54.70	197.80	174.83	427.33	35832
State share (M US$)	13.10	41.90	4.92	59.92	5024
Local Communities (M US$)	35.91#	71.90	22.30	130.10	10909
Total project cost (M US$)	103.71	311.60	202.05	617.35	51765

@ The exchange rate of 1 USD=83.85 Indian Rupee; M=million, # estimated from the share of local community that was 36% of the total project cost. Source: World Bank, 2004; World Bank, 2008a; World Bank, 2008b and World Bank, 2019.

Table 3. Coverage of the Sodic Lands Reclamation Project

	Phase-1 (1993 to 2001)	Phase-II (1997 to 2007)	Phase-III (2009-2018)	Total
Reclamation area (ha)	68,414[a]	189,700[b]	142,677[c]	4,00,791
Irrigation development (ha)	-	-	69,496	-
Reclamation of ravine land (ha)	-	-	23,943	-
Rehabilitation of Main Drains (km)	2988	7,603	3,256	13,847
Farm to market roads (km)	-	1330	-	-
Water-user groups (no)	~7000[d]	46,000	34,883	87,883
Women self-help groups (no)	2116	7193	6,555	15,864
District	10	18	29	76
Villages	1,003	3369	2993	7,365
Number of Households	155,892	367,621	-	-

Note: [a&c]In the total reclaimed area which >50% was totally barren 'Class C land. [b]In the total reclaimed area which ~67% was totally barren 'Class C land. [d]Assumed on average 7 WUGs were formed in each treated village. Source: World Bank, 2004; World Bank, 2008a; World Bank, 2008b and World Bank, 2019.

Table 4. Performance indicators of the projects

		Phase-1 (1993 to 2001)		Phase-II (1997 to 2007)		Phase-III (2009-2018)	
		Pre-P	Post-P	Pre-P	Post-P	Pre-P	Post-P
Productivity gains	Paddy	1.49	2.99 (101)	0.90	3.40 (278)	4.09	6.02 (47)
	Wheat	1.67	2.61 (56)	0.40	3.00 (650)		
Annual incremental production (mt)		NA		0.96		NA	
Cropping intensity				63%	198%	45%	211%
Land values (Rs/ha)	Class C			55,000	224,000 (307)	20,4000	648279 (218)
	Class B			1,22,000	2,64,000 (116)		
	Class B+			1,67,000	3,52,000 (111)		
Milk productivity (litre/day/lactating animal)	Buffalo					6.2	7.8
	Cow					3.7	4.8
Soil Health (pH)		>10.0	8.5-9.0			10.4	8.4
EC (dS m^{-1})						2.9	0.30
Organic carbon (%)						~0.0	0.31
Economic rate of return (ERR)		28%		19.3%		19.7%	
Economic net present value (ENPV)		-		-		Rs 4 billion	

Note: For project purposes, the treated lands were classified as: "C class land" (the most severe case of sodicity - mostly barren); "Class B land" (single cropped sodic land - with very low productivity); and "Class B^+ land" (double-cropped land - with low productivity)Source: World Bank, 2004; World Bank, 2008a; World Bank, 2008b and World Bank, 2019.

to 6.02 Mg ha^{-1}, ~47% increase over the pre-project levels of productivity. Cropping intensity during the phase-II and phase-III increased from 63 to 198 and 45 to 211%, respectively. Furthermore, the value of the lands, an important indicator of the fertility, showed that during the phase-II, value of the land increased by 307, 116 and 111%, respectively for the class C, Class B and Class B^+, respectively. The overall, the economic return were 28, 19.3 and 19.7% during the phase-I, II and III, respectively (Table 4). Additionally, during the all the phases, an improvement in crop diversification, reduction in poverty by heading the farm-income, and improve in access to market (Table 5).

Table 5. List of other performance indicators of projects

Phase-1 (1993 to 2001)	Phase-II (1997 to 2007)	Phase-III (2009-2018)
• Value of all three classes of reclaimed land has increased substantially. • Significant increase in cropping intensity. • Increase in foodgrain production • Contributed to poverty alleviation particularly of smallholders • Gender equity was ensured through women self-help groups through micro-enterprises, and other income-generating activities.	• Incremental income farm of smallest farmers (0.4 ha) Rs 5,947 (@1998 real prices and excluding horticulture crops). • Overall poverty incidence declined from 72 % to 48 %. • By end-project, 24 % of the poor households crossed poverty line threshold income level. • Out-migration per migrant household of male labour fell from 98 to 45 and from 38 to 5 for women, respectively.	• Improved the crop diversification with increase in are under oilseeds and pulses. • Diversification increased crop incomes per hafrom Rs. 7,113 to Rs. 12,380 • From ravine reclamation, crop incomes increased from Rs. 9,325 to Rs. 12,800 per ha. • Improved infrastructures of rural *haats,* improved access to markets and resulted in better price realization.

Source: World Bank, 2004; World Bank, 2008a; World Bank, 2008b and World Bank, 2019

Lesions learnt

In Uttar Pradesh, during the implementation of the phase-I, it was observed that the majority of the extensive canal infrastructure is unlined, contributing to notable seepage problems. Land drainage is often overlooked in policy due to the slow onset of waterlogging and salinization, leading to funds being redirected to irrigation expansion and drought/flood management. Furthermore, it was noted that inadequate attention to drainage problems was considered as a major threat jeopardising the long-term sustainability of the reclamation efforts, additionally this was compounded by unaddressed institutional challenges in soil fertility management. These issues jeopardize reclaimed land and hinder the success of various initiatives due to poor coordination among the stakeholders Given the fact that financial constraints significantly affect short-term solutions (*e.g.,* sodicity management), it was recommended that there is a need of formulating a realistic long-term strategy for seepage reduction, which is as critical to managing sodicity The institutions at the village level, created as part of the project (SIC and WUGs), were seen by beneficiaries as temporary mechanisms for carrying out the project, rather than as sustainable organizations that could enhance empowerment and provide beneficiaries with authority over resources and decision-making. Ultimately, the form of community engagement that developed was characterized as "paternalistic participation," wherein the communities relied heavily on external assistance and did not internalize the project as their own initiative. The farmers perceived the reclamation efforts as an initiative led by UPBSN, rather than as a responsibility they were expected to undertake independently. Thus, the project was, in essence, not "community-driven," but rather "UPBSN-driven with community compliance. While the theoretical framework suggested that decision-making within the water user groups (WUGs) and the sub-committees (SICs) was intended to be fully participatory, the actual dynamics revealed a dominance of elite members within these groups (World Bank, 2004).

Phase-I: The high costs of reclamation involving gypsum were predominantly attributed to the considerable transportation expenses. The initiative proposed adaptive research to advance reclamation technology, with a specific emphasis on minimizing reclamation costs. The incentives for the water user groups (WUGs) to remain engaged as a cohesive unit and to take responsibility for the maintenance of both field and link drains were markedly limited. The UPBSN staff determined that it was more effective to focus primarily on engaging villagers in the cost-sharing process, leaving them with insufficient time to verify that equitable participation was genuinely occurring. The likelihood of reverting to sodic land is significant if appropriate crop and water management strategies are not implemented. The project's main goal was to develop participatory models for land reclamation. However, to enhance agricultural productivity and promote sustainable technologies, it's essential to focus on economic incentives for water management, operational resources, and drainage system maintenance, which requires policy reforms. The sustainability of the project might be jeopardized if other contributory factors in addition to the remedial interventions are not internalized and factors in the future programme. These identified issues were economic incentives related to water utilization and management, as well as the resources required for the operation and upkeep of drainage systems. Before taking-up large-scale projects, it was suggested to thoroughly evaluate the pilot experience. The insights from these small-scale projects will improve future interventions. In complex projects like the sodic lands reclamation initiative, forecasting long-term environmental impacts is challenging. Therefore, prioritizing monitoring and evaluation during implementation is essential, necessitating an appropriate system and a comprehensive assessment plan for effective feedback. Building community engagement demands considerable time for project design. The Bank's strict timelines hindered the implementing agency's ability to tackle key issues. Understanding the community's socio-economic context is vital, as participatory processes can drive lasting change. Emphasizing incentives and benefits for farmers, both individually and collectively, is crucial during and after project implementation (World Bank, 2004).

Phase-II: Sodic lands reclamation project project-II was implemented with consideration of lessons learnt from previous pilot programs, which assessed various development options and identified effective strategies for sodicity and waterlogging management. However, it was suggested that there is a need of considering institutional and physical constraints and, efforts must be made to mitigate them. It was noted that involvement of beneficiaries in the project design process at the grassroots level cultivates local ownership and enhances the capacity to manage and maintain project assets after the project's completion. Additionally, timely independent monitoring and evaluation (M&E) plays a crucial role in assisting project managers in achieving development goals. It was important to recognize that independent M&E replaces governmental efforts, necessitating attention to ensure that there must be sufficient capacity within the government or agency to sustain the M&E system after the project ends (World Bank, 2008a and World Bank, 2008b).

Phase-III: Functional farmer collectives are needed for improving market access. Formation of fully functional FPOs is a long and arduous process that is hard to accomplish within typical project timeframes. Even with the hiring of specialist service providers, to help the project with the formation and strengthening of FPOs, it was only in year 5 of implementation that the initial set of FPOs were deemed ready to undertake their activities and by project closing, many FPOs, (around 38 FPOs were still considered weak and in need of strengthening if they were to serve their roles. Identification and selection of project targets is critical to ensure timely implementation. The largest share of project investments was meant to reclaim sodic land patches identified and selected based on specific technical selection criteria. During implementation, it became evident that patches in the target districts, meeting the criteria were limited. An assessment of the available patches during preparation would have led to more pragmatic identification and selection criteria. The sustainability of project outcomes requires a thorough review of the Operation and Maintenance (OM) frameworks. The project design addressed anticipated OM issues and included maintenance provisions for the rehabilitated drainage systems, assigning responsibilities to the government agencies and beneficiaries (World Bank, 2019).

Conclusion and policy implications

This investigation examined the influence of various phases of the Sodic Soil Reclamation Projects in Uttar Pradesh, underscoring the essential lessons derived from these initiatives. It can be asserted that the reclamation activities, alongside the efforts of the *Uttar Pradesh Bhumi Sudhar Nigam* (UPBSN), had a profound effect on enhancing crop yields and agricultural production. Furthermore, these initiatives contributed to increasing the awareness and skill levels of local villagers, thereby instilling a greater sense of confidence in their ability to manage the limited natural resources available in the region. The establishment and engagement of grassroots institutions for the implementation of planned activities were fundamental components of the projects, serving as a crucial factor in achieving the primary goal of poverty alleviation through the reclamation of sodic soils in the state. Throughout the three phases of the project, the activities implemented had a beneficial effect on the entire production chain, characterized by enhanced soil health, the provision of quality inputs, and the management of natural resources through collaborative actions. The project also promoted crop diversification, increased the value of various land classes, supported gender equity and women's empowerment, and improved livestock productivity. Additionally, initiatives were taken to bolster the welfare of farmers by upgrading infrastructure and enhancing connectivity to rural markets, which facilitated better price realization for their crops. A key takeaway from the project was the recognition that, in addition to technological solutions for addressing waterlogged and sodic soils, the engagement of grassroots institutions and community involvement, along with favourable socio-economic conditions such as market accessibility and enabling policies, are vital for achieving successful outcomes in natural resource management projects. Also, for small land holdings, sodic soil reclamation plan to be strategized. Resodification probability need attention of the policy makers for future plans. In summary, the project placed a greater emphasis on long-term sustainability rather than merely pursuing short-term goals.

References

Arora S and Singh BP (2020) Status of soil degradation in state of Uttar Pradesh. *Journal of Soil and Water Conservation* ***19(2):*** 119-125.

Datta KK and Joshi PK (1993) Problems and prospects of co-operatives in managing degraded lands: case of saline and water-logged soils. *Economic and Political Weekly*, A16-A24.

Kuehnast K (2001) Learning from the past: India Uttar Pradesh sodic lands reclamation project. Social Development Note No. 56. Social Development Publications, World Bank, NW, Washington, DC, 04 pp.

Kumar S, Upadhay SK and Joshi D (2020) Sources of agricultural growth and its determinants: a regional analysis of Uttar Pradesh. *Indian Journal of Agricultural Economics* **75(1):** 74-89.

Mandal AK, Sharma RC, Singh G and Dagar JC (2010) *Computerized Database on Salt Affected Soil in India.* CSSRI Publ. No. 2/2010, Karnal, pp 15.

ESDMoAFW (2022) *Agricultural Statistics at a Glance 2022*, Economics & Statistics Division, Department of Agriculture & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India.

Nayak S (2006) Environmental degradation to land resources in Uttar Pradesh. *Review of Development and Change* **11**(1): 60-84.

SIP (2022) *Inter-state Comparative Statistics-2022*, Economics and Statistics Division, State Planning Institute, Uttar Pradesh.

Tiwari KN, Kumar A and Pathak AN (1983) Characterisation of salt-affected soils in central alluvial region of Uttar Pradesh. *Journal of the Indian society of soil science* **31**(2), 272-280.

Verma D, Yadav MS, Mathur A and Singh AN (2021) Mapping and monitoring sodic land reclamation in the Indo-Gangetic Plains of India using geo-information tools, global symposium on salt-affected soils, 20-22, October, 2021, accessed on: August, 2024, pp 3.

World Bank (2004) India - Uttar Pradesh sodic lands reclamation project (English). Washington, DC: World Bank Group, pp 14-15.

World Bank (2008a) ICR Review-UP Sodic Lands II, Report No. ICRR12907, pp 1.

World Bank (2008b) Implementation completion and results report (Report No: ICR0000653). Uttar Pradesh Sodic Lands Reclamation II Project, March 20, 2008, pp 43.

World Bank (2019) Implementation completion and results report (ICR00004665), Uttar Pradesh Sodic Lands Reclamation III Project, June 18, 2019, pp 35.

Yadav JSP (1993) Salt affected soils and their management with special reference to Uttar Pradesh. *Journal of the Indian Society of Soil Science* **41**(4): 623-629.

Yadav VK (2024) Genetic enhancement of rice for alkalinity-affected area of central Uttar Pradesh, India. In: *Genetic Improvement of Rice for Salt Tolerance*. Singapore: Springer Nature Singapore, pp 157-172.

Received: September 13, 2024; Accepted: October 1, 2024

Journal of Soil Salinity and Water Quality 16(2), 152-165, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156303

Halophytes and Agroforestry in the Restoration of Salt-affected Landscapes in Changed Environment

SR Gupta[1]*, JC Dagar[2] and HR Sharma[3]

[1]Department of Botany, Kurukshetra University, Kurukshetra-136119, Haryana, India
[2]Indian Council of Agricultural Research, Krishi Anusandhan Bhavan-II, Pusa, New Delhi-110012, India
[3]Institute of Environmental Studies, Kurukshetra University, Kurukshetra-136119, Haryana, India
*Corresponding author's E-mail: sgupta2002158@gmail.com

Abstract

Vast areas of salt-affected lands remain barren due to water scarcity globally, with 20% of irrigated agricultural land experiencing secondary salinization. Salt-affected landscapes present significant challenges for restoration and sustainable land management. This review examines the potential of halophytes and agroforestry systems as innovative strategies for rehabilitating these degraded landscapes. Naturally adapted to high salinity conditions, halophytes can play a crucial role in restoring productivity, and soil fertility and promoting resilience in saline areas. In addition to phytoremediation, halophytes are utilised to produce fuel, food, medicine, fodder, and timber. eHALOPH database has recognized the nine main categories of uses of halophytes including food and drink, domestic products, timber, forage, land use, fibers, toxins, medical and chemicals. Approximately 30% of the applications of halophyte plants are medicinal, with 20% being for fodder. Halophytes can be used for phytoremediation, to restore salty soils, address environmental issues, restore biodiversity, and provide food and medicinal sources. Site-specific strategies can be practicable for mangrove restoration. Integrating halophytes and salt-tolerant plants into agroforestry systems can enhance biodiversity, biological productivity, microbial diversity and activity, and carbon sequestration. Some successful applications of agroforestry, particularly enhancing ecosystem services are highlighted. By synthesizing current research and practice, a comprehensive understanding of using halophytes and agri-silvicultural and silvopastoral agroforestry systems can effectively restore salt-affected landscapes.

Key words: Diversity: Distribution of halophytes, Potential Economic Uses, Improving Microbial Activity Uses, Restoration

Introduction

A total of 1.257 billion hectares of salt-affected lands (about 8.5% of the total land area) across the world distributed in about 130 countries (FAO, 2022) remain barren due to salinity or water scarcity. About 20 % of the irrigated agricultural land faces secondary salinization, which is one of the major causes of soil degradation (FAO and ITPS, 2015). Between 1980 and 2018, secondary soil salinisation affected about 590 million hectares of land, according to the Global Framework on Water Scarcity in Agriculture (Garcia-Caparros *et al.,* 2023). Large areas of land, previously productive with irrigated soils, are expected to expand because of aridity, increasing demands of irrigation for agricultural production, and rising sea levels in coastal regions. In India, soil salinity and sodicity affect about 7 million ha of land (Mandal *et al.,* 2010). Extensive research has shown that physical, biological, and physiological limitations in salt-affected soils, affect marginal soil resources (Dagar *et al.,* 2023) and cause crop output losses for the agricultural sector (Qadir *et al.,* 2014). Soil salinisation significantly affects plant growth, reproductive success in plants, and crop production (Rengasamy, 2006) as well as soil biological activity, organic carbon content, greenhouse gas emissions, and soil ecosystem services (Qadir and Schubert, 2002; Machado and Serralheiro, 2017; Gupta *et al.,* 2020).

Studies conducted during the past 40 years have suggested methods for the use of salt lands, including the establishment of salty pastures, biosaline agriculture, and halophytic cropping systems (Dagar *et al.,* 2023, 2024; Dagar and

Gupta, 2024a, b). These lands have enormous potential using halophytes, salt-tolerant crop management techniques, and agroforestry interventions. Halophytes are versatile plants that can thrive in various saline habitats including arid and semi-arid areas, coastal zones, wetlands, and similar environments due to their ability to withstand, accumulate, or eliminate excess salt (Koyro and Breckle, 2024; Dagar *et al.,* 2024). Besides phytoremediation, halophytes are used to provide benefits like food, fodder, medicine, timber, and fuel (Reeves, 2003; Dagar *et al.,* 2022a, b; Bazihizina *et al.,* 2024; Garcia-Caparros *et al.,* 2023).

Utilizing marginally salty and sodic soils is feasible with agroforestry systems composed of salt-tolerant trees, grasses, and crop cultivars (Dagar *et al.,* 2016a, b; Dagar and Gupta, 2020a, b; Gupta et al., 2020). The various agroforestry interventions for rehabilitating saline and sodic soils in India are comprised of agri-silvicultural, silvopastoral and fruit-based agroforestry systems, and trees for biodrainage, energy plantations, and agroforestry for dryland salinity (Gupta and Dagar, 2016; Dagar and Gupta, 2020 a,b). This review provides an overview of the potential of halophytes and agroforestry systems as innovative strategies for restoring salt-affected landscapes. It also briefly discusses the role of halophytes in ameliorating coastal saline soils.

Distribution, Classification and Diversity of Halophytes

According to Flowers and Colmer (2008), halophytes can be defined as plants that can adapt to and complete their biological cycle in naturally saline conditions where salt concentrations exceed 200 mM NaCl. They have unique morphological, anatomical and physiological adaptations (Stuart *et al.,* 2012; Arora and Dagar, 2019; Koyro and Brackle, 2024), with obligatory halophytes requiring salt for optimal growth, and facultative halophytes growing normally without salt (Nikalje *et al.,* 2019). As obligate halophytes or eu-halophytes, these species undergo osmotic adjustments, morpho-anatomical, and physio-logical changes in response to salinity stress, thriving in high salt concentrations. Quinoa (*Chenopodium quinoa*), *Suaeda fruticosa*, species of *Salsola, Atriplex, Haloxylon,* mangroves (species of *Avicennia, Bruguera, Ceriops, Rhizophora* and *Sonneratia* etc.), and coastal marsh plants (*Arthrocnemum macrostachyum, Salicornia* spp., and *Spartina* spp.) are common examples of a few halophytes (Hameed *et al.,* 2024).

Halophytes encompass various trees, shrubs, forbs, and grasses that can thrive in harsh environments, including salty and alkaline ecosystems, ranging from xerophytic to wet conditions. Sen and Rajpurohit (1982) classified halophytes into five categories namely (i) True halophytes- plants growing in saline soil, (ii) Facultative halophytes-plants growing in saline as well as in non-saline-soils. (iii) Transitional halophytes- plants growing only at the transitional margin of saline and non-saline areas, (iv) Marshy halophytes, (v)True glycophytes- plants growing in non-saline soils. Jaradat (2003) classified halophytes from the Middle East into salt-requiring obligatory (dependent on salt for survival e.g., species of *Salicornia*), preferential, salt-enduring, salt-resisting, salt-evading, and salt-avoiding or pseudo-halophytes categories. This classification with minor modifications has been generally followed widely. Hameed *et al.* (2024) and Dagar and Gupta (2024a, b) discussed some classification schemes for halophytes in their respective reviews.

Potential Uses of Halophytes

Aronson (1989) compiled 'HALOPH- A Data Base of Salt Tolerant Plants of the World' to identify potential plants for domestication as crops. The primary criteria for inclusion were a minimum electrical conductivity of soil or irrigation water of 7.8 dS m^{-1}, allowing plants to survive and yield potential. This database aims to explore potential crops in arid and semi-arid areas. According to Flowers and Al-Azzawi (link: https://ehaloph.uc.pt/), there are approximately 1200 salt-tolerant species in the database belonging to 93 families, with 650 halophytes in 46 families. When families are ranked by the number of species, Amaranthaceae, Poaceae, Fabaceae, and Plumbaginaceae are the most dominant in both salt-tolerant species and halophytes. Conversely, the Zosteraceae, Cymodocaeae, and Acanthaceae are ranked higher among halophytes than in all salt-tolerant plants (Garcia-Caparros *et al.,* 2023). Approximately 1560 species are categorized as halophytes (Rozema and Flowers, 2008). Of these, 115 taxa including *Salicornia, Sarcocornia, Sesuvium, Suaeda*, and *Atriplex* spp have been evaluated as food crops and 331 as fodder in diverse regions and climates (Ozturk *et al.,* 2019). Further, 82 species (including 11 natural hybrids) are distributed among 30 genera and 17 families of true mangroves and more than a hundred associate mangrove species are found in tidal zones across the world (Raghavan *et al.,* 2019).

Based on various reports, Gupta *et al.* (2024) stated that some important edible halophytes and halo-tolerant species include *Capparis spinosa Salicornia* sp.; *Arthrocaulon macrostachyum, Crithmum maritimum, Cakile maritima, Beta vulgaris* subsp. *maritima*) *Allium commutatum*. Saltbushes, a group of halophytes in the Chenopodiaceae family, play a crucial role in providing forage and fodder in desert regions.

Halophytes are viable alternatives in saline agriculture, with many species used as food, fodder, or bioenergy crops (Bazihizina *et al.,* 2024). Garcia-Caparros (2023) recognized the nine main categories of uses of halophytes including food and drink, domestic products, timber, forage, land use, fibers, toxins, medical and chemicals. As of July 2022, Garcia-Caparros (2023) reported 1365 uses for all species listed in eHALOPH; however, among halophytes, this number reduced to 918 (Fig.1). Approximately 30% of the applications for both sorts of plants were medicinal, with 20% being for fodder (Garcia-Caparros, 2023).

Many halophytes such as *Distichlis palmeri, Chenopodium quinoa, C. alba*, cultivars of *Pennisetum typhoides, Salichornia bigelovii* and *Diplotaxis tenuifolia* have gained importance as stable food crops. In coastal areas, fruits of *Morinda citrifolia*, *Pandanus* and dry region *Phoenix dactylifera* and species of *Ziziphus* are consumed. Many halophytes such as *Chenopodium album, Portuleca oleracea, Asparagus officinalis, Amaranthus* spp, *Beta vulgaris*, some mangrove fruits, radicles

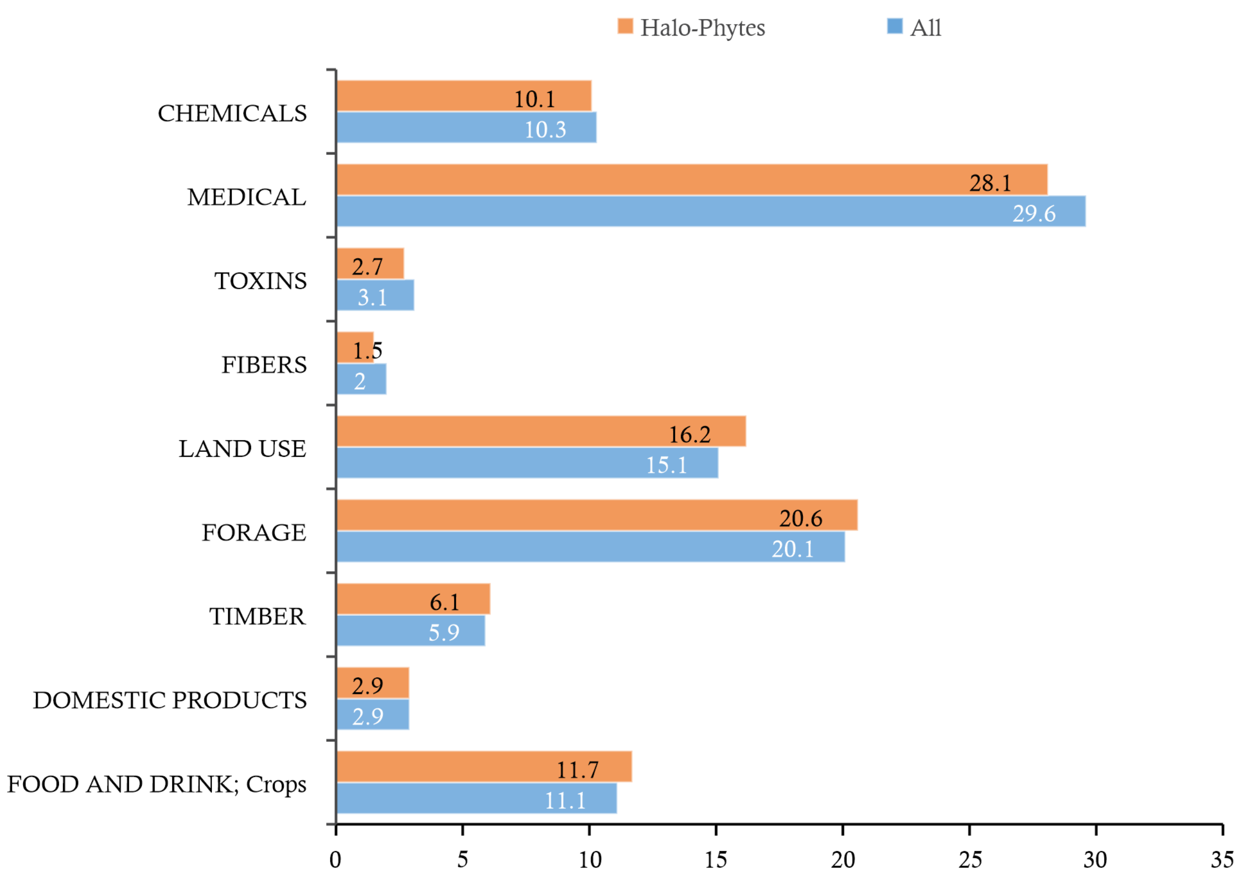

Fig. 1 Contribution of halophytes in total uses of plants (based on Garcia-Caparros *et al.*, 2023)

(germinating seeds) of *Borassus* and *Prosopis cineraria* pods are consumed as vegetables. Raw fruits of *Capparis decidua, Carissa carandus, Cordia rothii*, and raw pods of *Prosopis cineraria* are commonly used as pickles. At least fifty species of seed-bearing halophytes are potential sources of edible oil and proteins. *Salicornia bigelovii, Terminalia catappa, Suaeda moquinii, S. aralacaspica, S. salsa, Kosteletzkya virginica, Batis maritima, Chenopodium glaucum, Crithmum maritimum, Descurainia sophia, Niraria sibirica* and *Zygophyllum album* are few examples gaining importance.

Numerous halophytes have been utilized in traditional medicine for a long time (Fan *et al.,* 2019). Leaves, roots, seeds, fruits, barks, latex, and the entire plant are among the components of these plants that are used in a variety of ways, including juices, decoctions, infusions, macerations, powders, pastes, poultices, and even burning to ashes. Many salt-tolerant cultivars of *Brassica napus* and *B. juncea* have been developed as edible seed oil crops. Because of their seeds' oil content and lignocellulosic biomass, which may be utilised to produce biofuel, halophytes are being investigated as possible bioenergy crops (Panta *et al.,* 2014). One of the most promising halophyte crops is quinoa, which has a remarkable nutritional profile and can be grown in a variety of environments (see Afzal *et al.,* 2023). Dagar (2018) has listed many biofuel crops (for ethanol production) grown in salty soils or with high saline water which include *Tamarix chinensis, Phragmites australis, P. karka, Spartina alterniflora, Halopyrum mucronatum, Desmostachys bipinnata, Typha domingensis, Pandanus fuscicularis* (coasta), and *Nypa fruticans* (a mangrove palm) for liquid and gaseous fuel.

The most widespread genus, *Atriplex*, consists of 245 species found in arid and semi-arid areas (Osmond *et al.,* 1980). Other important genera include *Chenopodium, Kochia, Maireana, Salicornia, Salsola,* and *Suaeda*. These plants thrive in saline soils, providing valuable grazing for livestock and maintaining ecosystem stability. Wang *et al.* (2023) reported that *Salsola salsa* could be a potential forage crop in saline soils in arid China. They found that salinity increased protein and mineral content while decreasing fiber. The widest spread use of halophytes as wild or in silvopastoral systems or as isolated cultivated crops are for fodder. Many species of *Atriplex, Suaeda, Salsola, Maireana, Salicornia, Haloxylon* and grasses such as *Distichlis spicata, Paspalum vaginatum, Sporobolus arbicus, S. virginicus, Leptochloa fusca, Brachiaria mutica, Aeluropus lagopoides, Chloris gayana, Puccinellia ciliata, Thinopyrum ponticum, Hordeum marinum, Lolium rigidum, Pennisetum clendestinum* and many others are widely used as fodder. These grasses along with some legumes like *Trifolium michelianum, T. fragiferum, Melilotus alba, M. polymorpha* and *Medicago sativa* and fodder shrubs (species of *Atriplex, Halosarcia, Maireana*) are major constituents of Australian saline pastures and salt-tolerant trees such as *Acacia nilotica, Balanites roxburghii, Tamarix articulata, Prosopis juliflora, P. cineraria, Parkinsonia acumilata, Salvadora persica, Feronia limonia* are grown as pulp wood species.

Halophytes for Restoration in Salty Landscapes

The potential of using halophytes for phytoremediation, especially halo-phyto-remediation, to restore salty soils has been demonstrated by several workers (Ben Hamed *et al.,* 2021). Sustainable halophyte farming will address environmental issues connected to restoring biodiversity affected by human activity and climate change and provide new, health-promoting food sources to arid and semi-arid locations (Bazihizina *et al.,* 2024). Some examples of halophytic plant species for the restoration of salt-affected landscapes are given in Table 1.

Halophyte species like grasses, shrubs, and trees can remove salt from soils through morphological, anatomical, and physiological adaptations. Trees like species of *Tamarix, Acacia, Eucalyptus*, and *Prosopis* are used for phyto-remediation in arid environments (Ashraf *et al.,* 2006; Fall *et al.,* 2018; Newete *et al.,* 2019). *Suaeda maritima* and *Sesuvium portulacastrum* can accumulate salts in tissue and reduce them from saline soil, eliminating 504 and 474 kg of NaCl from 1 ha of the saline soil in 4 months, respectively (Ravindran *et al.,* 2007). In one study on saline-sodic vertisols (ESP 40), it was found that grasses *Leptochloa fusca, Brachiaria mutica* and

Table 1. Halophytic plant species for restoration of salty landscapes

Study sites	Plant species and their main effects	References
The soil amendment with peanut shells in greenhouse conditions, Centre of Senegal Peanut Basin	The amendment improves soil properties and tree growth of *Senegalia senegal, Vachellia seyal, Prosopis juliflora*	Fall *et al.* (2018)
Semiarid region of Brazil	*Atriplex nummularia* integrated with *Azadirachta indica, Leucaena leucocephala,* and *Mimosa caesalpiniifolia* Improvement of soil quality of saline-sodic soil	dos Santos *et al.* (2022)
Salinity-remediation after water level desiccation Urmia Lake, Iran	*Salicornia* and *Halocnemum* lowered salinity	Ahmadi *et al.* (2022)
Horizontal subsurface constructed wetlands using halophytes; Khorasan Province in Iran	*Bienertia cycloptera, Salicornia europaea*, *Salsola crassa* effective in desalination	Farzi et al. (2017)
Afforested mangroves in the east of the Bangladesh Sundarban	Restoration successful using *Sonneratia apetala* and *Avicennia officinalis*	Uddin *et al.* (2022)
Mangroves in coastal areas and islands of Gujarat	*Avicennia marina* plantation for restoration	Shah and Ramesh (2022)
Site-specific strategies for restoring mangroves in Indian Sunderban	*Phoenix paludosa* and native halotolerant grasses	Ray *et al.* (2024)
Site-specific strategies for restoring mangroves in Indian Sunderban	Mixed plantation of *Ceriops tagal*, *Ceriops decandra*, *Bruguiera cylindrica*, *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, *Derris* spp., *Dalbergia spinosa*, *Sonneratia apetala*, *Bruguiera parviflora*	Ray *et al.* (2024)

Vetivaria zizanioides harvested 144.8, 200.0 and 63.5 kg ha^{-1} sodium from the soil, respectively in 3 years of cultivation (AICRP 2000-2004).

In one study in Abu Dhabi Emirate (UAE), Rao *et al.* (2017) observed high dry biomass from four grasses *Distichlis spicata, Paspalum vaginatum, Sporobolus arbicus* and *Sporobolus virginicus* as 17.66, 15.90, 12.35 and 18.42 Mg ha^{-1}, respectively. Ismail *et al.* (2019) reported 23.6 to 28.6 Mg ha^{-1} dry biomass in 5 species of *Atriplex* with ash content of 30.7-32.4% showing the potential of *Atriplex* in removing salt from the soil. Newete *et al.* (2019) found that *Tamarix usneoides, T. chinensis, T. ramosissima*, and their hybrids are effective in phytoremediation under salt-induced stresses. *Halocnemum strobilaceous, Atriplex verruciferae, Salsola crassae*, and *Salicornia europaeae* were found to be effective in saline soils after desiccation of Urmia Lake in Iran (Ahmadi *et al.,* 2022). Halophytic grasses like *Aeluropus lagopoides* and *Eragrostis* sp show salt absorption of 43.9% and 39.7%, correspondingly, from a salty vertisol (Gururaja Rao and Dagar, 2020). Studies on various halophytic plant species for phytoremediation and desalination have been compiled by Gupta *et al.* (2024), in a couple of articles compiled by Dagar *et al.* (2024), and by Hameed *et al.* (2024).

Halophytes can improve soil quality by increasing soil organic matter, reducing soil salinity, enhancing soil aggregation and porosity, and stimulating soil microbial activity and enzyme activity (Akhter *et al,.* 2004; Chen *et al.,* 2018; Gürel *et al.,* 2019; Sadhe *et al.*, 2020, Karakas *et al.,* 2020; Shaygan and Baumgartl 2022; Hameed *et al.*, 2024). *Paspalum vaginatum, Spartina alterniflora*, and *Panicum virgatum* are salt-tolerant grasses that have proven efficient in lowering soil salinity and improving soil quality (Gürel *et al.,* 2019). Kallar grass can reduce salinity by 71% in salt-affected soil (Akhter *et al.,* 2004); and improve conditions of saline, sodic, and saline-sodic soils in Pakistan (Nadeem *et al.,* 2017). Some shrub species like *Atriplex, Suaeda fruticosa, Paspalum notatum*, and *Festuca arundinacea* have deep and strong root systems, thriving in compact soils. These species can reduce soil salinity, promote carbon sequestration, and enhance carbon sequestration (Chen *et al.,* 2018). Zhao *et al.,* (2024) reported studies on the microbial communities of saline fertile islands under the canopy of tamarisk (*Tamarix*), a halophyte shrub found in arid ecosystems. High salinity in these fertile saline islands reduced functional gene alpha diversity compared to bare soils. However, organic matter accumulation within islands promoted halophilic archaea taxa and improved nutrient cycles (Zhao *et al.*, 2024).

Role of Halophytes in Amelioration of Coastal Saline Soils

Coastal ecosystems, such as mangrove forests and coral reefs, are essential for protecting against storm surges, preventing erosion, and supporting the livelihoods of local communities. *Salvadora persica* and *Salicornia* are plant species known for oil production and suitability for cultivation in saline mangrove regions (Gururaja-Rao *et al.,* 2004, 2013). They are found on the Gujarat coast, of India, and are commonly used in silvopastoral systems with salt-tolerant forages. Mangrove restoration in Southeast Asian countries has been ongoing for decades, with direct planting being the most common method (Gerona-Daga and Salmo, 2022). *Rhizophora apiculata*, has been successful in areas affected by Agent Orange during the Vietnam War (Hong, 2001). Mangroves can accumulate copper and chromium and have the potential to reduce heavy metal levels (Afifudin *et al.,* 2022). Some halophytes, including *Chenopodium murale, Atriplex jubata, Suaeda* a*ustralis*, and *Enchylaena tomentosa*, can be grown in prawn ponds with sediments to help with soil remediation and to reduce the amount of carbon and nitrogen in the ponds (Colette *et al.,* 2022)

Kathiresan and Dagar (2024) have given a detailed account of mangrove utility in coastal agriculture. Bangladesh has afforested 280 km^2 of coastal areas with mangroves since 1996 primarily planting *Sonneratia apetala* and *Avicennia officinalis* (Uddin *et al.,* 2022). These mangroves are comparable to natural mangroves in aboveground biomass/ecosystem services but lagging in species richness and biodiversity. In India, the Gujarat Forest Department successfully planted 50,000 ha of mangroves with *Avicennia marina* (Shah and Ramesh, 2022), Table 1.

Ray *et al.* (2024) highlighted the use of site-specific strategies for mangrove restoration, these workers recommend a comprehensive restoration framework for degraded mangroves, focusing on erosion, salinity increase, and anthropogenic stressors. The study found that *Porteresia coarctata* and *Avicennia* spp. survived anoxic stress by colonizing in groups that amplified oxygen levels in their submerged roots and pneumatophores. *Phoenix paludosa* and native halotolerant grasses exhibited good results in clusters at restoration sites. Mixed planting of *Ceriops tagal, Ceriops decandra, Bruguiera cylindrica, Bruguiera gymnorrhiza, Excoecaria agallocha, Derris* spp. *Dalbergia spinosa, Sonneratia apetala*, and *Bruguiera parviflora* yielded successful establishment rates, indicating multiple interspecific facilitation cascades in reassembling on-site mangrove communities in small discrete degraded mangrove patches in Indian sunderban (Table 1).

The island and coastal regions support diverse types of agroforestry systems (Dagar 2014; 2020a). Kumar *et al.* (2023) have compiled extensive information on different types of agroforestry systems in biodiversity conservation, livelihood security, and carbon sequestration, with special reference to India and Southeast Asia. Based on their review, Table 2 summarizes the carbon storage potential of the agroforestry

Table 2. Carbon storage in the plant-soil system in agroforestry support system in coastal regions of Thrissur, Kerala (Based on Kumar *et al.*, 2023)

System	Above ground ($Mg\ C\ ha^{-1}\ yr^{-1}$)	Below ground ($Mg\ C\ ha^{-1}\ yr^{-1}$)	Total carbon ($Mg\ C\ ha^{-1}\ yr^{-1}$)	SOC (1m depth) ($Mg\ ha^{-1}$)
Black pepper on *casuarina*	6.12	0.77	6.89	63.62
Black pepper on *Macaranga peltata*	2.83	0.91	3.75	68.64
Black pepper on *Ailanthus triphysa*	2.68	0.52	3.2	65.56
Black pepper on jack	4.91	1.19	6.09	64.42
Black pepper on *Acacia auriculiformis*	5.66	1.37	7.03	71.39
Black pepper on *Grevillea robusta*	6.35	1.35	7.69	61.26

Table 3. Some prominent agroforestry systems for using saline and sodic soils in India (Gupta *et al*. 2024)

Salt-affected soil	Agroforestry system	Soil carbon sequestration (Mg C ha^{-1})	References
Highly Sodic soil, Bichhian, Haryana, India	Silvopastoral system with *Sporobolus marginatus*, and *Desmostachya bipinnata*	9.621 to13.431	Kaur *et al.* (2002a, b)
Highly sodic soil Lucknow, India	Energy plantation with *Jatropha curcas*	7.650 to10.428	Singh *et al.* (2013)
Saline vertisols, Gujarat, India	*Salvadora persica* with grasses	-	Gururaja Rao and Dagar (2020)
Highly sodic soils (pH>10) Bichhian, Haryana, India	*Acacia nilotica, Prosopis juliflora, Tamarix articulata* trees along with salt-tolerant grasses	-	Dagar (2014), Dagar *et al.* (2022 a and b)
Saline water irrigated semi-arid soils, Hisar, Haryana, India	Silvopastoral system of *Acacia nilotica, Salvodora persica* with salt tolerant grasses	19.48 to 21.50	Kumari *et al.* (2018)

support system in the coastal regions of Thrissur, Kerala.

Soil Biodiversity, Ecosystem Services and Soil Carbon in Agroforestry Systems

Dagar and Gupta (2020 a,b) and Dagar *et al.* (2023) provide an overview of agri-silvicultural, silvopastoral, fruit-based systems, energy plantations, and salt-tolerant plants that can contribute to the mitigation of dryland salinity. Successful establishment of fruit trees such as *Aegle marmelos*, *Carissa carandas*, and *Phyllanthus emblica* in combination with crops like barley, mustard, pearl millet, and cluster bean (*Cyamopsis tetragonoloba*) has been achieved in northern India, even when irrigating with saline water up to 10 dS m^{-1} (Dagar, 2018). Many agroforestry practices can restore salt-affected landscapes (Table 3).

Ecosystem services

Ecosystem services are the benefits the natural environment provides to humanity, categorized into four categories: provisioning, regulating, cultural, and supporting services (MEA, 2005) (Fig.2). Provisioning services include processes that yield resources, while cultural services include nonmaterial benefits like recreation and well-being. Regulating services involve ecosystem processes and include erosion control or soil stabilization, water purification, waste treatment, air quality maintenance, climate regulation, hydrological flows, and carbon sequestration; while supporting services are necessary for the production of other services. Restoration of degraded salty lands using halophytes improves provisioning services, including plant production, fuel, and fiber (Fig. 2). Many regulating services

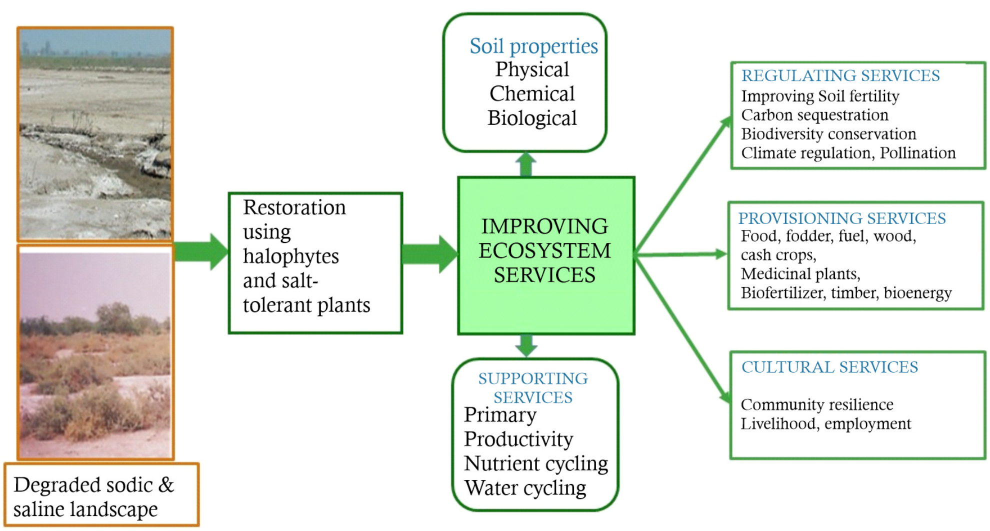

Fig. 2 Improvement of ecosystem services by restoring degraded saline landscapes using halophytes and salt-tolerant plants

can be improved by using halophytes and salt-tolerant plants. The supporting ecosystem services like nutrient cycling, plant productivity, soil formation, and habitat maintenance, are also improved. The social and cultural services are non-material and non-consumptive, affecting human psychological well-being.

Agroforestry practices can yield significant amounts of timber and fuelwood on marginal salt lands. Kaur *et al.* (2002a) estimated bole and branch wood production in silvopastoral systems of *P. juliflora, D. sissoo*, and *A. nilotica* for soil rehabilitation. It was 4.62–9.78 Mg ha^{-1} of bole wood and branch biomass production ranged from 4.16 and 20.82 Mg ha^{-1} $year^{1}$. Salt-tolerant trees like *Prosopis, Tamarix, Acacia, Casuarina, Pithecellobium, Parkinsonia*, and *Salvadora* provide fuelwood (Ladeiro 2012), while coastal mangrove species like *Rhizophora, Ceriops*, *Avicennia,* and *Aegiceras* contribute to charcoal production. The benefits of agroforestry in salt-affected lands include timber, fodder, fuelwood, fruit production, employment, income for local people, and business opportunities.

Soil Biodiversity and Microbial Activity

There are beneficial effects of agroforestry on soil ecosystem services including soil conservation, storage and cycling of nutrients, improving soil biological quality, and sequestering atmospheric carbon dioxide. The soil ecosystem services (Benefits for humans and non-human nature) and their associated properties, soil processes and soil functions (Rodrigues *et al.,* 2021). Soil organisms support multiple ecosystem services, which underpin global sustainability goals. According to Rodrigues *et al.* (2021), soil ecosystem services, functions and processes are largely regulated by the properties of soil, and also influenced by various soil degradation processes (FAO 2015).

The soil microbial biomass carbon and soil enzyme activities, serve as a good indicator of the amelioration of sodic soil (Kaur *et al.,* 2002 b; Singh *et al.,* 2013). The soil microbial biomass in different agroforestry systems was: 71.0 to 140.02 kg C ha^{-1}, 7.5 cm soil depth; 36 .00 to 54.35 kg C ha^{-1}, 7.5 to 15cm soil depth (Kaur *et al.* 2002b). In *Eucalyptus tereticornis* -based agrisilviculture systems, soil microbial biomass carbon was higher in the surface layers of soil due to higher organic matter input in the form of litterfall and fine roots of the trees (Gaur 2013; Gaur and Gupta 2012).

Arbuscular mycorrhizal (AM) fungi in salt-tolerant grasses growing on sodic soils, were found to be relatively diverse (Jangra *et al.,* 2011; Gupta *et al.,* 2016). The AM fungi associated with salt-adapted grasses such as *Sporobolus marginatus* and *Desmostachya bipinnata* may be crucial for soil carbon storage and bioamelioration. In the rhizosphere of two common types of grass on sodic soils, the main AM fungal species were *Glomus* spp. and *Acaulospora* spp. (Jangra *et al.,* 2011). There were 12 AMF in *Desmostachya bipinnata*, and 24 species in *Sporobolus marginatus*, the salt-adapted grasses; the mycorrhizal fungal colonization of the roots varied from 68 to 80 % in different seasons (Jangra *et al.,* 2011). These fungi have been shown to enhance plant growth and improve soil structure, making them valuable partners for plants in challenging environments. Understanding the diversity and function of AM fungi in salt-tolerant grasses can provide insights into sustainable agricultural practices for sodic soils.

In *Acacia nilotica* and *Salvadora persica* silvopastoral systems on calcareous soils at Hisar in northwestern India, the AM root colonization in various grass species (*Cenchrus ciliaris, Panicum miliare, Brachiaria reptans, Desmostacheya bipinnata, Dichanthiun annulatum)* varied from 47.8% to 71.2% (Kumari *et al.,* 2018). Some 23 species of mycorrhizal fungi belonging to *Glomus*, *Acaulospora,* and *Gigaspora*. Besides, in the silvopastoral system and the agro-horticulture system, the spore density in the rhizosphere of predominant grasses varied from 57.6 to 203.2 spores/10 g soil (Fig.3); the value is greatest in the case of *Hordeum vulgare* (Kumari *et al.* 2018), indicating the potential for increased nutrient uptake and plant growth in these systems. This highlights the importance of understanding the diversity and abundance of mycorrhizal fungi in different silvopastoral systems for optimising soil health and crop productivity.

In diverse crops grown in *Eucalyptus tereticornis* agroforestry systems on moderately alkali soils in

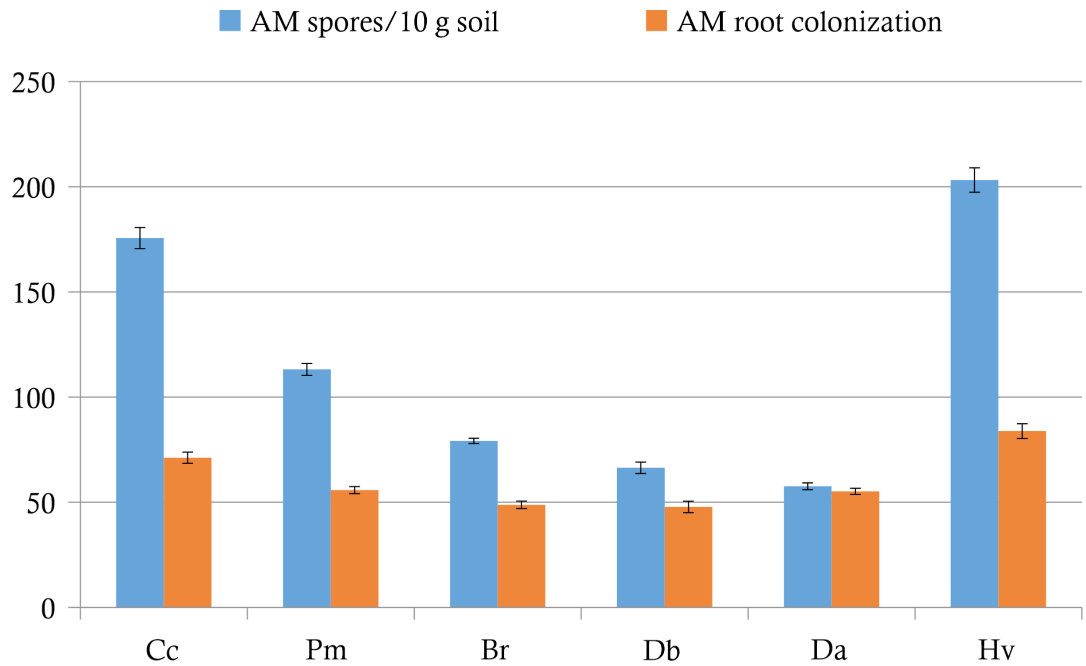

Fig. 3 Arbuscular mycorrhiza (AM) spore density and AM root colonization (%) in the rhizosphere soil of predominant grasses in silvopastoral, agrohorticulture systems, and the natural grassland on calcareous soil at Hisar, north-western India. (Cc=*Cenchrus ciliaris, Pm= Panicum miliare,* Br=*Brachiaria reptans, Db=Desmostacheya bipinnata, Da=Dichanthiun annulatum, Hv=Hordeum vulgare*) (based on Kumari *et al.,* 2018)

Kurukshetra, India, the arbuscular mycorrhizal species of *Glomus* and *Acaulospora* dominated the AM fungal communities. This issue has been covered previously (see Gaur 2013; Dagar *et al.,* 2023). When comparing the per cent root colonization and diversity of AM fungal species to those of *Sesbania aculeate*, *Pennisetum typhoides* (bajra), *Saccharum officinarum* (sugarcane), and *Sorghum vulgare*, the *Echinochloa* crop showed the greatest favourable effects. This suggests that *Echinochloa* may have a unique ability to support a diverse range of AM fungal species and promote high levels of root colonization compared to the other crops studied. Further research is needed to understand the specific mechanisms behind this phenomenon and its potential implications in the restoration of sodic soils.

The cultivation of *Jatropha curcas* on sodic soils for six years resulted in soil amelioration, according to a study conducted in an energy plantation on highly sodic soil by Singh *et al.* (2013). In this study, soil microbial biomass (MB-C, MB-N, and MB-P), enzyme activity (dehydrogenase, glucosidase, and protease), and soil organic carbon (SOC) were all significantly higher beneath the *Jatropha curcas* canopy than those found outside of it. These findings suggest that *Jatropha curcas* has the potential to improve soil quality and fertility on sodic soils over time. The increased microbial biomass and enzyme activity may contribute to enhanced nutrient cycling and overall soil health in these highly sodic soils.

Carbon Sequestration in Soil-plant System

In *Eucalyptus tereticornis* agroforestry systems on moderate alkali soils at Salimpur, Kurukshetra, the total carbon sequestration rates (trees+crop) varied from 20.836±0.579 to 6.752±0.148 Mg C $ha^{-1}yr^{-1}$(Gaur, 2013). In trees, the carbon sequestration rates ranged from 9.446±0.436 to 6.752±0.148Mg C $ha^{-1}yr^{-1}$. The soil organic carbon pool was found to vary according to soil depth, tree species, site conditions, and crop species. The soil organic carbon sequestration rates ranged from 0.696±0.049 to 5.910±0.073Mg C $ha^{-1}yr^{-1}$. Soil microbial biomass carbon was 0.197 to 0.430 Mg C g^{-1} soil. Soil carbon sequestration potential in 0–30 cm soil layers, ranged from 6.839 to 21.50 Mg ha^{-1} $year^{-1}$ (see Gupta and Dagar, 2016; Dagar and Gupta, 2020 a,b), Table 3. On moderately saline-alkaline soils (pH 8.36 to 8.41) at Kachchh, Gujarat, northwestern India, the silvopastoral system sequestered 36.3% to 60.0% more total soil organic carbon compared to the tree system; 27.1–70.8% more carbon in the silvopastoral system in comparison to the grass-only system (Mangalassery *et al.,* 2014).

The silvopastoral systems increased the content of the micro aggregates ranging from 0.250-0.053 mm which effectively stored soil organic carbon. The tree-based systems had a greater effect on macro- and micro-aggregates in the surface layer than other depths, suggesting an aggregate stratification phenomenon (Kumari *et al.,* 2018; Gupta *et al.,* 2023). This phenomenon indicates that tree-based systems play a crucial role in enhancing soil structure and carbon sequestration in the topsoil layers.

Conclusions

Recent research on the ecology, physiology, and genetics of halophytes has greatly enhanced our understanding of their survival in salty conditions. The utilization of salty water for a sustainable irrigation supply in waterlogged areas and saline and desert wastelands is possible with the application of new technologies for growing halophytes. Halophytes like *Chenopodium album, C. quinoa*, and others can be used as food crops, forages, essential oils, and medicinal plants. The soil microbial biomass carbon and soil enzyme activities, serve as good indicators of the bioamelioration of sodic soil. Biosaline agroforestry provides provisioning and regulatory services (storage and cycling of nutrients, bioamelioration, and carbon sequestration), and improved soil fertility. Improving soil quality through organic matter building, biological nitrogen fixation, nutrient recycling, soil microbial activity, and arbuscular mycorrhizal fungi. Agroforestry systems can also improve soil fertility by storing and cycling nutrients, promoting bioamelioration, and carbon sequestration. Mangroves are one of the greatest sinks of carbon and play an important role in restoring coastal ecosystems. Maintaining carbon stores in agroforestry could help mitigate climate change and adapt to changing environmental conditions. Silvopastoral systems are viable land-use options for improving biological productivity and ecosystem services. Including agroforestry techniques, halophytes should be used to rehabilitate saline-affected lands, ensuring food security and sustainability.

References

Afifudin AFM, Irawanto R and Purwitasari N (2022) Selection of potential plants as phytoremediation for heavy metals in estuarine ecosystem: A systematic review. Proceedings of the 4th International Conference on Life Sciences and Biotechnology (ICOLIB 2021), Atlantis Press.

Afzal I, Haq MZU, Ahmed S, Hirich A and Bazile D (2023) Challenges and perspectives for integrating Quinoa into the agri-food system. *Plants (Basel)* **12(19)**: 3361.

Ahmadi F, Mohammadkhani N and Servati M (2022) Halophytes play important role in phytoremediation of salt-affected soils in the bed of Urmia Lake, Iran. *Scientific Reports* **12(1)**: 12223.

AICRP (2000–2004) Biennial reports of the All India Coordinated Research Project on Management of Salt-affected Soils and Use of Saline Water in Agriculture. CSSRI, Karnal, India, 199p.

Akhter J, Murray R, Mahmood K, Malik KA, Ahmed S (2004) Improvement of degraded physical properties of a saline-sodic soil by reclamation with kallar grass (*Leptochloa fusca*). *Plant and Soil* **258**: 207–216

Aronson JA (1989) Salt-tolerant plants of the world. University of Arizona, Tucson.

Arora S and Dagar JC (2019) Salinity tolerance indicators. In: Dagar JC, Yadav RK and Sharma PC (eds) *Research Developments in Saline Agriculture*, Springer Nature, Singapore, pp 155–201.

Ashraf MY, Sarwar G, Ashraf M, Hussain F, Wahed RA and Iqbal MM (2006) Growth performance and nutritional values of salt tolerant plants growing under saline environments. In: Ozturk M, Waisel Y, Khan MA, Gork G (eds) *Biosaline Agriculture and Salinity Tolerance in Plants*. Birkhäusar Verlag, Basel, pp 35–44.

Bazihizina N, Papenbrock J, Aronsson H, Ben Hamed K, Elmaz Ö, Dafku Z, Custódio L, Rodrigues MJ, Atzori G and Negacz K (2024) The sustainable use of halophytes in salt-affected land: State-of-the-Art and next steps in a saltier world. *Plants* **13(16)**: 2322.

Ben Hamed K, Castagna A, Ranieri A, Garcia-Caparros P, Santin M, Hernandez JA and Barba Espin G (2021) Halophyte based Mediterranean agriculture in the contexts of food insecurity and global climate change. *Environmental and Experimental Botany* **191**: 104601.

Chen S, Guo Y, Zhao W, Du J (2018) Phytoremediation potential of *Zygophyllum spp.* for saline-sodic soil. *Journal of Environmental Management* **222**: 410–416.

Colette M, Guentas L, Gunkel-Grillon P, Callac N and Della Patrona L (2022) Is halophyte species growing in the vicinity of the shrimp ponds a promising agri-aquaculture system for shrimp ponds remediation in New Caledonia? *Marine Pollution Bulletin* **177**: 113563.

Dagar JC (2014) Greening salty and waterlogged lands through agroforestry systems for livelihood security and better environment. In: Dagar JC, Singh AK and Arunachalam A (eds) *Agroforestry Systems in India: Livelihood Security & Environmental Services.* Advances in Agroforestry, Vol 10. Springer, New Delhi/ Dordrecht/ New York, pp 273–332.

Dagar JC (2018) Utilization of degraded saline habitats and poor-quality waters for livelihood security. *Scholarly Journal of Food and Nutrition* **1(3)**: 115.

Dagar JC and Gupta SR (2020a) Agroforestry interventions for rehabilitating salt-affected and waterlogged marginal landscapes. In: Dagar JC, Gupta SR and Teketay D (eds) *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges, Vol 2*, Springer Nature, Singapore, pp 111–162.

Dagar JC and Gupta SR (2020b) Silvopasture options for enhanced biological productivity of degraded pasture/ grazing lands: an overview. In: Dagar JC, Gupta SR and Teketay D (eds) *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges*, *Vol2*, Springer Nature, Singapore, pp 163–227.

Dagar JC and Gupta SR (2024a) An ecological overview of halophytes: Phytogeographical distribution, floristic diversity, vegetation composition, and utilisation. In: Dagar JC, Gupta SR and Kumar A (eds) *Halophytes vis-à-vis Saline Agriculture*. Springer, Singapore. pp 19–65.

Dagar JC and Gupta SR (2024b) Introduction: definition, evolutionary trends, classification, historical background, and prospects of halophytes in agriculture. In: Dagar JC, Gupta SR and Kumar A (eds) Halophytes vis-à-vis Saline Agriculture. Springer Nature, Singapore pp 1–17.

Dagar JC, Gupta SR and Gaur A (2023) Tree-based farming systems for improving productivity and ecosystem services in saline environments of dry regions: An overview. *Farming Systems* **1(1**): 100003.

Dagar JC, Gupta SR and Kumar A (eds) (2024c) *Halophytes vis-à-vis Saline Agriculture*. Springer Nature, Singapore.

Dagar JC, Lal K, Ram J, Kumar M, Chaudhary SK, Yadav RK, Ahamad S, Singh G and Kaur A (2016a) Eucalyptus geometry in agroforestry on waterlogged saline soils influences plant and soil traits in North-West India. *Agriculture*, *Ecosystems & Environment* **233**: 33–42.

Dagar JC, Rai AK, Basak N, Yadav RK (2022a) Soil alkalinity/sodicity: degradation processes, constraints for crop production and their management. In: Dang Y, Menzies N, Dalal R (eds) *Soil Constraints On Crop Production*. Cambridge Scholars Publishing, UK, pp 116–138.

Dagar JC, Singh G and Gupta SR (2022b) Sustainable land use systems for rehabilitation of highly sodic lands in the Indo-Gangetic plains of north-western India: synthesis of long-term field experiments. *Journal of Soil Salinity and Water Quality* **14(1)**: 1–4.

Dagar JC, Yadav RK, Tomar OS, Minhas PS, Yadav G and Lal K (2016b) Fruit-based agroforestry systems for saline water-irrigated semi-arid hyperthermic camborthids soils of north-West India. *Agroforestry Systems* **90**: 1123–1132.

dos Santos MA, Freire MBGS, Freire FJ, da Rocha AT, de Lucena PG, Ladislau CMP and de Melo HF (2022) Reclamation of saline soil under association between *Atriplex nummularia* L. and glycophytes plants. *Agriculture* **12(8)**: 1124.

Fall D, Bakhoum N, Fall F, Diouf, F, Ndiaye C, Faye MN, Hocher V and Diouf D (2018) Effect of peanut shells amendment on soil properties and growth of seedlings of *Senegalia senegal* (L.) Britton, *Vachellia seyal* (Delile) *P. Hurter,* and *Prosopis juliflora* (Swartz) DC in salt-affected soils. *Annals of Forest Science* **75**: 32.

Fan, W, Fan, L, Peng, C, Zhang, Q, Wang, L, Li, L,Wang, J, Zhang, D, Peng, W,and Wu, C (2019). Traditional uses, botany, phytochemistry, pharmacology, pharmacokinetics and toxicology of *Xanthium strumarium* L.: A review. *Molecules **24***, 359.

FAO (2022) Global symposium on salt-affected soils: Outcome document. Rome. (https://doi.org/10.4060/ cb9929en)

FAO and ITPS (2015) Status of the world's soil resources (SWSR) – main report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome.

FAOSTAT. Food and Agriculture Data (2024) Available online: http://faostat.fao.org/site/375/ default.aspx (accessed on 24 June 2024).

Farzi A, Borghei SM and Vossoughi M (2017) The use of halophytic plants for salt phytoremediation in constructed wetlands. *International Journal of Phytoremediation* **19(7)**: 643-650. doi: 10.1080/ 15226514.2016.1278423. PMID: 28084800.

Flowers, TJ and Colmer, TD (2008). Salinity tolerance in halophytes. *New Phytologist*, **179(4)**: 945-963. https:// doi.org/10.1111/j.1469-8137.2008.02531.x

Garcia-Caparros P, Al-Azzawi, MJ and Flowers, TJ (2023) Economic uses of salt-tolerant plants. *Plants* **12**: 2669.

Gaur A (2013) *Plant Biomass Soil Microbial Activity and Carbon Sequestration in Agroforestry Systems*. Ph.D Thesis, Botany Department. Kurukshetra University, Kurukshetra.

Gaur A and Gupta SR (2012) Impact of agroforestry systems on carbon sequestration in Northern Haryana, India. *International Journal of Ecology and Environmental Sciences* **38**: 73–85.

Gerona-Daga MEB and Salmo SG III (2022) A systematic review of mangrove restoration studies in Southeast Asia: Challenges and opportunities for the United Nation's Decade on Ecosystem Restoration. *Frontiers in Marine Science* **9**: 987737.

Gupta SR, and Dagar JC (2016) Agroforestry for ecological restoration of salt-affected lands. In: Dagar JC, Sharma PC, Sharma DK, and Singh AK (eds) *Innovative Saline Agriculture*. Springer India, Dordrecht, pp 161–182.

Gupta SR, Dagar JC and Teketay D (2020) Agroforestry for rehabilitation of degraded landscapes: achieving livelihood and environmental security. In: Dagar JC, Gupta SR, and Teketay D (eds) Agroforestry for degraded landscapes: *Recent Advances and Emerging Challenges, Vol 1.* Springer, Singapore pp 23–68.

Gupta SR, Dagar JC, Singh, R and Sharma, HR (2024) Exploring the potential of halophytes for bioremediation of salt-affected soils: A review. In: Dagar JC, Gupta SR and Kumar A (eds) *Halophytes vis-à-vis Saline Agriculture*. Springer Nature, Singapore, pp 409–440.

Gupta SR, Sileshi WG, Chaturvedi RK and Dagar JC (2023) Soil biodiversity and litter decomposition in agroforestry systems of the tropical regions of Asia and Africa. In: Dagar JC, Sileshi WG and Gupta SR (eds) *Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa.* Springer Nature, Singapore, pp 515–568.

Gürel S, Kýrat G, Akça Y (2019) Seashore paspalum (*Paspalum vaginatum*) as a phytoremediation tool for saline soils: growth, physiological responses, and antioxidant capacity.*Journal* of *Plant Nutrition* **42**:1288–1302

Gururaja-Rao G and Dagar, JC (2020) Halophytes for utilizing and restoring coastal saline soils of India: emphasis on agroforestry mode. In: Dagar JC, Gupta SR and Teketay D (eds), *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges vol. 1.* Springer Nature, Singapore, pp 481–524.

Gururaja-Rao G, Chinchmalatpure AR, Arora S, Khandelwal MK and Sharma DK (2013) Coastal saline soils of Gujarat: problems and their management-Technical Bulletin 01/2013. CSSRI Regional Station, Bharuch, Gujarat, India, pp 60.

Gururaja-Rao G, Nayak AK, Chinchmalatpure AR, Nath A and Babu VR (2004) Growth and yield of *Salvadora persica* a facultative halophyte grown on saline black soil (vertic aplustept). *Arid Land Research and Management* **18**: 51–61.

Hameed A, Hussain S, Rasheed A, Ahmed MZ and Abbas S (2024) Exploring the potentials of halophytes in addressing climate change-related issues: A synthesis of their biological, environmental, and socioeconomic aspects. *World*, **5(1)**: 36–57.

Hong P (2001) Reforestation of mangroves after severe impacts of herbicides during the Vietnam war: The case of Can Gio. *Unasylva* **52(207)**: 57–60.

Ismail S, Rao NK and Dagar JC (2019) Identification, evaluation and domestication of alternate crops for saline environment. In: Dagar JC, Yadav RK and Sharma PC (eds) *Research Developments in Saline Agriculture*, Springer Nature, Singapore pp 505–536.

Jangra R, Gupta SR, Kumar R and Bhalla E (2011) Soil respiration, microbial biomass, and mycorrhizal diversity in sodic grassland ecosystems in northwestern India. *American-Eurasian Journal of Agricultural & Environmental Sciences* **10**: 863–875.

Jaradat AA (2003) Halophytes for sustainable biosaline farming systems in the Middle East. In: Alsherhan AS, Wood WW, Goudie AS, Fowler A, Abdellatif EM (eds) *Desertification in the Third Millennium.* AA Balkema Publishers, Lisse, pp 187–204.

Karakas, S, Dikilitas M, and Týpýrdamaz, R (2020) Phytoremediation of salt-affected soils using halophytes. In: Grigore, M.N (ed), *Handbook of Halophytes.* Springer: Cham, Switzerland, pp. 1–18.

Kathiresan K and Dagar JC (2024) Mangroves and associated flora: prospects for utilization in coastal agriculture. In: Dagar JC, Gupta SR and Kumar A (eds) Halophytes vis-à-vis Saline Agriculture. Springer Nature, Singapore pp 67–96.

Kaur B, Gupta SR and Singh G (2002a) Carbon storage and nitrogen cycling in silvi-pastoral systems on a sodic soil in northwestern India. *Agroforestry Systems* **54**: 21–29

Kaur B, Gupta SR and Singh G (2002b) Bioamelioration of a sodic soil by silvopastoral system in northwestern India. *Agroforestry Systems* **54**: 13–20.

Koyro HW and Breckle SW (2024) Ecophysiological constraints under salinity stress: Halophytes versus non-halophytes. In: Dagar JC, Gupta SR and Kumar A (eds) *Halophytes vis-à-vis Saline Agriculture*. Springer, Singapore. pp 179–209.

Kumar, P, Uthappa AR, Chavan SB, Chichaghare AR, Debta Harish, Bhat Shripad, and Dagar JC (2023). Achieving Biodiversity Conservation, Livelihood Security and Sustainable Development Goals Through Agroforestry in Coastal and Island Regions of India and Southeast Asia. In: Dagar, J.C., Gupta, S.R., Sileshi, G.W. (eds) Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa. Sustainability Sciences in Asia and Africa(). Springer, Singapore. https://doi.org/10.1007/978-981-19-4602-8_14

Kumari C, Gupta SR, Dagar JC, Singh V and Kumar M (2018) Carbon sequestration and microbial biodiversity in agroforestry systems for saline water irrigated semi-arid hyperthermic camborthids regions of north-west India. *Journal of Soil Salinity and Water Quality* **10**: 133–148.

Ladeiro B (2012) Saline agriculture in the 21st century: Using salt contaminated resources to cope food requirements. *Journal of Botany* 310705: 7 pages.

Machado RMA and Serralheiro RP (2017) Soil salinity: effect on vegetable crop growth management practices to prevent and mitigate soil salinization. *Horticulturae* **3**: 30.https://doi.org/10.3390/horticulturae3020030

Mandal AK, Sharma RC, Singh G and Dagar JC (2010) Computerized database on salt affected soils in India. Technical Bulletin No.2/2010. Central Soil Salinity Research Institute, Karnal, p 28.

Mangalassery S, Dayal D, Meena SL and Ram B (2014) Carbon sequestration in agroforestry and pasture systems in arid northwestern India. *Current Science* **107**: 1200–1293.

MEA (2005) A Report of the Millennium Ecosystem Assessment. Ecosystems and Human Well-Being. Island Press, Washington DC.

Nadeem MY, Umar W, Chattha MU, Khan I, Safeer M, Saif MA (2017) Kallar grass "The Salt Grass" an important fodder crop to ameliorate salt-effected soils. 05 – Technology Times.Pk. *https://www.adssc/Downloads/KallarGrass.pdf*

Newete SW, Allem SM, Venter N and Byrne MJ (2019) Tamarix efficiency in salt excretion and physiological tolerance to salt-induced stress in South Africa. *International Journal of Phytoremediation* **22(1)**: 3–9.

Nikalje GC, Bhaskar SD, Yadav K and Penna S (2019) Halophytes: prospective plants for future. In Hasanuzzaman M, Nahar K and Öztürk M (eds) *Ecophysiology, Abiotic Stress Responses and Utilization of Halophytes*. Springer, Singapore, pp 221–234.

Osmond CB, Björkman O, Anderson DJ (1980) *Physiological processes in plant ecology: towards a synthesis with* Atriplex. Berlin: Springer-Verlag.

Ozturk M, Altay V and Guvensen A (2019) Sustainable use of halophytic taxa as food and fodder: An important genetic resource in Southwest Asia In: Hasanuzzaman M, Nahar K and Ozturk M (ed) *Ecophysiology, Abiotic Stress Responses and Utilization of Halophytes*. Springer, Singapore, pp 235–257.

Öztürk M, Altay V, Gucel S and Guvensen A (2014) Halophytes in the East Mediterranean–their medicinal and other economical values In: *Sabkha Ecosystems.* Springer: Berlin/Heidelberg, Germany, pp. 247–272.

Panta S, Flowers T, Lane P, Doyle R, Haros G and Shabala S (2014) Halophyte agriculture: Success stories. *Environmental and Experimental Botany* **107**: 71–83.

Qadir M and Schubert S (2002) Degradation processes and nutrient constraints in sodic soils. *Land Degradation & Development* **13(4)**: 275–294.

Qadir M, Quillerou E, Nangia V, Murtaza G, Singh M, Thomas RJ, Drechsel P and Noble AD (2014) Economics of salt-induced land degradation and restoration. *Natural Resources Forum* **38(4)**: 282–295.

Raghavan P, Dubey SK, Dagar JC, Mohan PM, Ravichandran K, Jayaraj RSC and Rana TS (2019) Current understanding of the mangrove forests of India. In: Dagar JC, Yadav RK and Sharma PC (eds) *Research Developments in Saline Agriculture*, Springer Nature, Singapore pp 257–304.

Rao NK, McCann I, Shahid SA, Butt K, Al Araj B and Ismail S (2017) Sustainable use of salt-affected and abandoned farms for forage production using halophytic grasses. *Crop and Pasture Science* **68(5)**: 483–492.

Ravindran KC, Venkatesan K, Balakrishnan V, Chellappan KP and Balasubramani T (2007) Restoration of saline land by halophytes for Indian soils. *Soil Biology & Biochemistry* **39**: 2661–2664.

Ray K, Basak SK, Giri CK, Kotal HN, Mandal A, Chatterjee K, Saha S, Biswas B, Mondal S, Das I, Ghosh A, Bhadury P and Joshi R (2024) Ecological restoration at pilot-scale employing site-specific rationales for small-patch degraded mangroves in Indian Sundarbans. *Scientific Reports* **14(1)**: 1–23.

Reeves RD (2003) Tropical hyperaccumulators of metals and their potential for phytoextraction. *Plant and Soil* **249**: 57–65.

Rengasamy P (2006) World salinization with emphasis on Australia. *Journal* of *Experimental Botany* **57**: 1017–1023.

Rodrigues AF, Latawiec AE, Reid BJ, et al. (2021) Systematic review of soil ecosystem services in tropical regions. *Royal Society Open Science* **8**: 201584.

Rozema J and Flowers T (2008) Crops for a Salinized World. *Science* **322**: 1478–1480.

Saddhe AA,Manuka, R, Nikalje GC, and Penna, S (2020). Halophytes as a potential resource for phytodesalination. In: Grigore, M.N (ed), *Handbook of Halophytes.* Springer: Cham, Switzerland, pp. 1–21. *https://doi.org/10.1007/978-3-030-17854-3_92-1*

Santos ES, Abreu MM, Peres S, Magalhaes MCF, Leitao S, Pereira AS and Cerejeira MJ (2017) Potential of *Tamarix africana* and other halophyte species for phyto-stabilisation of contaminated salt marsh soils. *Journal of Soils and Sediments* **17**:1459–1473.

Sen DN, Rajpurohit KS (eds) (1982) Contributions to the ecology of halophytes. Task for vegetation science. Vol 2. Dr. W. Junk Publishers, Hauge.

Shah H and Ramesh R (2022) Development-aligned mangrove conservation strategy for enhanced blue economy: A successful model from Gujarat, India. *Estuarine*, *Coastal and Shelf Science* **274**: 107929.

Shaygan M and Baumgartl T (2022). Reclamation of salt-affected land: a review. *Soil Systems* **6(3)**: 61. https://doi.org/10.3390/soilsystems6030061

Singh K, Singh B, Tuli R (2013) Sodic soil reclamation potential of *Jatropha curcas*: a long-term study. *Ecological Engineering* **58**: 434–440.

Stuart JR, Tester M, Gaxiola RA and Flowers TJ (2012) Plants of saline environments. Access Science McGraw Hill. (http://www.accessscience.com)

Uddin MM, Hossain MM, Aziz AA and Lovelock CE (2022) Ecological development of mangrove plantations in the Bangladesh Delta. *Forest Ecology and Management* **517**: 120269.

Wang N, Zhao Z, Zhang X, Liu S, Zhang K and Hu M (2023) Plant growth, salt removal capacity, and forage nutritive value of the annual euhalophyte *Suaeda salsa* irrigated with saline water. *Frontiers in Plant Science* **13**: 1040520.

Zhao, S., van der Heijden, M.G.A., Banerjee, S. *et al.* (2024). The role of halophyte-induced saline fertile islands in soil microbial biogeochemical cycling across arid ecosystems. . *Communications Biology* **7**: 1061 https://doi.org/10.1038/s42003-024-06741-1.

Received: September 10, 2024; Accepted: October 21, 2024

Journal of Soil Salinity and Water Quality 16(2), 166-179, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156327

Remediation of Antagonistic Saline Effect on Crops Using Organic Amendments-A Review

BK Yadav[1]*, Hari Mohan Meena[2] and RL Meena[3]

[1]PAU, Regional Research Station, Bathinda-151001, Punjab
[2]Department of Soil Science, Punjab Agricultural University, Ludhiana-141004, Punjab
[3]PC-Unit, AICRP- SAS&USW, ICAR-CSSRI, Karnal-132001, Haryana
*Corresponding author's E-mail: bkyadav74@pau.edu

Abstract

The major abiotic stress that affects crop development, growth and yield is salinity. Rock weathering, seawater intrusion are main causes of primary salinization and overusing fertilizers, poor irrigation water quality, water logging, and depositing of industrial brine caused secondary salinization. Worldwide approximately 8000 lakh ha of arable land are impacted by salinity. India has 67.27 lakh hectares of arable land, of which 29.56 lakh ha are saline, whereas 37.71 lakh ha are sodic. Recently, several techniques have been developed to alleviate the adverse effects of salt stress on crops and enable them to adapt. Research starts to focus more on organic amendments, including compost, vermi-compost, vermi-wash, biochar, bio-fertilizer and plant growth promoting rhizobacteria. Research suggests organic amendments enhance salinity tolerance and improve plant growth and yield via altering ionic equilibrium, photosynthesis machinery, systemic antioxidants, and reducing oxidative damage. However, there is little study of the beneficial regulatory function that organic amendments play in plants and the ways in which they help them endure stress. As a result, the current study addresses recent findings about organic amendments in plants experiencing salt stress as well as how these amendments assist in reducing stress. The constraints and future potential of implementing organic amendments are also evaluated in this review.

Key words: Saline effect, Crops, Remediation, Organic amendments, Climate change

Introduction

The harmful effects of salinity on crop production make it one of the major global challenges. Every year, new areas become saline and unproductive due to increasing sea levels due to climate change and global warming. A major environmental stress that affects crop development, maturity, and yield through molecular, physical, biochemical and morphological changes is soil salinity (Hoque *et al.,* 2022a, Imran *et al.,* 2023). Primary salinization from rock weathering seawater obtrusion into coastal area is the main causes of salt buildup in soil. Man made (secondary) salinization is caused by overusing fertilisers, poor quality irrigation water, water logging, and deposition of industrial brine (Sahab *et al.,* 2021). Soil salinity has been attributed to various factors, including excessive fertilizer usage, ineffective irrigation and drainage systems, and rising underground water with high concentration of salt (Shahid *et al.,* 2018). Soil salinity affects over 8000 lakh hectares (23%) of all cultivated land worldwide, and it decreases 1-2 percent of cultivable area each year (Hoque *et al.,* 2022b). Mandal *et al.* (2018) estimates, indicating an area of 1,128 million hectares damaged by salt worldwide, indicate a growing tendency. By 2050, half of the world's cultivated land is predicted to suffer from salinization (Kumar and Sharma, 2020). In India, 67.27 lakh ha (2.1%) of total geographical area are salt-affected, of these, 29.56 lakh ha are saline and the remaining 37.71 lakh ha are sodic (Arora and Sharma, 2017). Approximately 75% of the country's salt-affected soils are found in the states of Gujarat (22.3 lakh ha), Uttar Pradesh (13.7 lakh ha), Maharashtra (6.1 lakh ha), West Bengal (4.4 lakh ha) and Rajasthan (3.8 lakh ha) (Mandal *et al.,* 2018). Stavi *et al.* (2021) stated that soil salinity is considered as a symptom of soil degradation because it is thought to affect not just plant growth but also soil microbial properties, soil biological and chemical reactions, and additional assistance provided by the soil ecosystem.

Soil salinization

The process of build up the salt concentration in soil up to a point that affects economics, quality of life, environmental health, and agricultural productivity is known as soil salinization. Salt precipitation and separation, transportation of salt, ion replacement, and evaporation are some of the mechanisms involved in soil salinization. Due to insufficient leaching of base-forming cations, the salt-affected soils have high concentrations of either exchangeable sodium or soluble salts, or both.

The main soluble mineral salts are anions such as carbonate (CO_2^{-3}), bicarbonate (HCO^{-3}), sulfate (SO_2^{-4}), chloride (Cl^-) and nitrate (NO^{-3}) and cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+). Both natural and man-made processes stimulate soil salinization and such soils are more likely to take place in arid and semi-arid regions with higher evaporation and little freshwater resources to eliminate excess salts away from the soil. The general processes of salinization of soil were presented in Fig. 1.

Salinity effect on soil parameters

High amounts of dissolved salts, including cations like calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+) and anions such as carbonate (CO_3^{2-}), bicarbonate (HCO^{3-}), chloride (Cl^-) and sulfate (SO_4^{2-}) are characteristics of saline soils. The electrical conductivity (EC) of these soils is generally higher than 4 dS m^{-1} at 25°C. An excessive Na^+ level degraded soil quality by decreasing bulk density, permeability and soil structural stability, as well as decreases the soil's ability to retain water and infiltration rate (Liu and She, 2017). The high salt content limit nitrification by inhibiting the activity of nitrifying bacteria which is essential for the release of nitrogen (N_2) into the soil for plant growth. Salinity also inhibits respiration and soil enzyme activity (Guangming *et al.,* 2017). The common salinity effects on different soil parameters were presented in Fig. 2.

Salinity effect on crop production

The salt stress inhibits crop development and yield by disturbing nutrients availability, which is synchronized by activity of rhizospheric microbes. Salinity results in osmotic stress, decreased shoot growth and stomatal closure due to buildup of Na^+ and Cl^- in leaves, where photosynthesis occurs (Hedrich and Shabala, 2018). Additionally, it speeds up older leaves' senescence by degrading chlorophyll. Increased Na^+ buildup in the cytosolic apartment (an intracellular space) can impede enzyme activity, decrease water relations, photosystem II and CO_2 uptake in plants. In addition to denature proteins and nucleic acids, excessive salinity also raises reactive oxygen species, damages cells, and reduces antioxidant activity (Siddiqui *et al.,* 2017, Seleiman *et al.,* 2020).

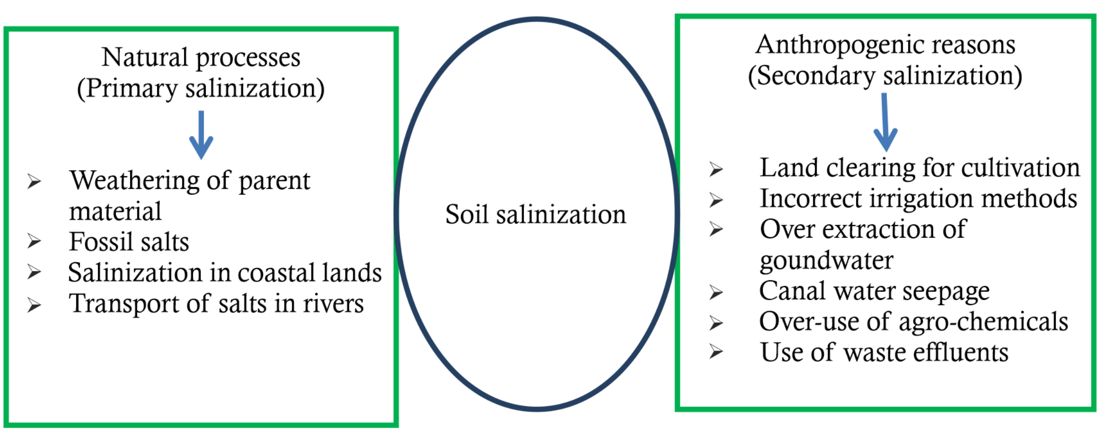

Fig. 1 General processes of soil salinization

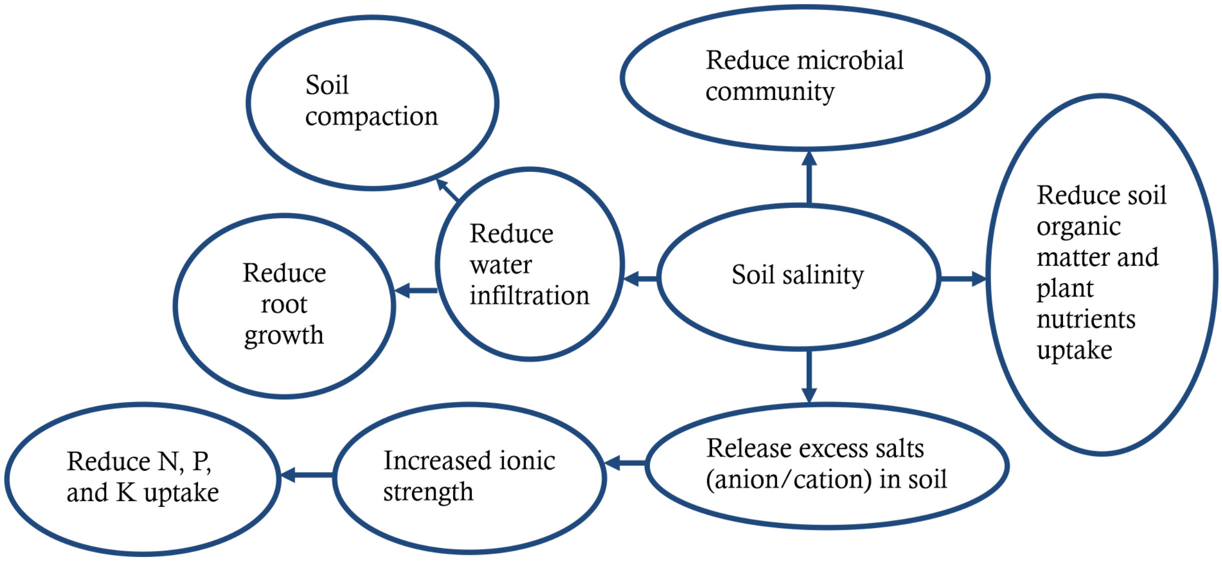

Fig. 2 Salinity effect on soil parameters

Organic amendments as a source to mitigate adverse effect of salinization

Scientists are using methods like sand mixing, sub soiling, bed planting, and throw away of salts to reduce excess soil salinity (Shilev, 2020, Meena *et al.,* 2020, Bhowmik *et al.,* 2021). Additionally, they apply different systems for irrigation, humic compounds, green manures, polymers that are hydrophilic, gypsum, sulphuric acids, farm yard manures and the development of salt-tolerant crops. In order to alleviate the adverse effects of salinity, various organic amendments including plant growth-promoting rhizobacteria, bio-fertilizers, biochar, compost, vermi-compost and vermi-wash) have been applied recently (Hoque *et al.,* 2022a, Imran *et al.,* 2023). The organic amendments are generally originated from plants and animals, which were illustrated in Fig. 3.

Numerous studies (Demir, 2020, Hafez, *et al.,* 2020, Muhie *et al.,* 2020, Ahmadi and Akbari, 2021, Bziouech *et al.,* 2022, Song *et al.,* 2022) have demonstrated that addition of organic amendments are successful protection strategy used for raising farmland production, especially in areas with low-quality soils like saline-alkaline soils. Humic acid (HA) is an organic colloid with intense cation adsorption and exchange abilities, is a soil amendment that can efficiently enhance soil structure, induce the creation of soil agglomeration structure, enhance soil organic matter, reduce soil salinity or alkalinity and stimulate the crop growth. Additional materials include cellulose ether derivatives with carboxymethyl structures, such as carboxymethyl cellulose (CMC), which can be produced from natural cellulose that has undergone etherification and alkylation modifications (Rahman *et al.,* 2021). Its benefits include having no taste or smell, being harmless and water soluble, and having excellent photo thermal constancy (Zhang *et al.,* 2022). As a result, it works particularly effectively

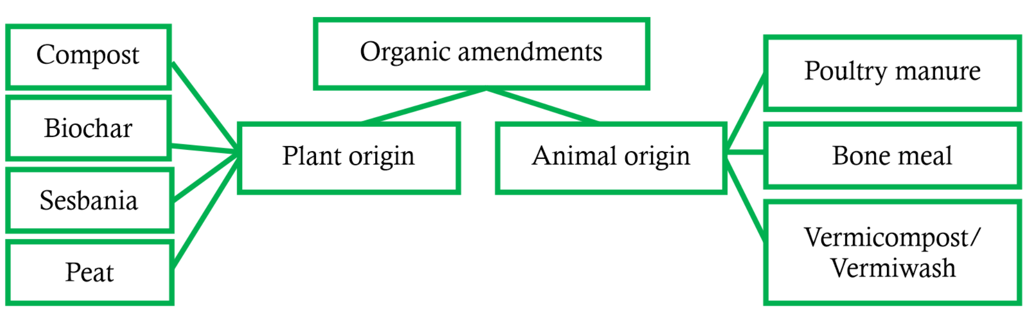

Fig. 3 Different types of organic amendments

in saline-alkaline soils as a water-holding substitute. Its aqueous solution is particularly well-known for its wide range of valuable attribute, involving its film creation, suspension, thickness, water-holding characteristic and adhesion (Fu *et al.,* 2023). Furthermore, the fermentation tail liquid of amino acid (AA), which is obtained from the synthesis of monosodium glutamate, higher organic components source, sugars, and inorganic nutrients. As a result, it can be used as an affordable, easily accessible, and high-quality raw fertilizer material. Because of its capacity to significantly enhance soil physical, chemical and microbiological conditions, it is in fact steadily gaining recognition as a novel kind of soil conditioner (Leogrande and Vitti, 2019). In light of the function of organic amendments in salinized environments, this review investigates the potential of contemporary, commonly applied organic amendments for mitigating salt stress as well as their regulating mechanisms.

Impact of compost, vermicompost/ vermiwash on salinity remediation

Compost, which is high in organic matter (OM) and essential plant nutrients including potassium, phosphate, and nitrogen, compensates for deficiencies in soils affected by salt. By raising the Ca^{2+} level in the soil solution, it also lowers the sodium absorption ratio (SAR). Additionally, compost improves soil organic matter through making aggregates by binding soil particles and increased soil aeration, penetration, increases micronutrient availability, and stimulates microbial and plant growth. Compost improves soil fertility for crop production by changing the characteristics of the soil. Additionally, it increases rates of photosynthesis and chlorophyll content, reduces oxidative stress, and fosters crop growth. Ahmed *et al.* (2021) support amending deteriorated saline-sodic soils with low priced water hyacinth compost in order to increase agricultural yields. Livestock excrement can be promptly converted into a bio-fertilizer by composting, which also gets rid of diseases, dangerous compounds, heavy metals, and antibiotics (Wang *et al.,* 2023). The vermicompost (VC) is an organic fertiliser that is rich in various enzymes, such as fulvic and humic acids, and is made by converting organic wastes by worms. It has anti-stress properties and is packed enzymes, hormones and vitamins along with macro and micro nutrients that together regulate plant growth. Vermi-wash is highly contain vitamins, auxins, cytokinins, amino acids and a rich source of macro (N, P, Mg) and micro (Zn, Cu and Fe) nutrients (Nadana et *al.,* 2020). Vermiwash also reduces electrolyte leakage, increases photosynthetic efficiency, and stimulates antioxidant enzyme activity to alleviate salt stress effects. The VC lowers the toxicity of salt and accelerates the emergence and growth of seedlings in a variety of plants. By lowering bulk density, electrical conductivity (EC), saturated hydraulic conductivity, and cation exchange capacity while raising field capacity, cation exchange capacity, and field capacity, it also improves soil organic matter in saline soils (Demir, 2020). Numerous studies (Bidabadi *et al.,* 2017, Zurbano, 2018, Khatun *et al.,* 2019, Zhou *et al.,* 2019, Ahmadi and Akbari, 2021, Alamer *et al.,* 2022) demonstrate that VC improved the morphological traits such leaf area, vigour index, length/ fresh and dry weight of root-shoot and dry weight per plant as well as salinity tolerance. It has been reported that VC increased K^+ accumulation and Na^+ exclusion, enhanced root activity, reduced oxidative damage, improved leaf colour pigment concentrations,and enhanced salt tolerance (Song *et al.,* 2022). Furthermore, VC addition under salinity reduced H_2O_2, malondialdehyde (MDA) and enhanced chlorophyll a, b and total, carotenoids, catalase (CAT), peroxdase (POD), and superoxide dismutase (SOD) (Bziouech *et al.,* 2022). In the saline soil, the VC soil amendment reduced exchangeable Na^+ and increased the plant height, total dry matter, and replaceable K^+, Ca^{2+}, and Mg^{2+} (Demir, 2020). Additionally, vermi-compost reduced salt-induced damage to plants growing in saline soil by increasing ascorbate peroxidase (APX), relative water percent, chlorophyll-a, stomatal conductance, superoxide dismutase, and catalase activities while lowering malondialdehyde and electrolyte seepage (Hafez *et al.,* 2020, Muhie *et al.,* 2020). The Fig. 4 illustrates how vermi-compst affects crops and soil. The compost, vermi-compost, and vermi-wash are low-cost methods to reduce the harmful effects of salts on plants

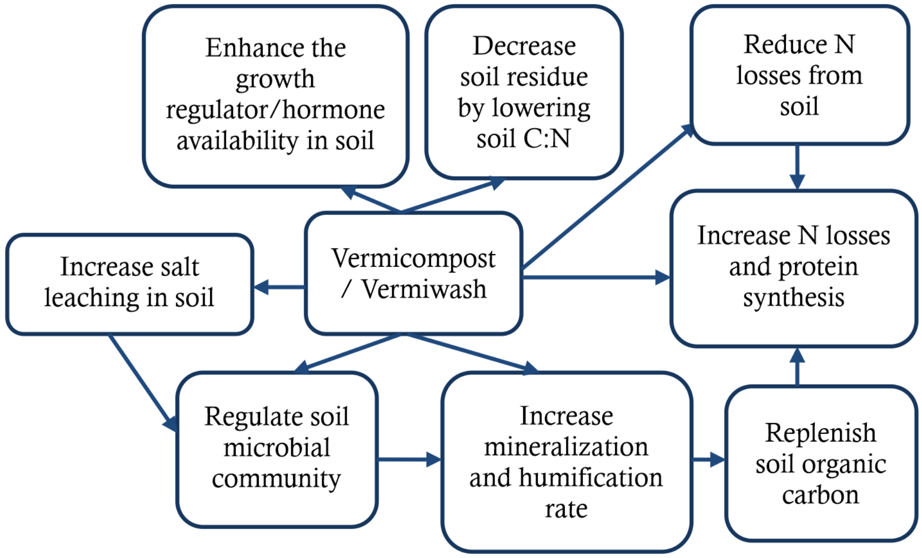

Fig. 4 Vermicompost effect on crops and soil and under salinity conditions

among the different organic amendment strategies.

Many workers research showed that compost, vermi-comopost and vermi-wash mitigate harmful salinity impact and improved crop yield, which were presented in Table 1.

Impact of biochar on salinity remediation

The physical properties of agricultural soil are improved by biochar (BC), an organic substance rich in carbon that has a high ion exchange capacity, a wide surface area, and a porous structure. It has been demonstrated that adding BC improves morphological characteristics such seed germination, plant height, fresh and dry biomass of shoot and root, leaf area, crop yield under salinity conditions (Ibrahim *et al.,* 2021). Moreover, in salinity stress, biochar treatment increased transcription rate, stomatal conductance, and photosynthetic rate. On the other hand, adding BC to saline soil increased the availability and nutrients (N, P, K, Fe, Mn, Zn, and Cu) uptake. Moreover, BC reduces osmotic stress and releases mineral nutrients from the soil by capturing excess Na^+ in saline environments

Table 1. Remediation of salinity impact from crops and soil by using vermi-compost, compost and vermi-wash

Crop species	Salinity stage	Treatments/ application methods	Amendments response
Paddy (*Oryza sativa* L.)	EC (dS m^{-1}) 2.9	VC with rice husk ash @1000 kg ha^{-1}	Decreased soil EC and increased exchangeable K^+, Ca^{2+}, and Mg^{2+} in soil; improved plant growth and grain yield (Penkam *et al.,* 2019).
	EC (dS m^{-1}) 7.5	15 t ha^{-1} compost	Improved soil nutrient availability and reduced salinity; enlarged crop yield and micronutrients. (Litardo *et al.,* 2022).
Maize (*Zea mays* L.)	EC (dS m^{-1}) 10.6	72 g VC pot^{-1} + 33 g cowdung pot^{-1}	Enhanced soil physico-chemical properties, seed germination, plant height, root length and yield (Khatun *et al.,* 2019).
	NaCl, 6 and 12 dS m^{-1}	5 and 10% VC	Improved fresh, dry weight of root and shoot; increased a, b, total chlorophyll and carotenoids; increased CAT, SOD, POD activities and salinity tolerance; decreased MDA content and H_2O_2 (Alamer *et al.,* 2022).

Contd...

Crop species	Salinity stage	Treatments/ application methods	Amendments response
Wheat -rice	EC (dS m^{-1}) 5.02	10 and 15 t ha^{-1} Hyacinth compost with 50%gypsum	Increased soil water-holding capacity, soil CEC and soil aggregation; increased rice and wheat yield (Ahmed *et al.,* 2021).
Sugarcane (*S. officinarum* L.)	EC (dS m^{-1}) 4.12	10 and 20 t ha^{-1} VC + N 50, 75 and 100 kg N ha^{-1}	Decreased soil Na^+/K^+ ratio and EC, alleviation of salinity; increased sugarcane growth and production (Djajadi *et al.,* 2020).
Lettuce (*LactucaSativa L.*)	EC (dS m^{-1}) 8.32	50%VC and 12.5% eggshell	Decreased salinity; increased seedlings germination and growth and crop yield (Zurbano, 2018).
Potato (*Solanum Tuberosum* L.)	NaCl,15, 20, 25 mM	VC @ 300, 580, and 860g $plant^{-1}$; VW @ 5, 10, 15 mL $plant^{-1}$	The addition of VC and VW increased the plant height, stem diameter; reduced salinity effects on the plant (Pérez-Gómez *et al.,* 2017).
	EC (dS m^{-1}) 2.85	Exogenous VC, proline + glycine betaine	Improved crop growth and yield, bio-component and antioxidant enzymatic activity; potatoes salt tolerance of improved (Ezzat *et al.,* 2019).
	NaCl, 0, 50, 100, 150, 200 mM	VC with bacteria having ACC eaminase activity	Improved seed germination, growth of seedlings; increased proline, chlorophyll and reduced salt stress (Zhou *et al.,* 2019).
Pomegranate (*Punica Granatum*L.)	NaCl, 0, 30, 60 mM	VW-foliar spray	Significantly increased leaf area, photosynthetic efficiency, fresh and dry weight of shoot and root; increased antioxidant enzymes activity; oxidative stress and electrolyte leakage decreased; reduced damage caused by salt stress (Bidabadi *et al.,* 2017).
Tomato (*Solanum Lycopersicon* L.)	NaCl, 150 mM	6 mL L^{-1} VW	Improved foliar growth and leaf water content; reduced root osmotic potential and leaves Na content; proline and total sugars accumulation promoted (Benazzouk *et al.,* 2018).
	NaCl,40 and 80 mM	25 t ha^{-1} compost	Crop yield and nutrient content increased; saline effect reduced; increased soluble sugars and amino acids accumulation (Savy *et al.,* 2022).
	NaCl, 125 mM	VW @ 18 mL L^{-1}	Lowered Na^+ deposition and improved plant growth in salinity stressed plants and young leaf senescence delayed (Benazzouk *et. al.,* 2020).
	NaCl,0, 50 and 150 mM	10 and 20% VC	Increased stem length, diameter, fresh and dry weight, leaves number, chlorophyll a, b, carotenoid, CAT and plant salt tolerence; decreased MDA (Bziouech *et al.,* 2022).
Fennel (*Foeniculum vulgare L.*)	NaCl,40, 80, and 120 mM	VW @ 10%	Increased Ca^{2+}content; alleviated plants salinity stress; reduced Na content and increased root Ca^{2+}, germination and crop growth (Beykkhormizi *et al.,* 2018).
Fenugreek (*Trigonella foenmgraecum L.*)	NaCl, 0, 100 and 200 mM	VC @ 0, 5 and 10% by weight	Reduced salinity effects and increased plant height, sub branch, number of pods and number of seed per pod (Barahouee and Sabbagh, 2017).
Allium cepa L. cv. Metan	NaCl,50, 100 mM	VC used as seed priming	Vermicpmpost mitigated salinity effects; improved germination, seedling growth, APX, SOD, CAT activities increased (Muhie *et al.,* 2020).
*Capsicum annuum*L.	NaCl,160 mM	7 mL L^{-1} VW	Roots sugar content and leaves proline content increased; leaf fresh weight and property of salt-stress resistance enhanced (Ahmadi and Akbari, 2021).
Helianthus Annuus L.	EC (dS m^{-1}) 0.5, 4.8,8.6	VC @ 1 kg pot^{-1}	Increased growth, yield, nitrate and protein content in plants; reduced Na^+, Cl^- and increased N-assimilation (Jabeen and Ahmad, 2017).
Brassica napus L.	NaCl,100 mM	VW (1:10, v/v)	Enhanced germination and oxidative stress of crop managed (Benazzouk *et al.,* 2019).

Abbreviations: ascorbate peroxidase (APX), catalase (CAT), peroxidase (POD) malondialdehyde (MDA) and superoxide dismutase (SOD).

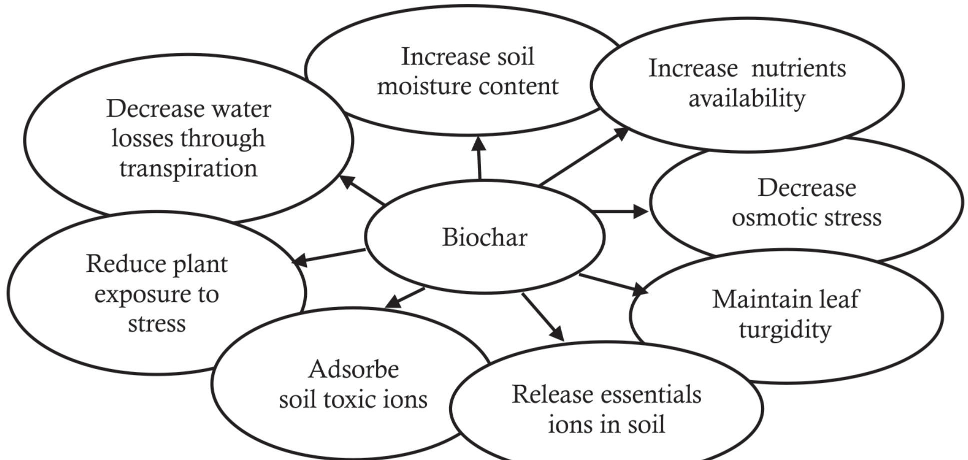

Fig. 5 Biochar effect on crops and soil under salinity

(Ibrahim *et al.,* 2021). Research revealed applying BC helped to decrease harmful salinity effect on plants by reducing Na^+ level and plants Na^+/K^+ ratio. Furthermore, BC treatment enhances osmotic balance under salt stress by raising water content and CO_2 absorption, that eventually leads to improved transcription and photosynthetic rate, stomatal transmittance (Ibrahim *et al.,* 2021). Furthermore, the BC treatment significantly decreased sucrose, proline, H_2O_2, and MDA while significantly increasing leaf relative water content (LRWC), Chla, Chl b, and total Chl., showed a considerable enhancement in salinity tolerance. Furthermore, decreasing the levels of phytohormones like abscisic acid, 1-aminocyclopropane-1-carboxylic acid, jasmonates and raising the quantity of indole-3-acetic acid, BC application lowered salinity effects. Additionally, under salinity stress, nodule formation, nitrogen status, rubisco activity, glutamate Dehydrogenase, glutamine synthetase, glutamate synthase and nitrate reductase were improved in plant by BC application.

According to several studies, applying BC enhances various physio-biochemical functions in plants, including photosynthesis, hormones and enzymatic activity. It also decreases the negative effects of salt stress on plants (Fig. 5). These findings are compiled in Table 2.

Impact of bio-fertilizer with organic amendments on salinity remediation

Bio-fertilizers (BFs) are a type of fertiliser that are made of live cells from different microorganisms and are capable of biological transformations, which change the form of nutrients from inaccessible to accessible. Bio-fertilizers can be sprayed directly onto the soil or inoculated into the seeds and roots of certain crop plants. However, bio-fertilizers along with organic substances afford substitute sources of plant nutrients for better crop production and conflict beside ecological stresses (Fasusi *et al.,* 2021, Kumar *et al.,* 2022). Numerous research conducted recently have detailed prospective of bio-fertilizer in improving salinity acceptance (Table 3). Furthermore, Khatami *et al.* (2022) stated that bio-fertilizer application increased essential oil output, LRWC, chlorophyll a, b and total in lavender and improved its ability to survive against salt stress. Similarly, BF application improved micro and macronutrient content, growth and yield indices, and alleviated adverse salt impacts on plants. Furthermore, BF application facilitated osmotic balance between soil and root, enhanced rhizospheric microbial activity, decreased harmful salts effect, and promoted growth and biomass of the plant. According to reports, BF helps plants produce proline, a secondary metabolite, and phytohormones including abscisic acid, cytokinins, and Indole-3-acetic acid to lessen salt stress impacts (Goswami and Deka, 2020, Yasmin *et al.,* 2021). Bio-fertilizers (BFs) enhanced enzyme activity of phyto-nutrients, minor metabolite buildup, and synthesis of plant hormones, leading to an overall debate concluded that bio-fertilizers boosted plant development and output, although simultaneously increasing salinity tolerance.

Table 2. Impact of biochar (BC) on crops and soil salinity reclamation

Crop species	Salinity stage	Treatments	Amendments effect
Rice (*Oryza sativa* L.)	50, 75 mM NaCl	BC along with phospogypsum and trico- compost	Increased N, P, K^+/Na^+, Ca^{2+}/Mg^{2+}, SO_4^{2-}, NO^{3-}, Mn^{4+} and Fe in rice rhizosphere soil; increased height, biomass, and crop yield and reduced ammonia production (Khatun *et al.,* 2021).
	EC (dS m^{-1}) 1 and 3	0.3% paddy straw BC	Improved physical and chemical soil properties, granum lamellae in mesophyll cells structure and crop yield; reduced soil Na^+ and Cl^- contents in soil (Zhang *et al.,* 2019).
	EC (dS m^{-1}) 2, 4, 6, and 8	BC @2 kg m^{-2}	Increased moisture content, physico-chemical properties of soil; improved relative water content, chl content, stomatal transmittance, plant growth and productivity; reduced proline content (Hafez *et al.,* 2019).
Wheat (*Triticum aestivum*L.)	3000 ppm NaCl	5% soybean straw BC (w/v) + 0.15% selenium	Improved salt tolerance and increased plant biomass, plant nutrient uptake, photosynthesis rate and leaf chlorophyll, (Soliman *et al.,* 2022).
	Saline (10 dS m^{-1}) water irrigation	10 and 20 t ha^{-1} BC of wheat straw	Soil bulk density and aging of leaves decreased; soil permeability, soil nutrient, photosynthesis and plant growth improved (Huang *et al.,* 2019).
	NaCl, 150 mM	@5% BC +5 µM jasmonic acid	Na^+ buildup and oxidative stress reduced and boost activity of phytonutrients (Alharbi and Alaklabi, 2022).
	EC (dS m^{-1}) 7.17	2% BC (w/w) + 1.0 and 2.0 mM Lysin	Reduced soil salinity, MDA, H_2O_2, and EC and improved soil nutrients; increased all chlorophyll content, photosynthesis, carotenoid, growth, biomass, and grain yield (Alharbi and Alaklabi, 2022).
Maize (*Zea mays* L.)	100 mM NaCl	BC of wheat straw + AMF	Mitigated soil salinity and improved nutrient status; reduced oxidative injury, improved photosynthetic performance and enhanced maize production (Ndiate *et al.,* 2021).
Soyabean (*Glycine Max L.*)	EC (dS m^{-1}) 5 and 10	50 and 100 g BC kg^{-1} soil	Lower soil Na^+ content and increased nutrient; improved leaf chlorophyll a, b and total content (Farhangi-Abriz and Torabian, 2018).
Mungbean (*Vigna radiate* L.)	EC (dS m^{-1}) 5 and 10	50 and 100 g BC kg^{-1}	Improved SOM, mitigate salt stress; xylem structure improved; ABA and ACC decreased; root/shoot ratio, total root area, and plant growth increased (Nikpour-Rashidabad *et al.,* 2019).
Sorghum (*Sorghum bicolour* L.)	EC (dS m^{-1}) 0.8, 4.1, and 7.7	2.5, 5, and 10% BC (w/w)	Reduced salinity and decreased soil degradation; plant height, DM, RWC, yield, and nutrients increased; osmotic stress decreased (Ibrahim *et al.,* 2021).
	Saline (400 mM) water irrigation	BC @ 5% (w/w)	Reduced Na^+ and increased soil water and nutrient; plant height, biomass, grain yield, photosynthetic rate and stomatal conductance increased; ionic balance also maintained (Yang *et al.,* 2020).
	EC (dS m^{-1}) 1 and 3	2, 4, 8% biochar	Released mineral ion K^+, Ca^{2+} and Mg^{2+}; soil organic matter, growth and crop yield improved (She *et al.,* 2018).
Cabbage (*Brassica Oleracea L.*var. Capitata)	NaCl, 150 mM	BC@ 2.5%, and 5% by soil weight)	Salt stress, oxidative stress, ABA and Na^+ content reduced; increased cabbage seedling growth (Ekinci *et al.,* 2022).

Abbreviations: relative water content (RWC), abscisic acid (ABA), salicylic acid (SA).

Application of PGRP with organic amendments and its effect on soil salinity remediation

Microorganisms called plant-growth-promoting rhizobacteria (PGPR) live in plant roots and are used in agricultural fields as chemical substitutes for crop protection and production. (Hoque *et al.,* 2022a). The plants can withstand saline conditions by using PGPR, which is resistant to salinity. Numerous molecules, such as extracellular polymers, 1-aminocyclopropane-1-carboxylate

Table 3. Application of bio-fertilizer with organic amendments for salinity alleviation

Crop species	Salinity stage	Treatments	Amendments effect
Wheat (*Triticum aestivum* L.)	NaCl, 0, 2.76, 5.53, and 8.3 dS m^{-1}	Seed inoculated with *A. chroococcum*, *B.* strain 5; *P. putida Trevisan*) *Migula strain 186*.	Relative water content, chlorophyll index, dry matter and grain yield increased; decreased the proline content (Khalilzadeh *et al.,* 2017).
Lettuce (*Lactuca sativa* L.)	EC (1.2 dSm^{-1}) Saline water irrigation	5 kg bio- fertilizer ha^{-1}	Activity of peroxidase, catalase, malondialdehyde, superoxide dismutase increased; disruption of endohormones, osmotic stress decreased and mitigates salinity stress (Al-Taey and Majid, 2018).
Cowpea (*Vigna unguiculata* L.)	25, 50, 100, 200, and 300 mM NaCl	0.8 g bio-fertilizer kg^{-1} mixed with sand	Plant growth parameters, total pigments, protein and proline contents increased and superoxide dismutase and catalaseactivities, H_2O_2 production reduced and alleviated salinity stress (Al-Abdallah *et al.,* 2017).

deaminase, phytohormones, antioxidants, and volatile chemical compounds, can be generated by these plant-associated rhizobacteria. Rhizosphere bacteria give plants with N, P, K, auxin, cytokinin, and abscisic acid, which help crop develop while reducing salinity stress (Gao *et al.,* 2022). The application of PGPR has a beneficial impact on the growth and yield of crops grown in saline soil (Table 4). In addition, with salinity, PGPR improved height, biomass, chlorophyll concentrations, all of which reduced harmful soil salinity impacts. Plants depend on water potential, stomatal opening for their survival; in fact, PGPR has been shown to alter salinity-stressed conditions to counteract salt stress. Furthermore, it has been demonstrated that applying certain PGPR helps plants stressed by salt enhance nodule formation and fix nitrogen. However, in several applications, PGPR enhanced not only the number of nodules but also the plant weights, amount of N output, protein content (Omara *et al.,* 2017). Numerous research have reported that PGPR improves photosynthetic characteristics, minor metabolite buildup, oxidative stress decline, positively regulates ion equilibrium and activity of phyto-nutrients enzyme to alleviate growth suppression caused in plants due to salinity (Table 4). Furthermore, certain PGPR boosted the K^+/Na^+ ratio and decreased Cl_2 and NO_2 concentrations, which improved stomatal conductance, preserved hormonal balance, and promoted photosynthesis under salt stress (Hoque *et al.,* 2022a). Therefore, it is clear from the study findings that the exogenous application of PGPR might promote healthy development and yield outcomes in plants grown in saline conditions. This makes it a viable current agronomic strategy for enhancing plant survivability in saline environments.

The efficiency of PGPR and techniques to improve its ability to respond rapidly to stress throughout a vast region for sustainable agricultural yield may be revealed in the future by dealing with substantial molecular research.

Limitations on organic amendments and prospects for the future

Plant growth, development, and soil characteristics are all significantly impacted by the addition of organic amendments. These supplements have unique physiochemical characteristics. The aforesaid description explains how external organic processes act as a strong growth regulator, enhancing plant growth performance under salt stress. An effective strategy for preventing soil salinization and improve soil organic carbon is the use of organic amendments by various methods in agriculture. However, Hoque *et al.* (2022b) pointed out some limitations of these methods such as:

- For preparations of organic amendments require more manpower, time, area, and raw materials because they are naturally transformed as a result of weathering processes.
- Maintaining environmental factors such as temperature, moisture content, and respiration for the manufacture of organic

Table 4. Response of PGPR with organic amendments for enhancement of plant growth and alleviation of salt stress

Crop species	Salt level	PGPR Inoculation	Effects of Inoculation
Wheat (*Triticum aestivum* L.)	NaCl, 10% solution	*Pseudomonas fluorescence*, *Bacillus pumilus*, and *Exiguobacteriumaurantiacum*	Recorded maximum root growth and dry biomass; found high proline and total soluble proteins; improved phyto nutrients activity, water and osmotic potential (Nawaz *et al.,* 2020).
	NaCl, 10% and 15% solution	*Enterobacter cloacae*	Decreased Na^+ accumulation, K^+ uptake by shoots and roots increased and high K^+/Na^+ ratios; phyto-chemicals activity improved (Singh *et al.,* 2017).
	NaCl, 100 and 200 mM	*Kocuriarhizophila*	IAA and ABA activity increased; enhanced salinity tolerant genes such as $ZmNHX_1$, $ZmNHX_2$, $ZmNHX_3$, $ZmWRKY_{58}$ and $ZmDREB_2A$, improved Plant growth parameters; higher chlorophyll, proline, total soluble sugar content and higher K^+/Na^+ ratios (Li *et al.,* 2020).
Maize (*Zea mays* L.)	0, 300, 600 and 900 mM NaCl	*Enterobacter cloacae*	Enhanced radical scavenging capacity, RWC, soluble sugars, proteins, minor metabolite content; improved photosynthetic pigments, plant growth, plant biomass under salinity stress (Ali *et al.,* 2022).
	KCl -500 µM and $CaCl_2$-100 µM	*Piriformos poraindica*	Maximum biomass and stomatal transmission, reduced K^+ efflux from roots, and higher K content in shoots (Yun *et al.,* 2018).
Soybean (*Glycine max L.*)	NaCl, 100, 250, and 500 mM	*Rhizobium* sp., *BradyrhizobiumJaponicum* and *Hydrogenophaga* sp.	Improved seed weight and shoot K+/Na+ ratio; increased biomass during the vegetative and reproductive stages (Ilangumaran *et al.,* 2021).
	Salinity, 0.170 dS m^{-1}	*Methylobacterium aminovorans* and *Methylobacterium rhodinum*;*Bradyrhizobium japonicum* and *Bacillus megaterium*	Nodule dry weight and number increased; N, P, and K levels significantly increased; pod count, seed index, and seed yield increased (Omara *et al.,* 2017).
Paddy (*O. sativa* L.)	120 and 250 mM NaCl	*Bacillus amyloliquefaciens*	Increased amino acid synthesis, enhanced endogenous ABA and SA, and enhanced plant physiology (Shahzad *et al.,* 2017).
Mung bean (*Vigna radiate L.*)	10% solution of NaCl	*Rhizobium*sp. and *Enterococcus mundtii*	Improved soil physical, chemical, and biological characteristics; increased chlorophyll content and macro-micronutrient uptake; increased seed germination and seedling growth and biomass (Kumawat *et al.,* 2020).
Pea (*Pisum Sativum L.*)	NaCl, 75, 100 and 150 mM	*Acinetobacterbereziniae*, *Enterobacterludwigii*, and *Alcaligenesfaecalis*	Improved plant growth parameters; higher chlorophyll, proline, total soluble sugar; improved electrolyte leakage and antioxidant enzymes behavior (Sapre *et al.,* 2022).
Rapeseed (*Brassica napus L.*)	NaCl, 50 and 100 mM	*Enterobacter cloacae*	Improved seed germination and seedling growth; improved chlorophyll, water potential and physiological movement (Li *et al.,* 2017).
Tomato (*Solanum lycopersicum L*)	NaCl, 200 mM	*Bacillus megaterium*	Enhanced biomass and growth measures for plants, as well as increased levels of proline, chlorophyll, and total soluble sugar (Nascimento *et al.,* 2020).

Abbreviations: Indole-3-acetic acid (IAA), relative water content (RWC), abscisic acid (ABA), salicylic acid (SA).

amendments requires both scientific understanding and experienced and qualified individuals.

- There is a bad smell and a fly population associated with certain preparation techniques of vermi-composting, charcoal and bio fertilizers. In certain instances, toxic fungi and bacteria are commonly developed on the worm-feeding materials.

Even though organic amendment requires more time and additional management techniques to prepare. Several proactive and preventive measures have been employed over time to enhance plant nutrition in salt-stressed agro-ecosystems, with established negative consequences. Many techniques, such as applying organic amendments, have shown promise in lowering salt stress and other agricultural restrictions. The organic amendments minimize the harm caused by salt stress by improving the physico-chemical parameters of degraded soils, decreasing soil pH, salinity and improve salinity effect. In order to increase crop yield, further research is needed to fully comprehend the geological, physical, chemical and biological, transcriptomics, and proteomics of applying natural amendment in a saline atmosphere.

Conclusion

By reducing soil permeability, bulk density, structural stability, and water-holding capacity, soil salinity has a negative impact on soil quality. Excess salt content slow down soil microbes activity, enzyme activities, reduced available plant nutrients and results poor plant development and crop yield. The application of compost, vermi-compost, vermiwash, biochar, biofertilizer and PGPR decreased these negative impacts of salinity. Although several investigations on physiological, chemical, biological and molecular actions of compost, vermi-compost, vermiwash, biochar, biofertilizer and PGPR regulation in different crops under salt stress have been conducted, despite the fact that several studies on these functions have been undertaken.

References

Ahmadi N and Akbari E (2021) The preventive impact of vermicompost on bell pepper (*Capsicum annuum* L.) salinity resistance: an evaluation. *African Journal of Agricultural Research* **17**: 46–56.

Ahmed K, Sajib AI, Naseem AR, Qadir G, Nawaz MQ, Khalid M, Warraich IA and Arif M (2021) Use of hyacinth compost in salt-affected soils. *Pakistan Journal of Agricultural Research* **33**: 720-728.

Al-Abdallah NM, Basalah MO and Roushdy SS (2017) The promotive effect of algal biofertilizers on growth and some metabolic activities of (*Vigna unguiculata* L.) under salt stress conditions.*Egyptian Journal of Experimental Biology***13**: 187–195.

Alamer KH, Perveen S, Khaliq A, Zia Ulhaq M, Ibrahim, M U and Ijaz B (2022) Mitigation of salinity stress in maize seedlings by the application of vermicompost and sorghum water extracts. *Plants* **11**: 2548. https://doi.org/10.3390/plants11192548

Alharbi K and Alaklabi K (2022) Alleviation of salinity induced growth and photosynthetic decline in wheat due to biochar and jasmonic acid application involves up-regulation of ascorbate-glutathione pathway, glyoxylase system and secondary metabolite accumulation. *Rhizosphere* **24**:100603. https://doi.org/10.1016/j.rhisph.2022.100603

Ali B, Wang X, Saleem MH, Sumaira, Hafeez A, Afridi MS, Khan S, Zaib-Un-Nisa, Ullah I, Amaral Júnior ATD, Alatawi A and Al S (2022) PGPR-Mediated salt tolerance in maize by modulating plant physiology, antioxidant defense, compatible solutes accumulation and bio-surfactant producing genes. *Plants* **11**: 345. https://doi.org/10.3390/plant 11030345

Al-Taey DK and Majid ZZ (2018) Study effect of kinetin, bio-fertilizers and organic matter application in lettuce under salt stress. *Journal of Global Pharma Technology* **10**: 148–164.

Arora S and Sharma V (2017) Reclamation and management of salt-affected soils for safe guarding agricultural productivity. *Journal of Safe Agriculture* **1**: 1–10.

Barahouee M and Sabbagh E (2017) Influence of vermicompost and salt stress on some characteristics of fenugreek (*Trigonella foenumgraecum* L.). *International Journal of Agriculture and Biosciences* **6**: 60–63.

Benazzouk S, Djazouli ZE and Lutts S (2019) Vermicompost leachate as a promising agent for priming and rejuvenation of salt-treated germinating seeds in Brassica napus. *Communication in Soil Science and Plant Analysis* **50**: 1344–1357.

Benazzouk S, Dobrev PI, Djazouli ZE, Motyka V and Lutts S (2020) Positive impact of vermicompost leachate on salt stress resistance in tomato (*Solanum lycopersicum* L.) at the seedling stage: a phytohormonal approach. *Plant and Soil* **446**: 145–162.

Benazzouk S, Lutts S and Djazouli ZE (2018) Alleviation of salinity stress by vermicompost extract in *Solanum lycopersicum* L. by mobilizing salt tolerance mechanisms. *Agrobiologia* **8**: 1136–1144.

Beykkhormizi A, Hosseini S, Sarafraz AM, Moshtaghioun S, Mousavi K and Seyed M (2018) Alleviation of salinity stress by vermicompost extract: a comparative study on five fennel landraces. *Communication in Soil Science and Plant Analysis* **49**: 2123–2130.

Bhowmik U, Kibria MG, Rhaman MS, Murata Y and Hoque MA (2021) Screening of rice genotypes for salt tolerance by physiological and biochemical characters. *Plant Science Today* **8**: 467–472.

Bidabadi SS, Dehghanipoodeh S and Wright GC (2017) Vermicompost leachate reduces some negative effects of salt stress in pomegranate. *International Journal of Recycling Organic Waste in Agriculture* **6**: 255–263.

Bziouech SA, Dhen N, Helaoui S, Ammar IB and Dridi BAM (2022) Effect of vermicompost soil additive on growth performance, physiological and biochemical responses of tomato plants (*Solanum lycopersicum* L. var. Firenze) to salt stress. *Emirates Journal of Food and Agriculture***34**: 316–328.

Demir Z (2020) Alleviation of adverse effects of sodium on soil physicochemical properties by application of vermicompost. *Compost Science and Utilization* **28**: 100–116.

Djajadi D, Syaputra R, Hidayati SN and Khairiyah Y (2020) Effect of vermicompost and nitrogen on N, K, Na uptakes and growth of sugarcane in saline soil. *Agrivita Journal of Agricultural Sciences* **42**: 110–119.

Ekinci M, Turan M and Yildirim E (2022) Biochar mitigates salt stress by regulating nutrient uptake and antioxidant activity, alleviating the oxidative stress and abscisic acid content in cabbage seedling. *Turkish Journal of Agriculture and For*estry **46**: 28–37.

Ezzat AS, Badway AS and AbdelkaderAE (2019) Sequenced vermicompost, glycine betaine, proline treatments elevate salinity tolerance in potatoes. *Middle East Journal of Agriculture Research* **8**: 126–138.

Farhangi-Abriz, S and Torabian S (2018) Biochar improved nodulation and nitrogen metabolism of soybean under salt stress. *Symbiosis* **74**: 215–223.

Fasusi OA, Cruz C and Babalola OO (2021) Agricultural austainability: microbial biofertilizers in rhizosphere management. *Agriculture* **11**:163. https://doi.org/ 10.3390 /agriculture 11.20163

Fu X, Wu X, Wang H, Chen Y, Wang R and Wang Y (2023) Effects of fertigation with carboxymethyl cellulose potassium on water conservation, salt suppression, and maize growth in salt-affected soil. *Agricultural Water Management* **287**: 108436. https://doi.org/10.1016/ j.agwat.2023.108436

Gao Y, Zou H, Wang B and Yuan F (2022) Progress and applications of plant growth-promoting bacteria in salt tolerance of crops. *International Journal of Molecular Sciences* **23**: 7036. doi: 10.3390/ijms23137036

Goswami M and Deka S (2020) Isolation of a novel rhizobacteria having multiple plant growth promoting traits and antifungal activity against certain phytopathogens. *Microbiological Research* **240**: 126516. https://doi.org/10.1016/j.micres.2020.126516

Guangming L, Xuechen Z, Xiuping W, Hongbo S, Jingsong Y and Xiangping W (2017) Soil enzymes as indicators of saline soil fertility under various soil amendments. *Agriculture Ecosystems and Environment* **237**: 274–279.

Hafez EM, Alsohim AS, Farig M, Omara AED, Rashwan E and Kamara MM (2019) Synergistic effect of biochar and plant growth promoting rhizobacteria on alleviation of water deficit in rice plants under salt-affected soil. *Agronomy* **9**: 847. https://doi.org/10.3390/agronomy 9120847

Hafez EM, Omara AE, Alhumaydhi FA and El-Esawi MA (2020).Minimizing hazard impacts of soil salinity and water stress on wheat plants by soil application of vermicompost and biochar. *Physiologia Plantarum* **172**: 587–602.

Hedrich R and Shabala S (2018) Stomata in a saline world. *Current Opinion in Plant Biology* **46**: 87–95.

Hoque MN, Hannan A, Imran S, Paul NC, Mondal M, Sadhin M, Rahman M, Bristi JM, Dola FS, Hanif, M, Ye W, Brestic M and Rhaman MS (2022a) Plant growth-promoting rhizobacteria-mediated adaptive responses of plants under salinity stress. *Journal of Plant Growth Regulation* **28**: 1–20.

Hoque MN, Imran S, Hannan A, Paul NC, Mahamud MA, Chakrobortty J, Sarker P, Irin IJ, Brestic M and Rhaman MS (2022b) Organic amendments for mitigation of salinity stress in plants: A Review. *Life* **12**: 1632. https:/ /doi.org/10.3390/life 12101632

Huang M, Zhang Z, Zhai Y, Lu P and Zhu C (2019) Effect of straw biochar on soil properties and wheat production under saline water irrigation. *Agronomy* **9**: 457. https:// doi.org/10.3390/agronomy 9080457

Ibrahim MEH, Ali AYA, Elsiddig AMI, Zhou G, Nimir NEA, Agbna GH and Zhu G (2021) Mitigation effect of biochar on sorghum seedling growth under salinity stress. *Pakistan Journal of Botany* **53**: 387–392.

Ilangumaran G, Schwinghamer TD and Smith DL (2021) Rhizobacteria from root nodules of an indigenous legume enhance salinity stress tolerance in soybean. *Frontiers in Sustainable Food System* **4**:617978. https:// doi.org/10.3389/fsufs.2020.617978

Imran S, Sarker P, Hoque MN, Paul NC, Mahamud MA, Chakrobortty J, Tahjib-Ul-Arif M, Latef AA, Hasanuzzaman M and Rhaman MS (2023) Biochar actions for the mitigation of plant abiotic stress. *Crop and Pasture Science* **74**: 6-20.

Jabeen N and Ahmad R (2017) Growth response and nitrogen metabolism of sunflower (*Helianthus annuus* L.) to vermicompost and biogas slurry under salinity stress. *Journal of Plant Nutrition* **40**: 104–114.

Khalilzadeh R, Seyed SR and Jalilian J (2017) Growth, physiological status, and yield of salt stressed wheat (*Triticum aestivum* L.) plants affected by biofertilizer and cycocel applications. *Arid Land Research and Management* **32**: 71–90.

Khatami SA, Kasraie P, Oveysi M, Moghadam HRT and Ghooshchi F (2022) Mitigating the adverse effects of salinity stress on lavender using biodynamic preparations and bio-fertilizers. *Industrial Crops and Products* **183**: 114985. doi:10.1016/j.indcrop.2022.114985

Khatun L, Ali MA, Sumon MH, Islam MB and Khatun F (2021) Mitigation rice yield scaled methane emission and soil salinity stress with feasible soil amendments. *Journal of Agricultural Chemistry and Environment* **9**: 16–36.

Khatun M, Shuvo MAR, Salam MTB and Rahman SMH (2019) Effect of organic amendments on soil salinity and the growth of maize (*Zea mays*L.). *Plant Science Today* **6**: 106–111.

Kumar P and Sharma P K (2020) Soil salinity and food security in India. *Frontiers in Sustainable Food Systems* **4**: 533781. http://doi.org./10.3389/fsufs.2020.533781

Kumar S, Diksha, SindhuSS and Kumar R (2022) Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. *Current Research in Microbial Sciences* **3**:100094. https://doi.org/10.1016/j.crmicr.2021.100094.

Kumawat KC, Sharma P, Nagpal S, Gupta RK, Sirari A, Nair RM, Bindumadhava H and Singh S (2020) Dual microbial inoculation, a game changer?—Bacterial biostimulants with multifunctional growth promoting traits to mitigate salinity stress in spring mungbean. *Frontiers in Microbiology***11**: 576. https://doi.org/10.3389/fmicb.2020.600576

Leogrande R and Vitti C (2019) Use of organic amendments to reclaim saline and sodic soils: a review. *Arid Land Research and Management* **33**:1-21.

Li H, Lei P, Pang X, Li S, Xu H, Xu Z and Feng X (2017) Enhanced tolerance to salt stress in canola (*Brassica napus*L.) seedlings inoculated with the halo tolerant Enterobacter cloacae HSNJ4. *Applied Soil Ecology* **119**: 26–34.

Li X, Sun P, Zhang Y, Jin C and Guan C (2020) A novel PGPR strain KocuriarhizophilaY1 enhances salt stress tolerance in maize by regulating phytohormone levels, nutrient acquisition, redox potential, ion homeostasis, photosynthetic capacity and stressresponsive genes expression. *Environmental and Experimental Botany* **174**: 104023. https://doi.org/10.1016/j.envexpbot.2020.104023

Litardo RCM, Bendezú SJG, Zenteno MDC, Pérez-Almeida IB, Parismoreno LL and García EDL (2022) Effect of mineral and organic amendments on rice growth and yield in saline soils. *Journal of the Saudi Society of Agricultural Science* **21**: 29–37.

Liu D and She D (2017) Can rock fragment cover maintains soil and water for saline-sodic soil slopes under coastal reclamation? *Catena* **151**: 213–224.

Mandal S, Raju R, Kumar A, Kumar P and Sharma P C (2018) Current status of research, technology response and policy needs of salt-affected soils in India – a review. *The Indian Society of Coastal Agriculture Research* **36**: 40–53.

Meena KK, Bitla UM, Sorty AM, Singh DP, Gupta VK, Wakchaure GC and Kumar S (2020) Mitigation of salinity stress in wheat seedlings due to the application of phytohormone-rich culture filtrate extract of methylotrophic actinobacterium nocardioides sp. NIMMe6. *Frontiers in Microbiology* **11**: 2091. doi: 10.3389/fmicb.2020.02091

Muhie SH, Yildirim E, Memis N and Demir I (2020) Vermicompost priming stimulated germination and seedling emergence of onion seeds against abiotic stresses. *Seed Science and Technology* **48**: 153–157.

Nadana GV, Rajesh C, Kavitha A, Sivakumar P, Sridevi G and Palanichelvam K (2020) Induction of growth and defense mechanism in rice plants towards fungal pathogen by eco-friendly coelomic fluid of earthworm. *Environmental Technology and Innovation* **19**: 101011. Doi.10.1016/j.eti.2020.101011

Nascimento FX, Hernández AG, Glick BR and Rossi MJ (2020) Plant growth-promoting activities and genomic analysis of the stress-resistant Bacillus megateriumSTB1, a bacterium of agricultural and biotechnological interest. *Biotechnology Reports* **25**:e00406. https://doi.org/10.1016/j.btre.2019.e00406

Nawaz A, Shahbaz M, Imran A, Marghoob MU, Imtiaz M and Mubeen F (2020) Potential of salt tolerant PGPR in growth and yield augmentation of wheat (*Triticum aestivum* L.) under saline conditions. *Frontiers in Microbiology* **11**: 2019. https://doi.org/10.3389/fmicb.2020.02019

Ndiate NI, Saeed Q, Haider FU, Liqun C, Nkoh JN and Mustafa A (2021) Co-application of biochar and *arbuscular mycorrhizal* fungi improves salinity tolerance, growth and lipid metabolism of maize (*Zea mays*L.) in an alkaline soil. *Plants* **10**: 2490. https://doi.org/10.3390/plants10112490

Nikpour-Rashidabad N, Tavasolee A, Torabian S and Farhangi-Abriz S (2019)The effect of biochar on the physiological, morphological and anatomical characteristics of mung bean roots after exposure to salt stress. *Archives in Biological Sciences***71**: 321–327.

Omara AE, Hauka F, Afify A, Nour EM and Kassem M (2017) The role of some PGPR strains to biocontrol *Rhizoctonia solaniin* soybean and enhancement the growth dynamics and seed yield. *Environment, Biodiversity and Soil Security***1**: 47–59.

Penkam C, Iwal CB and Kume T (2019) Effects of vermicompost and rice husk ash on the change of soil chemical properties and the growth of rice in salt affected area. *International Journal of Environmental and Rural Development* **10**: 129–132.

Pérez-Gómez JD, Abud-Archila M, Villalobos-Maldonado JJ, Enciso-Saenz S, Hernández de LH, Ruiz-Valdiviezo VM and Gutiérrez-Miceli FA (2017) Vermicompost and vermiwash minimized the influence of salinity stress on growth parameters in potato plants. *Compost Science and Utilization* **25**: 282–287.

Rahman MS, Hasan MS, Nitai AS, Nam S, Karmakar AK, Ahsan MS, Shiddiky MJA and Ahmed MB (2021) Recent developments of carboxymethyl cellulose. *Polymers* **13**: 1345. https://doi.org/10.3390/polym13081345

Sahab S, Suhani I, Srivastava V, Chauhan PS, Singh RP and Prasad V (2021) Potential risk assessment of soil salinity to agroecosystem sustainability: Current status and management strategies. *Science of the Total Environment* **764**: 144164. https://doi.org/10.1016/j.scitotenv.2020.144164

Sapre S, Gontia-Mishra I and Tiwari S (2022) Plant growth-promoting rhizobacteria ameliorates salinity stress in pea (*Pisum sativum*). *Journal of Plant Growth Regulation* **41**: 647–656.

Savy D, Cozzolino V, Vinci G, Verrillo M, Aliberti A, Maggio A, Barone A and Piccolo A (2022) Fertilization with compost mitigates salt stress in tomato by affecting plant metabolomics and nutritional profiles. *Chemical and Biological Technologies in Agriculture* **9**:104. https://doi.org/10.1186/s40538-022-00373-5

Seleiman MF, Semida WM, Rady MM, Mohamed GF, Hemida KA, Alhammad BA, Hassan MM and Shami A (2020) Sequential application of antioxidants rectifies ion imbalance and strengthens antioxidant systems in salt-stressed cucumber. *Plants* **9**: 1783. https://doi.org/10.3390/plants9121783

Shahid SA, Zaman M and Heng L (2018) Salinity and sodicity adaptation and mitigation options.*In:* Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques. Springer: Cham, Switzerland, pp. 55–89.

Shahzad R, Khan AL, Bilal S, Waqas M, Kang SM and Lee IJ (2017) Inoculation of abscisic acid-producing endophytic bacteria enhances salinity stress tolerance in *oryza sativa*. *Environmental and Experimental Botany* **136**: 68–77.

She D, Sun X, Gamareldawla AH, Nazar EA, Hu W, Edith K and YuSE (2018) Benefits of soil biochar amendments to tomato growth under saline water irrigation. *Science Reports* **8**: 14743. dOI: 10.1038/s41598-018-33040-7

Shilev S (2020) Plant-growth-promoting bacteria mitigating soil salinity stress in plants. *Applied Science* **10**: 7326. https://doi.org/10.3390/app10207326

Siddiqui MN, Mostofa MG, Akter MM, Sivastava AK, Sayed MA, Hasan MS and Tran LSP (2017) Impact of salt induced toxicity on growth and yield-potential of local wheat cultivars: Oxidative stress and ion toxicity are among the major determinants of salt-tolerant capacity. *Chemosphere* **187**: 385–389.

Singh RP, Jha P and Jha PN (2017) Bio-inoculation of plant growth-promoting rhizobacteriumEnterobacter cloacae ZNP-3 increased resistance against salt and temperature stresses in wheat plant (*Triticum aestivum*L.). *Journal of Plant Growth Regulator* **36**: 783-798.

Soliman MH, Alnusairi GS, Khan AA, Alnusaire TS, Fakhr MA, Abdulmajeed AM, Aldesuquy HS, Yahya M and Najeeb U (2022) Biochar and selenium nanoparticles induce water transporter genes for sustaining carbon assimilation and grain production in salt-stressed wheat. *Journal of Plant Growth Regulator* **42**: 1522-1543.

Song X, Li H, Song J, Chen W and Shi L (2022) Biochar/vermicompost promotes hybrid pennisetum plant growth and soil enzyme activity in saline soils. *Plant Physiology and Biochemistry* **183**: 96-110.

Stavi I, Thevs N and Priori S (2021) Soil salinity and sodicity in drylands: a Review of causes, effects, monitoring and restoration measures. *Frontiers in Environmental Science* **9**:712931.https://doi.org/10.3389/fenvs.2021.712831

Wang Y, Gao M, Chen H, Chen Y, Wang L and Wang R (2023) Organic Amendments promote saline-alkali soil desalinization and enhance maize growth. *Frontiers Plant Science* **14**: 1177209. doi: 10.3389/fpls.2023.1177209.

Yang A, Akhtar SS, Li L, Fu Q, Li Q, Naeem MA, He X, Zhang Z and Jacobsen SE (2020) Biochar mitigates combined effects of drought and salinity stress in quinoa. J. Agron. **10**: 912. https://doi.org/10.3390/agronomy 10060912

Yasmin H, Mazher J, Azmat A, Nosheen A, Naz R, Hassan MN, Noureldeen A and Parvaiz AP (2021) Combined application of zinc oxide nanoparticles and biofertilizer to induce salt resistance in safflower by regulating ion homeostasis and antioxidant defence responses. *Ecotoxicology and Environmental Safety* **218**:112262. doi: 10.1016/j.ecoenv.2021.112262.

Yun P, Xu L, Wang SS, Shabala L, Shabala S and Zhang WY (2018) *Piriformospora indica* improves salinity stress tolerance in zea mays L. plants by regulating Na^+ and K^+ loading in root and allocating K^+ in shoot. *Plant Growth Regulators* **86**: 323–331.

Zhang J, Bai Z, Huang J, Hussain S, Zhao F, Zhu C, Zhu L, Cao X and Jin Q (2019) Biochar alleviated the salt stress of induced saline paddy soil and improved the biochemical characteristics of rice seedlings differing in salt tolerance. *Soil and Tillage Research* **195**:104372. doi:10.1016/j.still.2019.104372

Zhang J, Wang Q, Shan Y, Guo Y, Mu W, Wei K aand Sun Y (2022) Effect of sodium carboxymethyl cellulose on water and salt transport characteristics of saline–alkali soil in Xinjiang, China. *Polymers* **14**: 2884. doi: 10.3390/polym14142884

Zhou J, Ahmed N, Cheng Y, Qin C, Chen P, Zhang C and Zhang L (2019) Effect of inoculation of strains with accdeaminase isolated from vermicompost on seed germination and some physiological attributes in maize (*Zea mays* L.) exposed to salt stress. *Pakistan Journal of Botany* **51**: 1169–1177.

Zurbano LY (2018) Response of lettuce (*Lactuca sativa*) on saline soil amended with vermicompost and pulverized eggshell. *Indian Journal of Science and Technology* **11**: 1–8.

Received: September 10, 2024; Accepted: September 29, 2024

Journal of Soil Salinity and Water Quality 16(2), 180-193, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156291

Genome Editing Technologies for Enhancing Plant Resilience to Biotic and Abiotic Stresses - Brief Review

Anita Mann*, Poonam Ranga*, Priti Choudhary, Sujata Yadav, Noyonika Kaul, Avni Dahiya, Nitish Ranjan Prakash, Ashwani Kumar, Arvind Kumar and Satish Kumar Sanwal

ICAR-Central Soil Salinity Research Institute, Karnal-132001, Haryana India
**Corresponding author's E-mail: anitadgr13@gmail.com; poonamranga27@yahoo.com*

Abstract

Global climate change is the biggest threat to the agriculture, leading to environmental stresses thereby, reducing crop quality and yield. For a sustainable food future along with demand and supply, economic accessibility to the galloping population, a 25-70% increase in agricultural productivity is sufficient. To meet these universal targets, developing climate-resilient crops will rebalance the prevailing discourse on the agricultural narrative of food security. Although, traditional plant breeding tools have uplifted the agricultural practices for developing improved crop plants but the cumbersome duration of conventional breeding limits availability of new varieties/ plants for cultivation. To exaggerate this process, the recently developed technologies of genome editing, such as CRISPR/Cas9, are accurate and efficient solutions by enabling targeted alterations in plant genomes to enhance desirable traits for crop improvement. Moreover, these gene editing technologies are preferable over GM crops due to modifications in the host genome itself than the insertion of any foreign gene into it. Additionally, the use of SDN technology for edits pertaining to SDN-1 and SDN-2 category are categorised as non-transgenic, hence, safe to use. This review is briefly compiled including evolution of different genome editing strategies, highlighting its advantages in developing crops resistant to both biotic and abiotic stresses, e.g. salt tolerance, drought resistance, and disease resistance to ensure stable food production in a changing climate.

Key words: Climate change, Genome editing, nucleases, TALENs, ZFNs, CRISPR Cas9

Introduction

During 2023, Intergovernmental Panel on Climate Change (IPCC), highlights the escalating impacts of human-induced climate change, particularly emphasizing water scarcity and its effects on agriculture. Water scarcity directly affects irrigation, soil moisture and crop yields, altered rainfall patterns and increased frequency of droughts and floods. By 2050, as the human population will approach to 10 billion, the demand for food will surge, necessitating innovations in agriculture, such as climate-resilient crops and improved water-use efficiency (Tilman *et al.*, 2011). Rising global temperatures further exacerbate these challenges, as heatwaves increase evapotranspiration creating stress in crops, particularly staples like wheat, maize, and rice.

In addition, climate change is also exacerbating the consequences of biotic stresses on plants. Biotic stress refers to the harmful effects caused by pathogens (including fungi, bacteria, and viruses), insects, and weeds, which can severely impact plant health, growth, and productivity. Research indicates that higher temperatures accelerate the development and increase the number of generations per year for many insect pests, leading to larger populations and greater potential crop damage. For example, a 2°C rise in temperature could encompass 1-5 additional insect life cycles per season worsening the pest outbreaks (Subedi *et al.*, 2023) as a disturbed intraspecific competition has been observed in *Camnula pellucida* (Scudder) and (Orthoptera: *Acrididae*) (Laws and Belovsky, 2010). Additionally, climate change enhanced the viability and spread of the barley yellow dwarf virus (BYDV) strain, transmitted by the corn leaf aphid, *Rhopalosiphum maidis* (Fitch), in wheat and barley (Porras *et al.*, 2020).

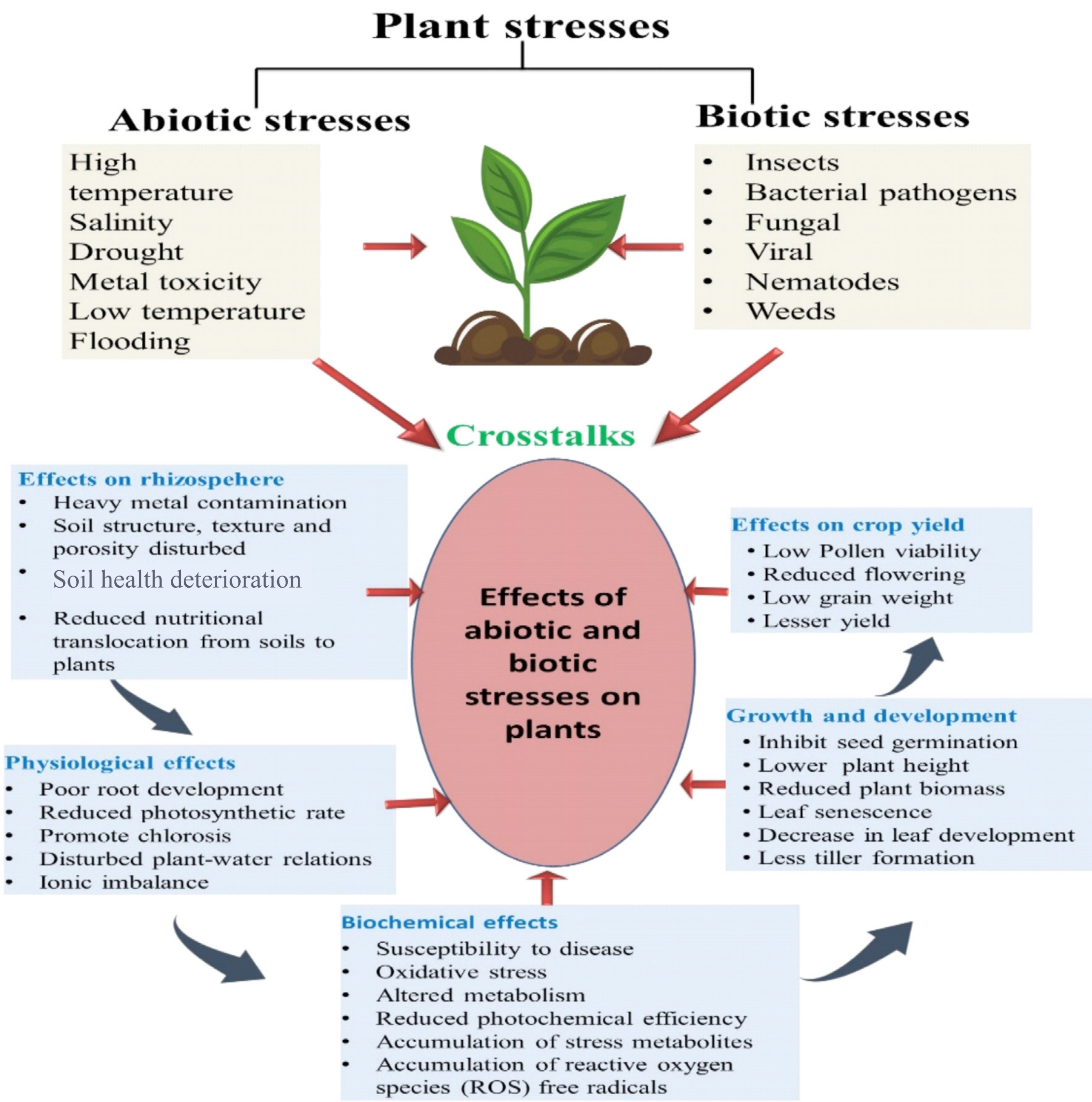

Fig. 1 Impact flow diagram of abiotic and biotic stresses on the physiological and biochemical properties of plants

These biotic and abiotic challenges will impose selection pressures on various plant physiological processes (Fig. 1) in crops, such as chlorophyll degradation, reduced photosynthetic activity, and decreased water potential, ion redox potential ultimately affecting plant growth and reducing yields (Oerke, 2006). Hence, developing crop plants that are resilient to these stresses is critical for achieving the United Nations Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger) (Cappelli *et al.*, 2021) and SDG 13 (Climate Action) (Campbell *et al.*, 2018; UN, 2020). Genome editing has emerged as an advanced technology to slightly paving a way in this scenario for designing trait specific crop plants suitable for changing environmental conditions.

Genome editing is basically an enzyme based genetic engineering technique which allows the inserting or deleting single or many nucleotide base pairs of any gene by transitions and transversions at specific sites in an organism genome (Dunn and Pinkert, 2014). DNA, the genetic material of every living organism, consists of all trait specific information in the genes located on different chromosomes. The sequences of most of the genes and whole genome sequencing in the previous decades provide all information about their functions making their editing very easy and precise. This can be compared with a book editing where the editor has all available information and need to precisely cut or change or add the required part using different tools just like adding or deleting gene sequences on particular chromosome or genome of plant with specific enzymes. Here, in this review, we have summarised about the evolution of genome editing technologies from the initiation of mutation to present techniques, including their various types, mechanisms of action, and applications. Additionally, how till date, these technologies have been utilized to address both biotic and abiotic stresses, enhancing crop resilience and productivity.

Evolution of Genome Editing Technologies

Advances in agricultural technology have moved beyond conventional breeding to include methods such as selective breeding, mutagenesis, transgenic technology, and genome editing (Kharkwal, 2012; de Vries, 1901; Prado *et al*., 2014). While conventional breeding is often labor-intensive and time-consuming, sometimes taking decades to develop new varieties, whereas the genetically modified (GM) crops created through transgenic technologies have accelerated this process by introducing desired traits more rapidly (Qiu *et al*., 2021). For instance, Bt cotton is a widely cultivated transgenic crop that has been genetically modified to express proteins from the bacterium *Bacillus thuringiensis* (Bt). These proteins, specifically Cry proteins, act as insecticides, providing protection against a variety of insect pests, particularly the cotton bollworm (*Helicoverpa armigera*) and other lepidopteran larvae. Bt cotton reduces the need for chemical insecticides, as the Cry proteins produced by the plant are toxic to certain insect pests. This can lead to more environmentally friendly pest management. By reducing pest damage, Bt cotton often results in higher crop yields, benefiting farmers economically. However, the broader adoption of GM crops has been slowed by strict regulations and concerns over environmental biosafety (Prado *et al*., 2014). Bt cotton is the only GM crop currently approved for commercial use in India by the GEAC, while other Bt crops like brinjal and mustard remain under regulatory consideration.

The study of gene functions through loss and gain-of-function experiments, rooted in Thomas Morgan's discovery of genes on chromosomes, led to the systematic induction of mutations via chemicals, radiation, and virus integration (DeMarini *et al*., 1989). Although these techniques have been instrumental in linking specific genes to traits, they pose challenges when applied across entire genomes. In earlier decades, various types of mutations and nucleases were used for modifying the genomic constituent of living organisms (Fig. 2) which has now advanced to use of CRISPR-Cas enzyme and base priming. Term mutation was introduced in 1901 and then radiations were used for changing the plant genome during 1928. Zinc finger nuclease, came into existence during late nineties (1996). RNAi advanced the modification of genetic material. A biological phenomenon known as RNA interference (RNAi) occurs when RNA molecules participate in the sequence-specific translational or transcriptional repression of double-stranded RNA to suppress the expression of genes. Afterwards, another type of nucleases, TALENs, advanced the gene editing to a larger scale most prominently cutting DNA at precise and specific locations. CRISPR-Cas system was a Nobel prize winning technology by two scientists, Emmanuelle Charpentier and Jennifer Doudna during 2020 which uses a combination of RNA-guided nucleases and Cas9 protein. Unlike GM crops, genome editing does not introduce foreign genes. This precision has made genome editing a powerful tool for creating climate-smart crops that are resilient to various stresses (Ahmar *et al*., 2020).

Types of Genome Editing Enzymes

There are two primary approaches for genome editing: site-specific recombinase systems (SSRs) and site-specific nuclease systems (SSNs).

Site-specific recombinases (SSRs)

Site-specific recombinases (SSRs) are enzymes that recognize specific 35-40 nucleotides of DNA sequences and mediate precise DNA recombination at these sites. Initially discovered in bacteria and yeast, SSRs have become a key tool in genetic engineering for permanent genome modifications. They are particularly effective in

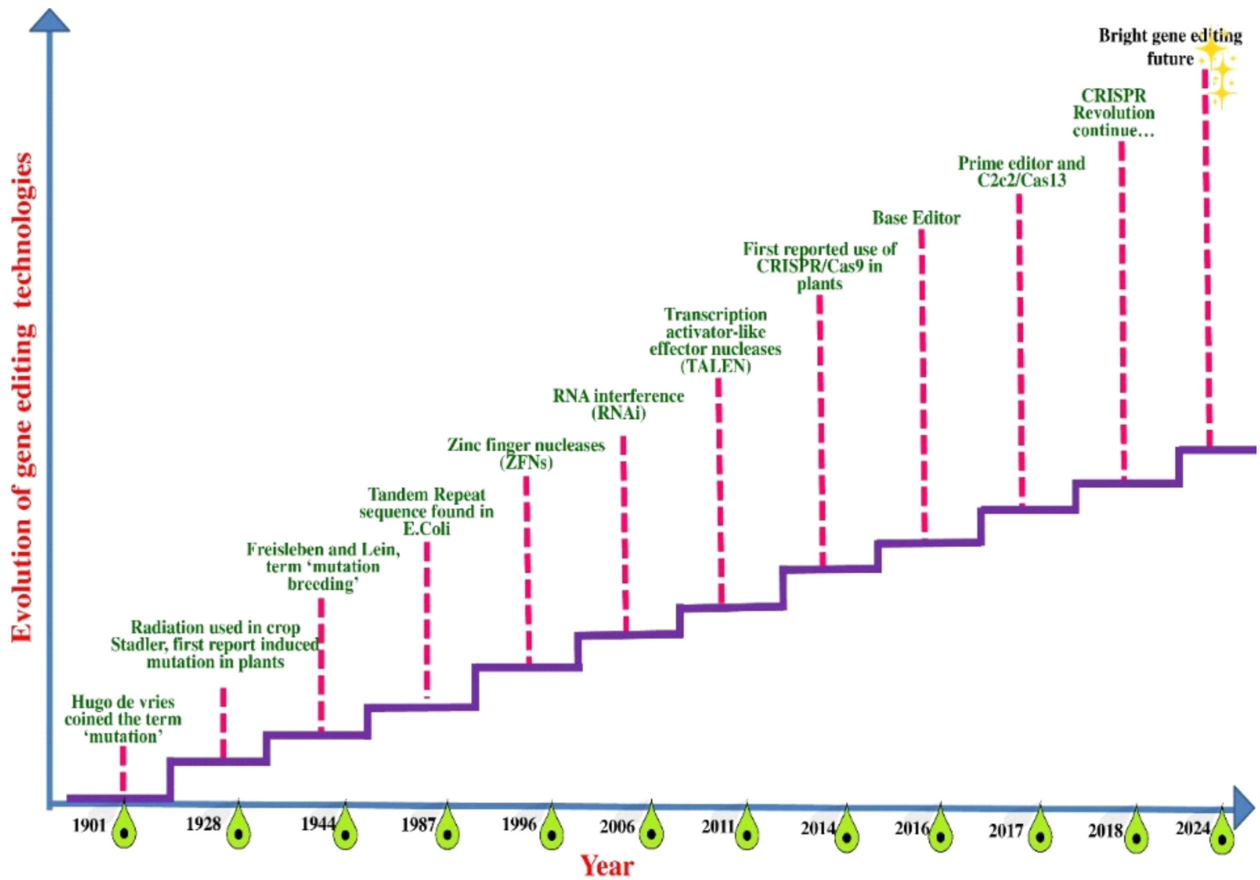

Fig. 2 The timeline of crop improvement technologies

manipulating plant genomes by simplifying complex transgene insertions into single copies, removing unwanted DNA segments, and enabling accurate integration of DNA into specific genomic locations (Van Duyne, 2015). SSR technology has been successfully applied to various plants, in addition to Arabidopsis, tomato, rice, Populus, maize and tobacco (Ebinuma and Komamine, 2001; Liu *et al.*, 2005; Sreekala *et al.*, 2005; Zuo *et al.*, 2001; Zhang *et al.*, 2006; Zhang *et al.*, 2003). The primary advantage of recombinases lies in their ability to function independently of intracellular repair mechanisms, avoiding double-strand breaks and simplifying the detection of gene insertions. However, a significant limitation of these chimeric enzymes is their tendency to cause off-target effects.

Site-specific nucleases (SSNs)

Site-specific nucleases (SSNs) are engineered endonucleases designed to cleave DNA at precise sequences within the genome. These nucleases feature a DNA-binding domain which binds specifically to target sequences (Gaj *et al.*, 2013), allowing for targeted gene modification followed by DNA repair at the cleavage site.

There are four major classes of nucleases currently applicable in genome editing; meganucleases (MegaN), zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and the recent one, CRISPR/Cas9 system.

Meganucleases (MegaN)

Meganucleases are found naturally, discovered during late 1980s (Stoddard, 2005). They can identify and cut large DNA sequences (15-40 base pairs) in most of the genomes. Companies like Cellectis have adapted meganucleases for genome editing by modifying DNA cleavage and binding regions, allowing them to target different sequences with high specificity. Precision Biosciences developed the Directed Nuclease Editor (DNE) method, which designs engineered meganucleases to precisely target and modify specific genomic sites (Abdallah *et al.*, 2015). Due to their ability to target large recognition sites, meganucleases are highly advantageous for genome engineering. However, their natural occurrence is limited, restricting their applicability to all potential genetic loci. Moreover, constructing sequence-specific meganucleases is not economic and takes more time compared to other site-specific nucleases, making them technically challenging to work with.

Zinc finger nucleases (ZFNs)

The concept of zinc finger proteins (ZFPs) as site-specific nucleases was first demonstrated in 1980. ZFNs are artificial endonucleases that combine zinc finger shaped DNA-binding domains with the DNA-cutting domain of the FokI endonuclease. Each ZFN is designed to recognize and bind specific sequences of DNA, enabling dimerization and double-stranded cleavage at the target site. Three to six zinc finger repeats make up the DNA binding domain, and each one can recognize nine to eighteen base pairs of DNA. ZFNs have been used to generate genome-edited crops, including tobacco (Cai *et al.*, 2009), Arabidopsis (Osakabe *et al.*, 2011), soybean (Shaun *et al.*, 2011), and corn (Shukla *et al.*, 2009). However, ZFN technology is little complex, and also the cost of constructing protein domains for specific genome loci is high. Additionally, off-targets repeatability is more due to substitutions of single nucleotide or improper interactions between zinc finger domains.

Transcription activator-like effector nucleases (TALENs)

In 2011, Transcription Activator-Like Effector Nucleases (TALENs) were developed as a more efficient and accessible alternative to Zinc Finger Nucleases (ZFNs) (Clarke *et al.*, 2012). TALENs are derived from transcription activator-like effectors (TALEs) found in phytopathogenic *Xanthomonas bacteria*, which use these proteins to activate specific plant genes during infection (Boch *et al.*, 2009). TALENs are restriction enzymes that can be modified to cleave particular DNA sequences. They are created by joining a DNA cleavage domain-a nuclease that splits DNA strands with a TAL effector DNA-binding domain. When paired with a nuclease, transcription activator-like effectors (TALEs) can be created to bind to almost any desired DNA sequence. This allows for the induction of double-strand breaks (DSB), which trigger cell repair processes. When there is little to no sequence overlap for annealing, non-homologous end joining (NHEJ) immediately ligates DNA from either side of a double-strand break. Gene products coded at that site may become non-functional as a result of mistakes caused by chromosomal rearrangement or indels (insertion or deletion) introduced by this repair mechanism. This activity should be monitored while creating new systems because it can change based on the species, type of cell, target gene, and nuclease utilized.

It is possible to perform a straightforward heteroduplex cleavage experiment to identify any variations between two PCR-amplified alleles which can be identified through electrophoresis. The first use of TALENs in crop improvement targeted the OsSWEET14 gene in rice, producing a mutant resistant to bacterial blight (Li *et al.*, 2012). Since then, TALENs have been used in other crops, such as wheat, where they were used to knock out three TaMLO homoeologs, resulting in powdery mildew-resistant plants (Wang *et al.*, 2014), in maize for knocking out the GL2 gene, creating a glossy leaf phenotype with reduced epicuticular wax and potential applications in surface manuring (Char *et al.*, 2015). In sugarcane, TALEN-mediated mutagenesis has enriched cell wall constituents and efficiency of saccharification (Jung *et al.*, 2016; Kannan *et al.*, 2018). In addition to Arabidopsis, TALENs have been efficiently used in other plants including sugarcane, rapeseed, potato, tomato, flax, Nicotiana, soybean, barley etc. (Gaj *et al.*, 2013; Martinez-Fortun *et al.*, 2017). However, TALENs face challenges due to their large size cDNA (approximately 3 kb), which complicates its targeted expression in cells. Additionally, the composition of TALE repeats can affect targeting efficiency, and their compatibility with some viral vectors is limited by their highly repetitive character.

CRISPR/Cas

CRISPR/Cas is a revolutionary technology for editing the whole genome, which originated from the bacterial immune system of *Streptococcus pyogenes*. CRISPR, short for clustered regularly interspaced palindromic repeats, represents specific DNA sequences in the bacterial genome, imparting protection against viruses, along with various forms of CRISPR-associated (Cas) proteins. Cas9 is one of the bound protein that functions as an RNA-guided endonuclease, that makes a cut in double strands of DNA and enabling precise modifications to the genome. To cut, a certain sequence of DNA ranging from 2-5 nucleotides (the actual sequence is determined by the bacteria that produces Cas9) must be present at the PAM sequence, the 3' end of the guide RNA, known as the protospacer adjacent motif. Other endonucleases associated with the CRISPR system include Cas1, Cas2, Cas10, and Cas13, which are utilized depending on the specific type of CRISPR-Cas system, as discussed later in this review.

The two main components are the Cas9 endonuclease and a single guide RNA (sgRNA), which work together to achieve target-specific DNA recognition and cleavage. The CRISPR/Cas9 system begins by identifying and binding to the targetted DNA sequence using the sgRNA, which is complementary to the target. This Cas9 protein complex cuts the double-strand DNA, triggering the cell's repair machinery. The repair process can lead to desired genetic changes through non-homologous end joining (NHEJ) or homology-directed repair (HDR). Unlike traditional breeding methods, which rely on random genetic recombination, CRISPR/Cas9 enables targeted genetic alterations with unprecedented accuracy.

CRISPR/Cas9 methodology

The CRISPR/Cas9 workflow begins with selecting the gene sequence for the desired trait from databases like NCBI and designing of respective primers. After PCR, amplified product is sequenced to confirm its accuracy, and the validated sequence is used to design the guide RNA (sgRNA). Cas9 - sgRNA cassette is then transformed into *E. coli*. Successful transformations are screened using colony PCR, Sanger sequencing, or restriction digestion. Positive colonies are introduced into plants or explants using *Agrobacterium tumefaciens* or other methods. Selected transformants are transferred to a greenhouse for gene edited plants.

Construction of guide RNA (sgRNA) for CRISPR/Cas9

The sgRNA directs the Cas9 nuclease to the target DNA sequence, disrupting transcriptional regulation. The gRNA-Cas9 complex recognizes the targeted sequence through gRNA-DNA pair between the gRNA spacer and the complementary DNA strand. The presence of protospacer adjacent motif (PAM) sequence is required by Cas9 protein at the target site for efficient binding. Several online tools can be utilized for designing of sgRNAs with low off-target effects. Some of these tools include CRISPR direct (Naito *et al.*, 2015), CRISPR-P 2.0 (Liu *et al.*, 2017), and CHOPCHOP (Montague *et al.*, 2014). Off-target effects can be checked using BLAST, and the structural characteristics of sgRNAs can be analyzed using tools like the RNAfold web server.

Classification of CRISPR/Cas9 system

The CRISPR-Cas complex is classified into four major types (I, II, III, and IV) based on signature genes as well as the typical organization of loci. Type I systems, characterized by the signature gene cas3, contain a helicase with ATPase activity and an HD domain with nuclease activity. They usually have a single operon with cas1, cas2, and genes for the Cascade complex subunits, divided into six subtypes (I-A to I-F), with some lacking the cas4 gene. Type II CRISPR-Cas systems are identified by the cas9 gene, essential for crRNA maturation and DNA cleavage. Cas9, a large multidomain protein, is crucial for these systems and has made significant strides as a genome editing tool. Type II systems are further grouped into three subtypes (II-A, II-B, and II-C), each with special features of either having or not additional genes like csn2.

Type III systems, marked by the cas10 gene, are more complex and diverse. Cas10 is a

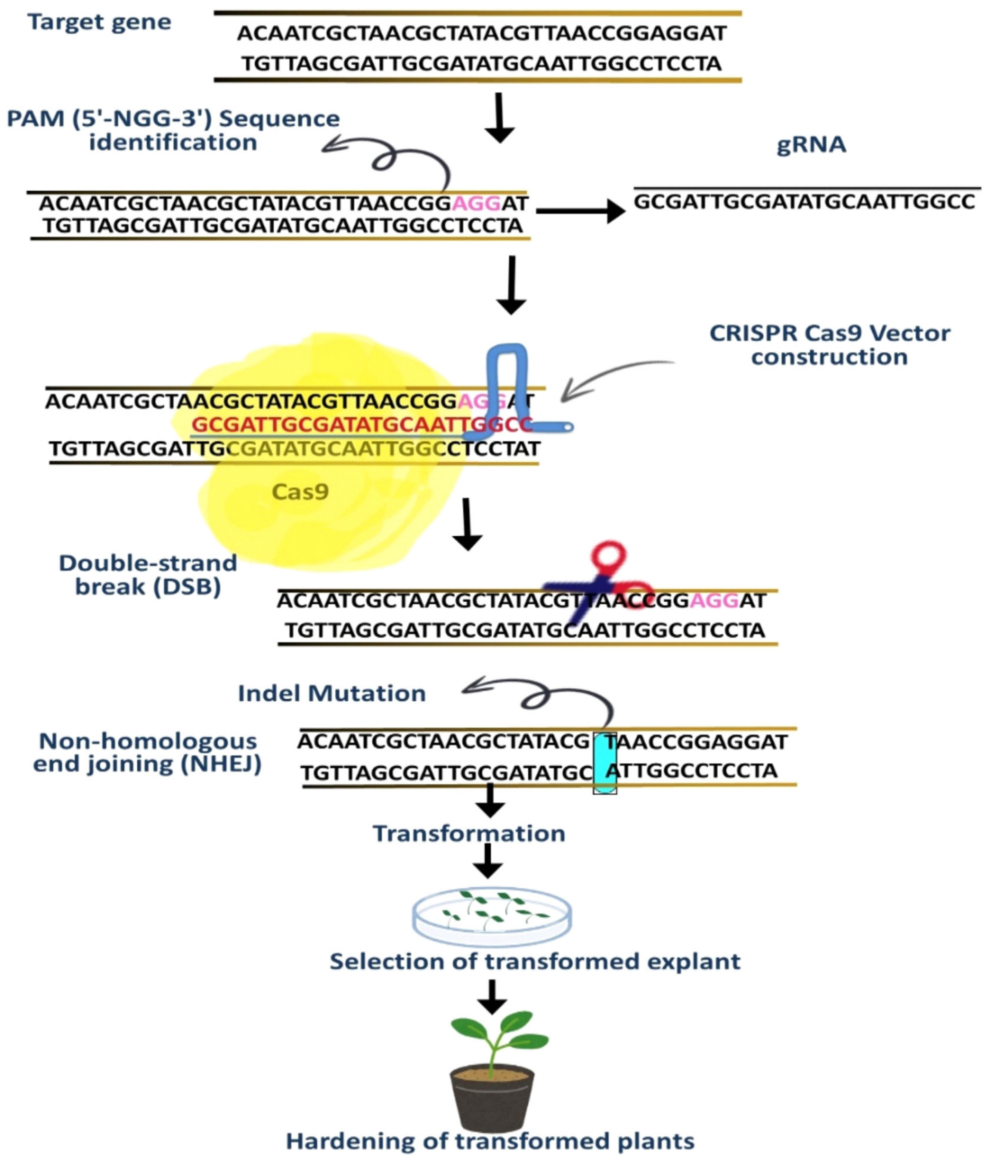

Fig. 3 Workflow diagram illustrating the CRISPR/Cas9 technology

multidomain protein and is the most effective protein in these Cas systems. Unlike Type I, Type III complex often lacks cas1 and cas2 genes, instead utilize crRNAs from other systems. They are further divided into subtypes III-A and III-B, with the former targeting DNA and the latter RNA. Type IV systems, commonly found on plasmids, are unique in lacking cas1 and cas2 genes and are are frequently not connected to CRISPR arrays. Their effector complexes include a reduced large subunit and various RAMP proteins, with some variants also containing a DinG family helicase. The classification of CRISPR-Cas systems continues to evolve as new variants are discovered. Recent research highlights the growing diversity of these systems and the need to possibly reconsider current classification principles.

Types of genome editing technologies

The molecular mechanism of genome editing is based on Site Directed Nucleases (SDN) using above mentioned systems, SSRs, SSNs, ZFNs, TALENs or CRISPR for target specific changes in the genome. Broadly, SDN defines the mechanism of technology, which enzyme (nuclease) is used for cutting specific or targeted DNA sequence (or site directed) in the double stand of DNA (Podevin *et al*., 2013).

SDN1: The nuclease cuts the double stranded-DNA without adding any foreign DNA. No template for joining DNA breaks is added from outside and DNA repair is done by the cell itself. If, two sides breaks are created in targeted DNA strand, SDN-1 can lead to deletion of quite big DNA sequence, that may be a complete gene or some promoter gene. This break leads to changes like gene knock-out or silencing.

SDN2. Here, a small DNA template is used for joining the cut in double strand of DNA creating mutations in the DNA strand. SDN2 is typically used for predesigned point mutation in targeted gene of interest.

SDN3. This is different from the other two SDNs since, it contains foreign DNA. The two ends of double strand break of DNA are joined using gene sequences of other organism.

These SDNs are further transferred to the host cell either transiently or using plant delivery system. After multiplication, the particular SDN is expressed and after segregation, it is removed from the recipient plant, having only the targeted change in the DNA sequence, leading to development of transgene free plant. These plants are further identified using wet lab technologies.

Implementation of gene editing technologies in agriculture

Genome editing, particularly CRISPR/Cas9, has emerged as an effective tool for developing crops with enhanced resistance to both biotic (against pests, diseases and viruses) and abiotic stresses (salinity, cold, heat or drought). A brief note of work done in mitigating biotic and abiotic stresses using genome editing technologies in different crop plants is depicted in Tables 1 and 2, respectively.

For biotic stress resistance

For instance, in sweet potato, the CRISPR/RfxCas13d system has been applied for Sweet potato chlorotic stunt virus, focusing on RNase III endoribonuclease, thereby, enhancing resistance against Sweet potato virus disease (Yu

Table 1. Applications of gene editing technologies to enhance biotic stress resistance in plants

S. No.	Crop	Candidate gene (s)*	Biotic stress	Genome editing type	References
1.	*Glycine max*	Calcium dependent protein kinase 38	Insect disease	CRISPR/Cas9	Li *et al.*, 2022
2.	*Solanum lycopersicum*	Tobamovirus Multiplication Ia, Ib, Ic, Id	Viral disease	CRISPR/Cas9	Ishikawa *et al.*, 2022
3.	*Solanum lycopersicum*	MiR482b and miR428c	Fungal disease	CRISPR/Cas9	Hong *et al.*, 2021
4.	*Solanum lycopersicum*	Pectate lyase (SIPL)	Grey mould	CRISPR/Cas9	Silva *et al.*, 2021
5.	*Citrus paradisi*	Lateral Organ Boundary 1 promoter	(Bacterial canker) *Xanthomonas citri*	CRISPR/tt LBCas12a	Jia *et al.*, 2022
7.	*Solanum tuberosum*	Eukaryotic Translation Initiation Factor 4E	Potato virus Y	CRISPR/Cas9	Noureen *et al.*, 2022
8.	*Ipomoea batatas*	RNase III endonuclease (pathogenesis-related factor)	Potyvirus and crinivirus	CRISPR/Cas9	Yu *et al.*, 2022
9.	*Oryza sativa*	CYTOCHROME P450 71A1 (OsCYP71A1)	Insect Disease	CRISPR/Cas9	Lu *et al.*, 2018
10.	*Solanum lycopersicum*	Mitogen Activated Protein Kinase 3	Grey mould	CRISPR/Cas9	Zhang *et al.*, 2018
11.	*Solanum lycopersicum*	Acetylenase 1a and 1b, Solyc12g100252 and Solyc12g100270	Grey mould	CRISPR/Cas9	Jeon *et al.*, 2020
12.	*Solanum lycopersicum*	MYC2	Grey mould	CRISPR/Cas9	Shu *et al.*, 2020
13.	*Oryza sativa*	OsSWEET14	Bacterial blight	TALENs	Li *et al.*, 2012
14.	*Triticum aestivum*	Three TaMLO homoeologs	Powdery mildew	Knockout-TALENs	Wang *et al.*, 2014
15.	*Zea mays*	*GL2*	Epiculticular wax in the leaves	TALENs	Char *et al.*, 2015

Table 2. Applications of gene editing technologies for abiotic stress resilience in plants

S. No.	Crop	Candidate gene (s)*	Abiotic stress tolerance	Genome editing type	References
1.	Cotton	AVP1/AtNHX1	Improved salt and drought tolerance	Transgenic	Shen *et al.*, 2015
2.	Cotton	TsVP/AtNHX1	Enhanced salt tolerance	Transgenic	Cheng *et al.*, 2018
3.	Cotton	AVP1/OsSIZ1	Enhanced combined heat, drought and salt	Transgenic	Esmaeili *et al.*, 2021
4.	Tomato	LeNHX2/SlSOS2	Enhanced salt tolerance	Double transgenic	Baghour *et al.*, 2019
5.	Tomato	SlARF4	Salinity and osmotic stress	CRISPR/ Cas9	Bouzroud *et al.*, 2020
6.	Tomato	AtDREB1A/BcZAT12	Enhanced drought tolerance	Double transgenic	Krishna *et al.*, 2021
7.	Tobacco	AhBADH/ SeNHX1	Improved salt tolerance	Transgenic	Zhou *et al.*, 2008
8.	Rice	OsbZIP46CA1/SAPK6	Improved drought, heat and cold tolerance	Double transgenic	Chang *et al.*, 2017
9.	Rice	OsbHLH044 (loss of function)	Salinity sensitivity	CRISPR/ Cas9	Alam *et al.*, 2022
10.	Rice	OsDST	Drought and salt tolerance	CRISPR/Cas9	Kumar *et al.*, 2020
11.	Rice	OsLEA gene	Salt and drought tolerance	Transgenic	Duan and Cai, 2012
12.	Potato	PaSOD/RaAPX	Increased salt tolerance	Transgenic	Shafi *et al.*, 2017
13.	Maize	*ZmGA20ox3*	Drought stress	CRISPR/Cas9	Liu *et al.*, 2024
14.	Rice	OsNCED5	Salt and water stress	CRISPR/Cas9	Huang *et al.*, 2019
15.	Wheat	*TaDREB2, TaERF3*	Drought tolerance	CRISPR/Cas9	Kim *et al.*, 2018
16.	Wheat	*TaASR1-D*	Osmotic and drought tolerance	Transgenic	Qiu *et al.*, 2021

et al., 2022). DMR6 and BMV genes have been targeted for increasing disease resistance in Banana (Pixley *et al.*, 2022). Similarly, in tomatoes, CRISPR/Cas9 has been employed to target different isoforms of eIF4E, resulting in varieties resistant to *Potyviridae* viruses (Noureen *et al.*, 2022). Additionally, multiplexed targeting through CRISPR/Cas9 for susceptible genes in tomatoes has led to strong resistance against multiple viral diseases, with the quadruple-mutant of SlTOM1a-d showing enhanced resistance to Tobamo viruses (Ishikawa *et al.*, 2022). In citrus, CRISPR/Cas9 modified effector-binding elements in the LOB1 gene, conferring partial to complete resistance to *Xanthomonas citri* caused citrus canker (Jia *et al.*, 2016; 2022). Moreover, knocking out the PL gene in tomatoes using CRISPR/Cas9 significantly reduced grey mould infection, demonstrating its effectiveness against fungal pathogens (Silva *et al.*, 2021). In rice, disrupting the OsCYP71A1 gene via CRISPR/Cas9 led to increased salicylic acid content, enhancing resistance to biotic stressors such as plant hoppers and stem borers (Lu *et al.*, 2018). Also, in rice, TALENs were used to disrupt the OsSWEET14 gene, imparting resistance against bacterial blight (Li *et al.*, 2012) and powdery mildew-resistance in wheat varieties though knock out of TaMLO homoeologs (Wang *et al.*, 2014).

For abiotic stress resistance

In addition, genome editing has also shown great promise in enhancing crop resilience to various abiotic stresses, with major ones salinity, drought, elevated temperatures, which are becoming increasingly problematic due to climate change. To improve drought and salt tolerance in cotton, researchers developed transgenic plants by co-expressing the Arabidopsis AtNHX1 and the H^+-pyrophosphatase gene AVP1. This dual gene approach proved more effective in improving stress tolerance compared to single-gene expression (Zhang *et al.*, 2011; Shen *et al.*, 2015). Further improvement in salt tolerance was achieved by co-expressing AtNHX1 with the TsVP gene from *Thellungiella halophila* (Cheng *et al.*, 2018). Additionally, co-overexpression of OsSIZ1 and

AVP1 significantly boosted tolerance to combined salt/drought and heat/drought stresses while also enhancing fibre yield (Esmaeili *et al.*, 2021). In wheat, overexpression of the abscisic acid-stress-ripening (ASR) protein TaASR1-D increased antioxidant capacity and ABA sensitivity, thereby enhancing abiotic stress tolerance (Qiu *et al.*, 2021). Transgenic tomato plants that overexpressed both LeNHX2 and SlSOS2 exhibited improved NaCl tolerance and better growth under saline conditions compared to those overexpressing only one of these genes (Baghour *et al.*, 2019).

The CRISPR/Cas9 genome editing method was employed in wheat protoplasts to modify stress-responsive transcription factor genes, specifically TaDREB2 and TaERF3. By transiently expressing short guide RNA and Cas9 protein in wheat protoplasts, targeted editing of TaDREB2 and TaERF3 was accomplished, enhancing drought tolerance without changing growth parameters (Kim *et al.*, 2018). Further, mutant alleles of drought and salt tolerance (DST) gene have been created indica rice cv. MTU1010 through CRISPR-Cas9 gene editing (Kumar *et al.*, 2020). TALEN-mediated genome editing has also been instrumental in improving abiotic stress resistance in crops., and in maize to produce mutants with reduced epicuticular wax, which could potentially improve water use efficiency along with drought tolerance (Char *et al.*, 2015). Genome editing may not be a panacea yet but this technology is being implemented at various national and international organizations for the agricultural system.

Regulations and Future Aspects

Genome editing (GE) with CRISPR/Cas offers a promising alternative to traditional GMOs by enabling precise alterations in plant traits through small mutations, such as deletions or insertions, without introducing foreign DNA. This fundamental difference makes GE distinct from GMOs. In recent years, CRISPR/Cas has revolutionized plant breeding by creating transgene-free plants that achieve desired agronomic traits, exempting them from GMO regulations. This regulatory flexibility is expected to fasten the process of development and commercialization of novel genome-edited plant/crop varieties. However, public acceptance of GE plants remains a challenge, as many people cannot distinguish them from GMOs. Clear communication about the benefits and safety of GE is essential to build trust and ensure responsible use.

With careful stewardship, CRISPR and other gene editing tools offer the potential to transform global agriculture by cultivating crops tolerant to disease, climate change, with higher yields, while navigating the challenges of public perception and regulatory oversight. Despite their promise, these technologies also pose risks to humans and the environment. One major concern is off-target effects, where unintended genetic changes could cause harmful mutations, including cancer. This risk can be reduced by refining guide RNA design and utilizing more precise Cas9 variants. Another challenge is the ecological impact of releasing gene-edited organisms, which could disrupt ecosystems and lead to the uncontrolled spread of modified genes. To mitigate this, strict containment protocols, controlled release trials, and genetic safeguards like "kill switches" are crucial protective measures.

A special session on genome-editing technologies was also held during the G20 Meeting of Agricultural Chief Scientists (G20 MACS) at Italy on June 15-16, 2021, highlighting the potential of genome editing towards sustainable climate change adaptation and food security along with its risk analysis. Department of Biotechnology, Government of India, guidelines for the safety assessment of genome edited plants, 2022 provide a road map for use of genome technologies in India for developing genome edited plants. As per these guidelines, genome edited products developed using SDN1 and SDN2 are not containing any exogenous introduced DNA and hence, are not subjected to a biosafety evaluation in pursuance of Rule 20 of the Manufacture, Use, Import, Export and Storage of Hazardous Microorganisms/Genetically Engineered Organisms or Cells Rules 1989. These genomes edited plants can be released as new variety following the prescribed protocols for new varieties. Although plants developed through SDN3 are still under regulation of Rules 1989 as for genetically engineered plants due to having foreign genetic material.

Regulatory systems differentiate three types of genome editing by site-directed nucleases (SDNs). SDN-1, SDN-2 and SDN-3. Four South American nations and other countries including USA, and Canada have adopted regulations, treating genome-edited crops produced via SDN-1 and SDN-2 equivalent to those developed through conventional breeding methods (Schmidt et al., 2020). Till 2019, Japan was the only Asian country not distinguishing between conventional methods of breeding and genome editing regarding safety concerns (Normile, 2019). By 2022, following the effective execution of genome editing regulations in Russia, several other Asian countries, including China and India, established similar frameworks. In China, the Ministry of Agriculture issued preliminary guidelines for the safety evaluation of genome-edited plants that do not contain exogenous DNA (Mallapaty, 2022). On March 30, 2022, the Indian government issued an Office Memorandum titled "Exemption of Genome Edited Plants Falling Under SDN-1 and SDN-2 Categories from the Provisions of the Rules, 1989." These guidelines state that genome-edited plants produced via SDN-1 and SDN-2 are exempted from existing GMO regulations if proven to be transgene-free, allowing them to be released as new varieties for further development and evaluation. In May 2022, the Department of Biotechnology, Government of India, introduced the 'Guidelines for the Safety Assessment of Genome Edited Plants, 2022,' outlining detailed regulatory requirements and standard operating procedure (SOP) for genome-edited plants.

References

Abdallah NA, Prakash CS, McHughen AG (2015) Genome editing for crop improvement: Challenges and opportunities. *GM Crops Food.* **6(4)**:183-205.

Ahmar S, Gill RA, Jung KH, Faheem A, Qasim MU, Mubeen M, & Zhou W (2020) Conventional and Molecular Techniques from Simple Breeding to Speed Breeding in Crop Plants: Recent Advances and Future Outlook. *International Journal of Molecular Sciences* **21(7)**: 2590.

Agricultural Chief Scientists (G20) Communique: G20 Italy (2021) 10th Meeting of Agricultural Chief Scientists (MACS). *https://www.macs-20.org/fileadmin/macs/Annual_Meetings/2021_Italy/ Documents/ Communique.pdf*

Alam MS, Yang ZK, Li C, Yan Y, Liu Z, Nazir MM, & Xu JH (2022) Loss-of-function mutations of OsbHLH044 transcription factor leads to salinity sensitivity and a greater chalkiness in rice (*Oryza sativa L.*). *Plant physiology and Biochemistry: PPB* **193**: 110–123.

Baghour M, Gálvez FJ, Sánchez, ME, Aranda MN, Venema K, & Rodríguez-Rosales, MP (2019) Overexpression of LeNHX2 and SlSOS2 increases salt tolerance and fruit production in double transgenic tomato plants. *Plant Physiology and Biochemistry* **135**: 77-86.

Boch J, Bonas U (2010) *Xanthomonas* AvrBs3 family-type III effectors: discovery and function. *Annu Rev Phytopathol.* **48**:419–36.

Bouzroud S, Gasparini K, Hu G, Barbosa MAM, Rosa BL, Fahr M, ... & Zouine M (2020) Down regulation and loss of auxin response factor 4 function using CRISPR/Cas9 alters plant growth, stomatal function and improves tomato tolerance to salinity and osmotic stress. *Genes* **11(3)**: 272

Cai CQ, Doyon Y, Ainley WM, Miller JC, DeKelver RC, Moehle EA and Petolino JF (2009) Targeted transgene integration in plant cells using designed zinc finger nucleases. *Plant Molecular Biology* **69**: 699-709.

Campbell BM, Hansen J, Rioux J, Stirling CM, & Twomlow S (2018) Urgent action to combat climate change and its impacts (SDG 13): transforming agriculture and food systems. *Current Opinion in Environmental Sustainability* **34**:13-20.

Cappelli A, Lupori L, & Cini E (2021) Baking technology: A systematic review of machines and plants and their effect on final products, including improvement strategies. *Trends in Food Science & Technology* **115**: 275-284.

Chang Y, Nguyen BH, Xie Y, Xia B, Tang N, Zhu W and Xiong L (2017) Co-overexpression of the constitutively active form of OsbZIP46 and ABA-activated protein kinase SAPK6 improves drought and temperature stress resistance in rice. *Frontiers in Plant Science* **8**: 1102.

Char SN, Unger Wallace E, Frame B, Briggs SA. Main M, Spalding MH and Yang B (2015) Heritable site specific mutagenesis using TALEN s in maize. *Plant Biotechnology Journal* **13(7)**: 1002-1010.

Cheng C, Zhang Y, Chen X, Song J, Guo Z, Li K and Zhang K (2018) Co-expression of AtNHX1 and TsVP improves the salt tolerance of transgenic cotton and increases seed cotton yield in a saline field. *Molecular Breeding* **38**: 1-15.

Clarke L, Zheng-Bradley X, Smith R, Kulesha E, Xiao C, Toneva I (2012) The 1000 Genomes Project: data management and community access. *Nature Methods* **9(5)**: 459-462.

de Vries H (1902) The origin of species by mutation. *Science* **15(384)**: 721-729.

De Marini DM, Brockman HE, de Serres FJ, Evans HH, Stankowski Jr LF and Hsie AW (1989) Specific-locus mutations induced in eukaryotes (especially mammalian cells) by radiation and chemicals: a perspective. *Mutation Research/Reviews in Genetic Toxicology*, **220(1)**: 11-29.

Dunn DA, Pinkert, CA (2014*) Gene Editing. Transgenic Animal Technology*, *Elsevier*, pp. 229–248.

Ebinuma H, & Komamine A (2001) Mat (Multi Auto T ransformation) vector system. The oncogenes of Agrobacterium as positive markers for regeneration and selection of marker-free transgenic plants. *In Vitro Cellular & Developmental Biology-Plant* **37**: 103-113.

Esmaeili N, Cai Y, Tang F, Zhu X, Smith J, Mishra N and Zhang H (2021) Towards doubling fibre yield for cotton in the semiarid agricultural area by increasing tolerance to drought, heat and salinity simultaneously. *Plant Biotechnology Journal* **19(3)**: 462-476.

Gaj T, Gersbach CA and Barbas CF (2013) ZFN, TALEN, and CRISPR/Cas-based methods for genome engineering. *Trends in Biotechnology* **31(7)**: 397-405.

Hong Y, Meng J, He X, Zhang Y, Liu Y, Zhang C and Luan Y (2021) Editing miR482b and miR482c simultaneously by CRISPR/Cas9 enhanced tomato resistance to *Phytophthora Infestans*. *Phytopathology®* **111(6)**: 1008-1016.

Huang Y, Jiao Y, Xie N, Guo Y, Zhang F, Xiang Z and Liang M (2019) OsNCED5, a 9-cis-epoxycarotenoid dioxygenase gene, regulates salt and water stress tolerance and leaf senescence in rice. *Plant Science* **287**: 110188.

Hunter MC, Smith RG, Schipanski ME, Atwood LW and Mortensen DA (2017) Agriculture in 2050: Recalibrating targets for sustainable intensification. *Bioscience* **67(4)**: 386-391.

IPCC (2023) Summary for Policymakers. In: Climate Change (2023) Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34.

Ishikawa M, Yoshida T, Matsuyama M, Kouzai Y, Kano A, & Ishibashi K (2022) Tomato brown rugose fruit virus resistance generated by quadruple knockout of homologs of TOBAMOVIRUS MULTIPLICATION1 in tomato. *Plant Physiology* **189(2)**: 679-686.

Jeon JE, Kim JG, Fischer CR, Mehta N, Dufour-Schroif C, Wemmer K and Sattely E (2020) A pathogen-responsive gene cluster for highly modified fatty acids in tomato. *Cell* **180(1)**: 176-187.

Jia H, Omar AA, Orboviæ V, & Wang N (2022) Biallelic editing of the LOB1 promoter via CRISPR/Cas9 creates canker-resistant 'Duncan' grapefruit. *Phytopathology®* **112(2)**: 308-314.

Jia H, Orbovic V, Jones JB, & Wang N (2016) Modification of the PthA4 effector binding elements in Type I Cs LOB 1 promoter using Cas9/sg RNA to produce transgenic Duncan grapefruit alleviating XccÄpthA4: dCs LOB 1.3 infection. *Plant Biotechnology Journal* **14(5)**: 1291-1301.

Jung JH, & Altpeter F (2016) TALEN mediated targeted mutagenesis of the caffeic acid *O-methyltransferase* in highly polyploid sugarcane improves cell wall composition for production of bioethanol. *Plant Molecular Biology* **92**: 131-142.

Kannan B, Jung JH, Moxley GW, Lee SM, & Altpeter F (2018) TALEN mediated targeted mutagenesis of more than 100 COMT copies/alleles in highly polyploid sugarcane improves saccharification efficiency without compromising biomass yield. *Plant Biotechnology Journal* **16(4)**: 856-866.

Kharkwal MC (2012) A brief history of plant mutagenesis. In *Plant Mutation Breeding and Biotechnology* (pp. 21-30). Wallingford UK: CABI.

Kim D, Alptekin B, & Budak H (2018) CRISPR/Cas9 genome editing in wheat. *Functional & Integrative Genomics* **18**: 31-41.

Krishna R. Ansari WA, Jaiswal D K, Singh AK, Verma JP, & Singh M (2021) Co-overexpression of AtDREB1A and BcZAT12 increases drought tolerance and fruit production in double transgenic tomato (*Solanum lycopersicum*) plants. *Environmental and Experimental Botany* **184**: 104396.

Kumar SVV, Verma RK, Yadav SK, Yadav P, Watts A, Rao MV, & Chinnusamy V (2020) CRISPR-Cas9 mediated genome editing of drought and salt tolerance (*OsDST*) gene in indica mega rice cultivar MTU1010. *Physiology and Molecular Biology of Plants* **26**: 1099-1110.

Laws AN, & Belovsky GE (2010) How will species respond to climate change? Examining the effects of temperature and population density on an herbivorous insect. *Environmental Entomology* **39(2)**: 312-319.

Li T, Liu B, Spalding MH, Weeks DP, & Yang B (2012) High-efficiency TALEN-based gene editing produces disease-resistant rice. *Nature Biotechnology* **30(5)**: 390-392.

Li X, Hu D, Cai L, Wang H, Liu X, Du H and Wang H (2022) CALCIUM-DEPENDENT PROTEIN KINASE38 regulates flowering time and common cutworm resistance in soybean. *Plant Physiology* **190(1)**: 480-499.

Liu HK, Yang C and Wei ZM (2005) Heat shock-regulated site-specific excision of extraneous DNA in transgenic plants. *Plant Science* **168(4)**: 997-1003.

Liu H, Ding Y, Zhou Y, Jin W, Xie K and Chen LL (2017) CRISPR-P 2.0: an improved CRISPR-Cas9 tool for genome editing in plants. *Molecular Plant* **10(3)**: 530-532.

Liu Y, Chen Z, Zhang C, Guo J, Liu Q, Yin Y, and Liu X (2024) Gene editing of ZmGA20ox3 improves plant architecture and drought tolerance in maize. *Plant Cell Reports* **43(1)**: 18.

Lu HP, Luo T, Fu HW, Wang L, Tan YY, Huang JZ and Shu QY (2018) Resistance of rice to insect pests mediated by suppression of serotonin biosynthesis. *Nature Plants* **4(6)**: 338-344.

Martínez-Fortún J, Phillips DW, & Jones HD. (2017). Potential impact of genome editing in world agriculture. *Emerging Topics in Life Sciences* **1(2)**: 117-133.

Montague TG, Cruz JM, Gagnon JA, Church GM and Valen E (2014) CHOPCHOP: a CRISPR/Cas9 and TALEN web tool for genome editing. *Nucleic Acids Research* **42(W1)**: W401-W407.

Naito Y, Hino K, Bono H and Ui-Tei K (2015) CRISPRdirect: software for designing CRISPR/Cas guide RNA with reduced off-target sites. *Bioinformatics* **31(7)**: 1120-1123.

Noureen A, Khan MZ, Amin I, Zainab T and Mansoor S (2022) CRISPR/Cas9-mediated targeting of susceptibility factor eIF4E-enhanced resistance against potato virus Y. *Frontiers in Genetics* **13**: 922019.

Oerke EC (2006) Crop losses to pests. *The Journal of Agricultural Science* **144(1)**: 31-43.

Pixley KV, Falck-Zepeda JB and Paarlberg RL (2022) Genome-edited crops for improved food security of smallholder farmers. *Nature Genetics* **54**: 364-367.

Podevin N, Davies HV, Hartung F, Nogue´ F and Casacuberta JM (2013) Site-directed nucleases: A paradigm shift in predictable, knowledge-based plant breeding. *Trends in Biotechnology* **31**: 375-383.

Porras MF, Navas CA, Marden JH, Mescher MC, De Moraes CM, Pincebourde S and Carlo TA (2020) Enhanced heat tolerance of viral-infected aphids leads to niche expansion and reduced interspecific competition. *Nature Communications* **11(1)**: 1184.

Prado JR, Segers G, Voelker T, Carson D, Dobert R, Phillips J and Martino-Catt S (2014) Genetically engineered crops: from idea to product. *Annual Review of Plant Biology* **65(1)**: 769-790.

Qin Z, Hou F, Li A, Dong S, Wang Q and Zhang L (2020) Transcriptome-wide identification of WRKY transcription factor and their expression profiles under salt stress in sweetpotato (Ipomoea batatas L.). *Plant Biotechnology Reports* **14**: 599-611.

Qiu D, Hu W, Zhou Y, Xiao J, Hu R, Wei Q and He G (2021) TaASR1 D confers abiotic stress resistance by affecting ROS accumulation and ABA signalling in transgenic wheat. *Plant Biotechnology Journal* **19(8)**: 1588-1601.

Ran Y, Liang Z and Gao C (2017) Current and future editing reagent delivery systems for plant genome editing. *Science China Life Sciences* **60**: 490-505.

Shafi A, Pal AK, Sharma V, Kalia S, Kumar S, Ahuja PS and Singh AK (2017) Transgenic potato plants overexpressing SOD and APX exhibit enhanced lignification and starch biosynthesis with improved salt stress tolerance. *Plant Molecular Biology Reporter* **35**: 504-518.

Shen G, Wei J, Qiu X, Hu R, Kuppu S, Auld, D and Zhang H (2015) Co-overexpression of AVP1 ad AtNHX1 in cotton further improves drought and salt tolerance in transgenic cotton plants. *Plant Molecular Biology Reporter* **33**: 167-177.

Shu P, Li Z, Min D, Zhang X, Ai W, Li J an Li X (2020) CRISPR/Cas9-mediated SlMYC2 mutagenesis adverse to tomato plant growth and MeJA-induced fruit resistance to Botrytis cinerea. *Journal of Agricultural and Food Chemistry* **68(20)**: 5529-5538.

Silva CJ, van den Abeele C, Ortega-Salazar I, Papin V, Adaskaveg JA, Wang D and Blanco-Ulate B (2021) Host susceptibility factors render ripe tomato fruit vulnerable to fungal disease despite active immune responses. *Journal of Experimental Botany* **72(7)**: 2696-2709.

Sreekala C, Wu L, Gu K, Wang D, Tian D and Yin Z (2005) Excision of a selectable marker in transgenic rice (Oryza sativa L.) using a chemically regulated Cre/loxP system. *Plant Cell Reports* **24**: 86-94.

Stoddard BL (2005) Homing endonuclease structure and function. *Quarterly Reviews of Biophysics* **38(1)** 49-95.

Tilman D, Balzer C, Hill J and Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences* **108(50)**: 20260-20264.

Van Duyne GD (2015) Cre recombinase. *Mobile DNA* III: 119-138.

Wang Y, Cheng X, Shan Q, Zhang Y, Liu J, Gao C and Qiu JL (2014) Simultaneous editing of three homoeoalleles in hexaploid bread wheat confers heritable resistance to powdery mildew. *Nature Biotechnology* **32(9)**: 947-951.

Yu Y, Pan, Z, Wang X, Bian X, Wang W, Liang Q and Sun J (2022) Targeting of SPCSV RNase3 via CRISPR Cas13 confers resistance against sweet potato virus disease. *Molecular Plant Pathology* **23(1)**: 104-117.

Zhang H, Shen G, Kuppu S, Gaxiola R and Payton P (2011) Creating drought-and salt-tolerant cotton by overexpressing a vacuolar pyrophosphatase gene. *Plant Signaling & Behavior* **6(6)**: 861-863.861-863.

Zhang S, Wang L, Zhao R, Yu W, Li R, Li Y and Shen L (2018) Knockout of SlMAPK3 reduced disease resistance to *Botrytis cinerea* in tomato plants. *Journal of Agricultural and Food Chemistry* **66(34)**: 8949-8956.

Zhang W, Subbarao S, Addae P, Shen A, Armstrong C, Peschke V and Gilbertson L (2003) Cre/lox-mediated marker gene excision in transgenic maize (*Zea mays L.*) plants. *Theoretical and Applied Genetics* **107**: 1157-1168.

Zhang Y, Li, H, Ouyang B, Lu, Y and Ye Z (2006) Chemical-induced autoexcision of selectable markers in elite tomato plants transformed with a gene conferring resistance to lepidopteran insects. *Biotechnology Letters* **28**: 1247-1253.

Zhou S, Chen X, Zhang X and Li Y (2008) Improved salt tolerance in tobacco plants by co-transformation of a betaine synthesis gene BADH and a vacuolar Na+/H+ antiporter gene SeNHX1. *Biotechnology Letters* **30**: 369-376.

Zuo J, Niu, QW, Møller SG and Chua NH (2001) Chemical-regulated, site-specific DNA excision in transgenic plants. *Nature Biotechnology* **19(2)**: 157-161.

Received: September 10, 2024; Accepted: October 14, 2024

Journal of Soil Salinity and Water Quality 16(2), 194-206, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.158032

Critical Review of Irrigation Water Quality Parameters for Assessing Sodium and Bicarbonate Hazards and Gypsum Application for Quality Improvement

Suresh Kumar Gupta[1]* and Vijay Kumar[2]

[1]Formerly, AICRP on Use of Saline Water in Agriculture,
ICAR-Central Soil Salinity Research Institute, Karnal-132001, Haryana
[2]Formerly Regional Research Station, Karnal, Chaudhary Charan Singh Haryana
Agricultural University, Hisar-125004, Haryana
*Corresponding author's E-mail: drskg1949@yahoo.com

Abstract

Traditional parameters such as sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and exchangeable sodium percentage (ESP) used to assess water/soil quality have been critically reviewed. Limitations of these parameters especially related to neglect of potassium and the assumption that calcium and magnesium have similar effects on soil flocculation are highlighted. It emerged that the role of Mg in water is least understood rendering these parameters to underestimate the problems related to sodium and bicarbonate hazards. Latest research for devising new parameters to overcome the limitations by incorporating relative dispersive and flocculating role of four cations namely Na, K, Mg and Ca is reviewed. New parameters such as sodium to calcium adsorption ratio (SCAR), cation ratio of structural stability (CROSS), optimized cation ratio of structural stability ($CROSS_{opt}$), exchangeable dispersion percentage (EDP), residual sodium bicarbonate (RSBC), and modified adjusted residual sodium (mod. R_{Na}) have been included and their relative merits over the existing parameters have been discussed. Since most of these equations have been developed for specific soil water and agro-climatic conditions, final forms of these equations in generalized forms have been included for testing and evaluating their constants for the Indian monsoonal environment. Equations have been developed and reported for the first time to determine the gypsum requirement of high SAR alkali water to manage high SAR and high RSC and for managing Mg/Ca ratio of water having high Mg/Ca ratios. Application of these new parameters has great significance as India is at the verge of increasing use of recycled municipal wastewaters, surface water polluted by industrial wastes, drainage water discharged from agricultural fields, and even groundwater associated with high concentrations of K and Mg. These parameters may answer some of the unresolved issues such as resodification of alkali lands and productive use of water having high magnesium concentrations. It is concluded that research actions to test these new parameters should be initiated as early as possible for switchover from the traditional to these new parameters.

Key words: Cation ratio of structural stability (CROSS), Gypsum requirement, Irrigation water quality, Magnesium hazard, Magnesium calcium ratio, Sodium Adsorption ratio, Residual sodium carbonate

Introduction

According to All India Coordinated Research Project (AICRP) on Use of Saline Water and ICAR-CSSRI guidelines, four most important chemical parameters to assess irrigation water quality are electrical conductivity (EC), sodium adsorption ratio (SAR), residual sodium carbonate (RSC) and magnesium to calcium ratio (Mg/Ca). *Per se* even high values of these parameters in irrigation water either alone or in combination do not directly affect the crop yield. But the adverse effects on chemical/physical properties of the soils upon continuous use of these waters for irrigation results in yield penality. The most important soil chemical changes manifest from increase in the EC, pH and SAR/ESP of the soil water. These chemical changes in turn affect soil physical properties namely aggregate stability, clay dispersion including clay swelling, infiltration rate, hydraulic conductivity, soil tilth and surface crusting. Increasing EC, within reasonable limits, in general has a positive impact. On the other hand, increasing SAR, RSC and Mg/Ca ratio have adverse impacts on the soil physical properties. Researchers around the globe have been attempting to understand the correlation between the irrigation water quality parameters and soil quality. In this pusuit, some easily assessable parameters have been developed to evaluate the long-term use of water for irrigation. In spite of more than 75 years of research, these attempts have met with little success mainly because of the limited reach of the researchers to soil and water samples from their own regions. In our opinion, SAR, the most widely used parameter governing the soil and water quality, is the least understood because of its definition and its interactive effect with other parameters notably EC, RSC and Mg/Ca ratio. This paper is mainly devoted to the critical review of the SAR concept used around the globe, highlighting its limitations and recent innovations. Since concentration of magnesium in water also governs RSC, some discussion related to RSC and Mg hazard is included. The main objectives of this paper are to raise few important concerns on the use of these parameters, to generate fruitful discussions on SAR and RSC, to propose new equations to calculate gypsum requirement for high SAR alkali water and water having high Mg/Ca ratios, to suggest appropriate changes in reporting water quality and to argue in favour of initiating further investigations to refine these concepts of vital importance in poor quality soil and water research.

Sodium Adsorption Ratio

Sodium adsorption ratio (SAR) has been the standard diagnostic parameter to understand and assess the sodicity hazard of irrigation water to decipher the effect of sodium on crop growth and soil properties (US Salinity Laboratory Staff, 1954). SAR of irrigation water may be written as:

$$SAR = Na/[(Ca+Mg)/2]^{1/2} = 1.414\ Na/(Ca+Mg)^{1/2} \quad \ldots(1)$$

Here Na, Ca and Mg are all in $meqL^{-1}$. Sodium adsorption ratio of the irrigation water is often denoted as (SAR_{iw}) and that of the soil as (SAR_e). Since soil ESP is the key governing factor that impacts soil physical properties (Bresler *et al.*, 1982, Keren *et al.*, 1984, Levy *et al.*, 2012, Shainberg and Letey, 1984), researchers have attempted to relate SAR_{iw}, SAR_e and soil ESP either empirically or through rigorous thermodynamic arguments (Oster and Sposito, 1980). Not much success has been achieved in fully achieving this objective. It is mainly attributed to widely varying anionic and cationic concentration of irrigation water, limited understanding of water and soil interactions and several limitations of the SAR concept itself.

Limitations of SAR

The first but not very significant objection arises from the fact that SAR omits the role of potassium (K) and its effect on soil properties. This omission has been justified firstly for the reason that Na concentrations in irrigated soils/or waters are usually much higher than K. Secondly, exchangeable K has either slight or no adverse effect upon soil's physical properties (US Salinity Laboratory Staff, 1954). Nonetheless, a term Potassium Adsorption Ratio (PAR) was proposed in which sodium in the numerator of eq. (1) was replaced by potassium (US Salinity Laboratory Staff, 1954). Unfortunately, no guidelines exist even today to assess irrigation water quality based on PAR. Later on, these two parameters were combined to give an all-encompassing parameter termed as monovalent cation adsorption ratio (MCAR), which is given as:

$$MCAR = (Na+K)/[(Ca+Mg)/2]^{1/2} = 1.414\ (Na+K)/(Ca+Mg)^{1/2} \quad \ldots(2)$$

The water quality assessment guidelines for MCAR are basically similar to the ones used for the SAR. In parallel with this concern on K, the most important objection to SAR has been the clubbing of Ca and Mg in the denominator of eq. (1). The simplest argument for clubbing has been that Ca and Mg in the past were commonly determined and reported together as (Ca+Mg). Therefore, it was necessary to put them together. But aside this simple argument, many scientists believed that Mg, owing to its divalent nature, acts like Ca in influencing the physico-chemical properties of the soil. On the contrary, others believed that Mg should not be coupled with Ca owing to its varying affinity for adsorption on the exchange complex of the soil. It seems that the concept of SAR has been developed in regions where Mg/Ca ratios of water were in general either less than or equal to 1.0. It is why, Bresler *et al.*, (1982) observed that this customary grouping failes to truely reflect the negative effect of Mg because of two to five fold higher concentration of Ca over Mg in irrigation water. On the contrary, SAR may underestimate the sodium hazard of irrigation waters having high Mg/Ca ratios often going up to 5 or even more (Gupta, 1979, Gupta and Gupta, 1987, Gupta, 1990, Gupta and Gupta, 2001). Many researcher have invariably established that hydraulic conductivity is greatly governed by the type of cation concentration in the leaching water, magnitude of decrease following the order: Na > K > Mg > Ca. Scientists are now veering around the view that there is no theoretical justification for combining Ca and Mg ions except that the ion valency, the most sensitive parameter for predicting ion-exchange relations, is same. In spite of these limitations, SAR concept is widely used being relatively simple and it generally works under many situations.

Besides what has been stated about SAR_{iw}, an important issue with respect to SAR_e has been that at many places both saline and alkali soils in India have high SAR as high as 100 (Bhargava, 1989, Bhargava, 2003, Gupta *et al.*, 2019). But saline soils neither show high ESP nor high pH (Gupta *et al.*, 2007). It is ascribed to excessive soluble salt concentration of neutral salts predominated by chlorides and sulphates depressing the soil pH. It is why, SAR as a diagnostic criterion to categorize saline and alkali soils has not been adopted in India. Chhabra (2004) suggested that anionic and cationic concentrations become important to clearly distinguish two soils having high SAR. He postulated that soils having $(2CO_3 + HCO_3)/(Cl+2SO_4)$ and/or $Na/(Cl+2SO_4) > 1$ where all ions are expressed in $molm^{-3}$ should be treated as natric needing amendment for reclamation. If these ratios are < 1 then irrespective of their SAR, the soils should be treated as salic requiring no chemical amendment for reclamation. He also confirmed the observations of Sharma and Rao (1998) that leaching highly saline soils reduces both the EC and SAR simultaneously. Singh *et al.* (1992) however observed that salt accumulation is higher in soils irrigated with high SAR water having the same EC. Therefore, more water is required to leach the accumulated salts in soils irrigated with high SAR.

Modifications of the SAR Concept

Many new theories have been advanced to take care of the limitations of the SAR concept leading to a better understanding of the problems. Contrarily, our knowledge is still limited and therefore concerted efforts on global scale are needed to arrive at some logical and universally applicable concept.

Adjusted SAR

Ayers and Westcot (1976) postulated the concept of adj. SAR to replace SAR. It is calculated by the relation:

$$\text{Adj. SAR} = \text{SAR}\,[(1 + (8.4 - pH_c)] \qquad \ldots(3)$$

Here pH_c is the theoretically calculated pH of the irrigation water in contact with lime and in equilibrium with soil CO_2. The pH_c values above 8.4 indicate the tendency of the water to dissolve lime from the soil. The values less than 8.4 indicate a tendency to precipitate lime (Bower, 1961). The pH_c is calculated using the following equation:

$$pH_c = (pk_2 - pk_c) + p(Ca) + P(Alk) \qquad \ldots(4)$$

In eq. (4) pk_2 and pk_c are the negative logarithms of the second dissociation constant of H_2CO_3 and solubility product of $CaCO_3$, respectively corrected for ionic strength. Bower (1961) replaced p(Ca) by p(Ca+Mg) in eq. (4) arguing that behavior of Ca and Mg in the soil is similar. Accordingly, p(Ca+Mg) and p(Alk) are the negative logarithm of the molal concentration of (Ca+Mg) and equivalent concentration of titratable bases (CO_3+HCO_3). Ayers and Westcot (1976) prepared a table for easy calculation of pH_c. The tests proved that eq. (3) is no better than SAR and it over predicts the sodium hazard. The values calculated using this equation need to be multiplied by a factor of 0.5 to evaluate the effect of HCO_3 on calcium precipitation (Ayers and Westcot, 1985). Therefore, authors withdrew the concept of adj. SAR in their latest report observing that it does not make any improvement over the existing equation (Ayers and Westcot, 1985). Therefore, it is suggested that this concept should be withdrawn from the text books and from the new publications to avoid confusion.

Sodium to Calcium Adsorption Ratio

Gupta (1980) argued that the application of SAR concept to waters having EC higher than 5 dSm^{-1} and Mg/Ca ratio greater than 1 is questionable. He advanced a new criterion termed as Sodium to calcium adsorption ratio (SCAR) defined as:

$$SCAR = Na/(Ca)^{1/2} \quad \ldots(5)$$

Although visually, eq. (5) does not include Mg but practically, it includes Mg to the extent of Ca content in the water i.e. it assumes that Mg/Ca ratio of the water is 1.0 irrespective of the actual value. It can be shown by writing eq. (1) in the following form.

$$SAR = Na/[Ca^{1/2}(1+Mg/Ca)/2]^{1/2} \quad \ldots(6)$$

For Mg/Ca ratio of 1.0, eq. (6) reduces to eq. (5). This argument is justified in view of the fact that real problems with Mg begins only when its concentration exceeds Ca concentration in the water. Gupta (1990) using the data of Gupta and Abichandani (1967) revealed that ESP of the soil following irrigation with poor quality water were better correlated with SCAR than with SAR even showing nearly one to one relation (between SCAR and ESP) at two sites (Table 1). Soil SAR is around 4 times that of the water when the irrigation water had a very high Mg/Ca ratio of 16.0 compared to low Mg/Ca ratios where it was nearly the same (Gupta, 2015, Table 1).

Cation Ratio of Structural Stability (CROSS)

Recent emphasis on recycling highly saline and polluted waste waters for irrigation has highlighted the need to consider the adverse effects of K and Mg (Rengasamy and Marchuk, 2011, Arienzo *et al.*, 2012; Marchuk *et al.*, 2013; Buelow *et al.*, 2015, Smith *et al.*, 2015). Most studies indicate that the negative effects of K and Mg on the soil saturated hydraulic conductivity are somewhere between those of Na, the worst soil dispersant and Ca, the best flocculent (Quirk and Schofield 1955, Keren *et al.*, 1984, Levy and van Der Watt, 1990, Quirk, 2001, Smith *et al.* 2015). However, it has not been possible to incorporate this fact into any standard irrigation water quality criteria until a new parameter, the cation ratio of structural stability (CROSS) appeared in the literature. The flocculating power, the inverse of dispersive power, of the three elements namely K, Mg, and Ca were derived to be 1.8, 27, and 45 respectively compared to 1.0 for Na (Rengasamy *et al.*, 1998). Thus, the measure of the dispersing power of K relative to Na is 1.0/1.8 = 0.56 and the flocculating power of Mg relative to Ca is 27/45 = 0.60. Considering these findings, Rengasamy and Marchuk (2011) proposed a new ratio and termed it as Cation Ratio of Structural Stability (CROSS), which is more or less analogous to the MCAR but giving due weightage to the relative role of K and Mg in dispersion and flocculation of soils compared to Na and Ca respectively.

$$CROSS = (Na + 0.56\ K)/\ [(Ca + 0.60\ Mg)/2]^{1/2} \quad \ldots(7)$$

The CROSS is the first ever improvement that addresses the major limitation of the MCAR or for that matter SAR. The relative performance of CROSS viz.-a-viz. SAR was tested using data on percent dispersible clays of irrigated lands which were irrigated with water containing different proportions of Ca, Mg, K, and Na resulting in CROSS values ranging from 2 to 10. Although corealtion with SAR was also significant but the correlation with CROSS was highly superior to SAR (Rengasamy and Marchuk, 2011). Similarly, tests conducted by Marchuk and Rengasamy (2012) revealed a highly significant linear correlation between CROSS and the electrical conductivity of irrigation water required to flocculate three Australian soils. The relative

Table 1. SAR and SCAR values of irrigation water and observed SAR and ESP of irrigated soils

Location	Irrigation water				Irrigated soils	
	EC (dSm^{-1})	Mg/Ca ratio	SAR	SCAR	SAR	ESP
Kaparda, Rajasthan	10.8	4.4	28	59	31	60
Jelwa, Rajasthan	5.9	8.1	23	36	28	38
Shikarpura, Rajasthan	4.5	16.0	8	26	32	35

performance of CROSS proved to be much superior to SAR. Qadir *et al*. (2012) however cautioned that use of CROSS in place of SAR is only advisable if EC of irrigation water is < 4 dS m^{-1} and Mg concentration is > Ca concentration or Mg/Ca ratio is more than 1.0. Oster *et al*. (2016) extended the works of Duan *et al.* (1993) and Rosenbrock (1960) by optimizing the coefficients appearing in CROSS (eq. 7) to arrive at a more or less similar equation but having lower coefficients both for K and Mg. They named this equation as $CROSS_{opt}$ to distinguish it from CROSS. Here "opt" means that the parameters have been derived using optimization technique.

$$CROSS_{opt} = (Na + 0.335\ (\pm 0.038)\ K) / [(Ca + 0.0758\ (\pm 0.012)\ Mg)/2]^{1/2} \quad (8)$$

The optimized mean value of 0.335 indicates that the dispersive power of K is about one-third that of Na while it was slightly more than half in eq. (7). It is important to note that the value of 0.0758 for Mg is much less than the value of 0.60 reported in eq. (8). In spite of the low value, we cannot say that Mg can be neglected since Mg can still contribute significantly in the calculated values of $CROSS_{opt}$ for waters having high Mg/Ca ratios. Excellent correlation has been reported between $CROSS_{opt}$ and threshold electrolyte concentration (TEC), a measure to assess the impact of cations on soil permeability, for a Sodosol irrigated with winery wastewater having significant concentrations of K and Mg (Laurenson *et al*., 2012). The r^2 was better with $CROSS_{opt}$ than with CROSS. Similarly, Yan *et al.* (2024) demonstrated that K_{sat} decreased with increasing $CROSS_{opt}$. The authors of CROSS and $CROSS_{opt}$ have suggested that guidelines currently used for characterizing irrigation water using SAR can also be used with these new irrigation water quality parameters. Besides, the precipitation concept of Ca of Suarez (1981) can also be incorporated in it for understanding the soil behaviour. We strongly suggest the use of CROSS or $CROSS_{opt}$ instead of SAR for water quality assessment and further refinement of the concept for the agro-climatic conditions of India.

Another important advancement made in this area is the replacement of exchangeable sodium percentage (ESP) with exchangeable dispersive percentage, EDP (Bennett *et al.*, 2016). Using the coefficients developed for CROSS and $CROSS_{opt}$, they defined EDP as:

$$EDP = [(Na+0.5565K+0.037Mg)/CEC]\times 100 \quad \ldots(9)$$

Here the coefficients attached to K and Mg take into account the equivalent dispersive effect in relation to Na. Here all concentrations are in the units of $cmol_c/kg$. Bennett *et al*. (2016) like Qadir *et al*. (2012) cautioned that the Mg term in eq. (9) should only be used where sufficient Mg exists in the system i.e. Mg/Ca ratio is high. Otherwise eq. (9) will not truely predict the clay dispersion (Bennett *et al*., 2016).

Residual Sodium Carbonate (RSC)

Eaton (1950) gave the concept of residual sodium carbonate (RSC). He observed that soils may become alkali or saline-alkali when water containing CO_3+HCO_3 higher than Ca+Mg is used for irrigation especially if the water is used so sparingly that little leaching occurs. Calcium and to some extent magnesium tends to precipitate as carbonates as the soil solution concentrates. With increasing Na concentration in the soil solution, clay particles absorb sodium and release magnesium and calcium ions resulting in poorly permeable soils. Besides, it results in weakening of the soil structure and causes serious drainage problems. Another very important problem associated with carbonate/bicarbonate waters is the formation of OH^{-1} ions. The hydroxyl ions increase soil pH that impacts the uptake of certain nutritional elements by the plants. As a result, deficiencies, growth problems and crop maintenance problems soon appear. According to Eaton, RSC is given as:

$$RSC = (CO_3+HCO_3) - (Ca+Mg) \quad \ldots(10)$$

Here all ions are expressed in $meqL^{-1}$. Though, Eaton (1950) suggested that RSC should be determined as per eq. (10), yet in all his experiments, no Mg salts were applied. The irrigation water contained only calcium and sodium. Wilcox *et al.* (1954) also carried out pot culture experiment to substantiate the RSC concept. In these experiments also RSC was determined as (HCO_3-Ca) as revealed by the data

Table 2. Composition of the irrigation waters and properties of irrigated soils under low leaching in non-calcareous soils

Irrigation water							Irrigated soil					
Na	Ca	HCO_3	Cl	TCC	SAR	RSC	After 42 irrigation			After 86 irrigation		
(%)	(%)	(%)	(%)	(meq L^{-1})		(meq L^{-1})	pH_s	ESP	EC (dS m^{-1})	pH_s	ESP	EC (dS m^{-1})
75	25	0	100	20	9.5	0	6.8	12	3.7	6.8	16	5.3
75	25	50	50	20	9.5	5	8.6	52	5.9	9.4	72	16.0
75	25	0	100	10	6.7	0	7.2	8	2.2	7.3	15	3.7
75	25	50	50	10	6.7	2.5	8.6	20	2.0	9.0	42	7.3
75	25	0	100	5	4.8	0	6.8	9	1.3	6.7	11	1.8
75	25	50	50	5	4.8	1.25	8.4	10	1.2	7.7	20	2.4

reported in Table 2. Similarly, Bower (1961) and Pratt *et al*. (1960) in several green house and lysimeter experiments also used HCO_3 and Ca salts only. Likewise, in many experiments conducted in India only $NaHCO_3$ salt was added in very low salinity waters to prepare waters of different RSC (Gupta, 1980; Anonymous, 1983; Bajwa *et al*., 1983; Manchanda *et al*., 1985).

Questions on including magnesium in evaluating RSC of irrigation water have been raised multiple times in the literature mainly because HCO_3 does not precipitate Mg. Moreover, Ca has high affinity to precipitate in the presence of CO_3 and HCO_3 ions compared to Mg (Shainberg and Levy, 2005). Christopher *et al*., (2009) studied the possibility of precipitation of Mg as Mg-carbonate (magnesite and dolomite) under natural conditions. These studies revealed that the magnesium precipitation requires enough energy to remove hydration shell around Mg atoms before it precipitates in the soil. Moreover, Bohn *et al*. (2001) observed that calcite preferentially precipitates in soil leaving little quantity of Mg to substitute into its structure. Dolomite precipitation as secondary minerals only occur under marine conditions. Shafiek *et al*. (2015) examined SEM-EDXRA images of disturbed soil samples and observed that while calcium carbonates was present in all samples, magnesium carbonate could not be detected. The quantitative differentiation of carbonate minerals determined according to Petersen *et al*. (1966) method indicated that 87.8% of carbonate minerals were calcite and the rest 12.2% was dolomite or Mg–bearing calcite. The most stable form of magnesium carbonate was found to be the crystalline nesquehonite ($MgCO_3.3H_2O$), which is hundred times more soluble than calcite (Bulakh and Wenk, 2004). This form of carbonate is easily lost from the soil to solution. Thus, it may be reasonable to conclude that magnesium may not precipitate as magnesium carbonate under normal conditions prevailing in irrigated soils (Hassett, 1970; Bohn *et al*., 2001; Oelkers, *et al*., 2003; Suarez, 1975).

Another major argument against the use of RSC is that it is only a quick test to determine if free calcium and magnesium in irrigation water will precipitate upon their application to the soil. The final outcome on the adverse effects on soil properties will be governed by SAR of the soil solution following irrigation with high RSC water. It is probably why Ayers and Westcot (1976) included RSC as one of the water quality parameter but withdrew it in their later revised version (Ayers and Westcot, 1985). Besides what has been stated, RSC guidelines for suitability of water are same for light, medium and heavy textured soils while it is known that adverse effects will be more in a heavy than medium and light textured soils for the same RSC water. Nonetheless, RSC is still used in few water quality reports although its use in developed countries is infrequent.

Improvements in RSC Concept

Residual sodium bicarbonate (RSBC)

Following the arguments of the US Salinity Laboratory (1954) for simplifying SAR, Gupta (1984) argued that carbonates in natural waters having pH more than 8.5 either do not occur or may occur in trace amounts seldom exceeding 1.0 $meqL^{-1}$. An examination of about 900 water samples collected from four districts of western Rajasthan showed that the percentage of waters having pH greater than 8.5 varies from less than one in Barmer and Jaisalmer districts to about two in Jodhpur and Bikaner districts (Bhandari *et al.*, 1970). Considering the results of the field studies reported in previous paragraphs that magnesium ions do not precipitate by bicarbonate ions, Gupta (1984) proposed that the alkalinity hazard of irrigation water can be determined by the simplified equation termed as "Residual Sodium Bicarbonate (RSBC)".

$$RSBC = HCO_3\text{-}Ca \quad \text{...(11)}$$

Eq. (10) and eq. (11) can be presented in a unified RSC equation.

$$RSC = (CO_3+HCO_3) - Ca\ (1+f\ Mg/Ca) \quad \text{...(12)}$$

Under the present state of knowledge f can be taken as zero for water having CO_3 as nil or in traces. In that case eq. (12) becomes eq. (11). Probably more research is needed to find values of f for other combinations of anions and cations in water. It becomes even more important as the precipitation reaction never reaches to completion even under equilibrium conditions. Some Ca and Mg remain in the soil solution. Water classification criterion/guidelines used for RSC remain valid to classify water while using RSBC.

Adjusted residual sodium (R_{Na})

As stated previously, SAR rather than RSC governs the soil physical behaviour under irrigation with poor quality high SAR or RSC water. Suarez (1981) combined the concept of RSC and SAR and proposed a new parameter adj.R_{Na} to take care of the dissolution and precipitation of calcium in modifying the SAR_e upon irrigation. The equation proposed by him is given as follows:

$$Adj.\ R_{Na} = Na\ /[(Ca_x + Mg)/2]^{½} \quad \text{...(13)}$$

Here, Ca_x is the value of Ca in the water that takes care of EC and HCO_3/Ca ratio of the water and the estimated partial pressure of CO_2 in the surface few mm of the soil. The Ca_x represents Ca that is likely to remain in the soil solution at equilibrium in $meqL^{-1}$. This equation better predicts the potential infiltration problems due to the presence of relatively high sodium (or low calcium) in irrigation water (Suarez, 1981; Rhoades, 1983). Drawback of this concept like SAR is that Mg once again has been clubbed with Ca in the calculation of Adj. R_{Na} although the same was not included while calculating HCO_3/Ca ratio. Obviously, the equation will under-predict the sodium hazard for waters having high Mg/Ca exceeding one. On this analogy, Gupta modified the SCAR (eq. 5) and termed it as adj. SCAR, which can be given as $Na/\sqrt{Ca_x}$.

Modified adjusted residual sodium (R_{Na})

Minhas and Sharma (2006) investigated the application of Adj. R_{Na} to predict soil ESP resulting from medium to long-term use of high RSC water for irrigation. They observed that the alkali hazard can be predicted using the Adj.R_{Na} albeit with certain modifications. Their contention was that an equation developed for a particular agro-climatic condition may not be applicable to monsoon climatic conditions of India, where dilution and dissolution processes occur simultaneously under field conditions. They accordingly postulated the concept of a concentration factor (that takes care of varying ET of the crop sequences) and a dilution factor (resulting from rainfall) to arrive at the modified eq. (13).

$$Adj.\ R_{Na}\ (mod.) = [(1+D_{rw}/ET)^{1/2}(D_{iw}/D_{rw})] \times Adj.\ R_{Na} \quad \text{...(14)}$$

or

$$Adj.\ R_{Na}\ (mod.) = A \times Adj.\ R_{Na} \quad \text{...(15)}$$

Here ET is the evapotranspiration of the cropping sequence, D_{rw} is the depth of rainwater during the cropping sequence, D_{iw} is the depth of high RSC irrigation water applied and A is equal to $[\{ET/(D_{rw}+ET)\}^{1/2}(D_{iw}/D_{rw})]$. The values of A reported by Gupta (2015) for various cropping systems and climatic conditions vary with crop rotation, rainfall, irrigation water applied and ET. In general the factor A follows the order Rice-wheat > Maize/millet-wheat > cotton-wheat >fallow-wheat in areas having rainfall in 60-70 cm range. But in low rainfall region (rainfall 30-

40 cm per annum), the factor A even for fallow - wheat may exceed than the maize/millet-wheat. The most important part of this modification has been that a one to one relation between the Adj. R_{Na} (mod.) of the water and soil ESP could be established. Needless to emphasize, water quality parameters developed elsewhere under entirely different agro-climatic conditions have to be carefully examined, understood and modified to suit the Indian conditions. Although, we agree with the statement and approach of modifying the parameters for various agro-climatic, soil and water conditions but still emphasize that the role of Mg in eq. (13) need further investigations.

Chemical Amendment Requirement for high RSC and high SAR Management

High SAR saline soils or high SAR saline water do not require much chemical amendment (gypsum). Only small quantities of amendment may be required during the rainy season to improve the electrolyte concentration of the percolating rain water. Contrarily, gypsum is required to amend alkali water and high SAR alkali water. The mathematical formulation for calculating amendment (gypsum) requirement for high RSC water is well defined in the literature and is reproduced below.

Gypsum requirement (t/ha) = $(12.3 \times (RSC_a - RSC_d) \times D_{iw})/1000$ ...(16)

Here RSC_a is the actual RSC, and RSC_d is the desired RSC, normally taken as 2.5 $meqL^{-1}$ in India (Gupta, 1979) and Pakistan (WAPDA,1974)) and D_{iw} is the amount of irrigation water applied (Number of irrigations times the depth of each irrigation). The factor 12.3 appears from the fact that 12.3 kg ha^{-1} of agricultural grade gypsum (70% pure) is required to add 1 $meqL^{-1}$ of Ca for each cm of water applied. Literature scan revealed that no such formula is available for managing high SAR of high SAR alkali water. An attempt is made to derive such an equation assuming that the actual (SAR_a) and desired SAR (SAR_d) of the water are known. Then

$SAR_a/SAR_d = [1.414\ Na_a/(Ca_a+Mg_a)^{1/2}]/[1.414\ Na_d/(Ca_d+Mg_d)^{1/2}]$ ...(17)

Since Na_a and Na_d and Mg_a and Mg_d will be same in the original and treated water, we have

$SAR_a/SAR_d = (Ca_a+Mg_a)^{1/2}/(Ca_d+Mg_a)^{1/2}$ ...(18)

Simplifying eq. (18), we have

$(SAR_a/SAR_d)^2 = (Ca_d+Mg_d)/(Ca_a+Mg_a)$ ...(19)

$(Ca_d+Mg_a) = (Ca_a+Mg_a)\ (SAR_a/SAR_d)^2$ ...(20)

$Ca_d = (Ca_a+Mg_a)\ (SAR_a/SAR_d)^2 - Mg_a$ ...(21)

$Ca_{add} = (Ca_a+Mg_a)\ (SAR_a/SAR_d)^2 - (Mg_a + Ca_a)$ ...(22)

$Ca_{add} = (Ca_a+Mg_a)[(SAR_a/SAR_d)^2 - 1]$ ...(23)

Here Ca_{add} is the additional Ca that needs to be added from outside besides the Ca initially present in the water. Note that only unknown parameter on the right hand side of eq. (23) is SAR_d, which may be taken as 15 for medium and 10 for heavy textured soils. It is now possible to solve eq. (23) to determine, Ca_{add}.

Gypsum requirement (t/ha) = $(12.3 \times Ca_{add} \times D_{iw})/1000$ ...(24)

Illustration

The laboratory determined chemical constituents of a water sample from village Kabulpur, block Assandh in district Karnal are reported in Table 3 (Data courtesy AICRP, Hisar center). As per AICRP and ICAR-CSSRI classification, the water is characterized as high SAR alkali water. If we assume that 30 cm of water is applied to the wheat crop then the gypsum requirement for managing high RSC and high SAR of this water is calculated as follows.

Ca_{add} for RSC = $RSC_a - RSC_d$ = 6.80-2.50 = 4.30

Gypsum requirement (t/ha) = 12.3 × 4.30 × 30/ 1000 = 1.59

Ca_{add} for SAR (light to medium soils) =3.8 $((15.72/15)^2-1)$ = 3.8(1.1-1) = 0.38

Gypsum requirement (t/ha) = 12.3× 0.38 × 30/ 1000 = 0.14

Ca_{add} for SAR (heavy textured soil) =3.8 $((15.72/10)^2-1)$ = 3.8(2.47-1) = 5.59

Gypsum requirement (t/ha) = 12.3 × 5.59 × 30/ 1000 = 2.1

The general principle is to apply higher amount of chemical amendment required to

Table 3. Chemical composition of high SAR alkali water

Parameter	Value
EC (dSm^{-1})	2.53
pH	8.50
Na (meq L^{-1})	21.70
Ca (meq L^{-1})	2.10
Mg (meq L^{-1})	1.70
Cl (meq L^{-1})	6.80
SO_4 (meq L^{-1})	9.80
CO_3+HCO_3 (meq L^{-1})	10.60
SAR (meq L)$^{1/2}$	15.72
RSC (meq L^{-1})	6.80
Mg/Ca ratio	0.81
Cl/SO_4 ratio	0.69

neutralize either RSC or SAR. For this illustration, amount of gypsum required to amend the water is higher for treating RSC for a medium textured soil. On the other hand, for a heavy textured soil the amendment need is higher to treat the water for SAR. Accordingly, amendment in the first case should be applied to treat RSC while in the other to treat SAR being higher than that of RSC. It is once again reiterated that this equation may not be used for high SAR saline waters.

Magnesium Hazard

Flocculating potential of Mg is about 60% (eq. 7) or even less than calcium (eq. 8). Accordingly, soil properties will be more adversely affected in the presence of excess Mg over Ca for the same amount of (Ca+Mg) in the water (Szabolcs and Darab, 1964, Khan, 1975, Girdhar and Yadav, 1981, Raghunath, 1987). Adverse consequences of high Mg in water on crop yields have also been reported (Girdhar and Yadav, 1982). The magnesium hazard (MH) also referred as magnesium adsorption ratio is widely used to evaluate the water quality for irrigation (Raghunath, 1987, Naseem et al., 2010). It is given as:

$$MH = Mg/(Ca + Mg) \qquad \ldots(25)$$

The water is suitable for irrigation if the value of MH<0.5 while it is unsuitable if MH > 0.5 (Singh and Singh, 2008). It can be interpreted to mean that all waters having Mg/Ca ratio ≤ 1 can be characterized as suitable for irrigation. AICRP and ICAR-CSSRI guidelines suggest that gypsum should be applied to soils irrigated with waters having Mg/Ca ratio ≥3. The amount of calcium to be added to correct the Mg/Ca ratio of the water can be easily calculated with the following equation.

$$Ca_{add} = Ca_a [(A/B) -1] \qquad \ldots(26)$$

Here A is the actual Mg/Ca ratio of the water and B is the desired Mg/Ca ratio of the water. All other notations have the same meaning as defined previously. The desired ratio may be taken as 1.0 or at the most 2.0 to minimize cost of amendment application. Gypsum requirement then is assessed from the following equation.

$$\text{Gypsum requirement (t/ha)} = 12.3 \times Ca_{add} \times D_{iw}/1000 \qquad \ldots(27)$$

For the example used in the illustration in the previous section (Table 3), Mg/Ca ratio being 0.81, no gypsum application is needed to correct the Mg/Ca ratio of the water.

Way Forward

Water quality parameters and guidelines are normally framed to achieve the following two objectives.

- To assess the irrigation water quality with respect to certain problems anticipated with its continuous use for irrigation
- To predict the adverse consequences of continuous use of water on soil properties

As per the review presented in relation to assess the sodium hazard of water, it can be said that no theoretically elegant parameter is available even after 75 years of theoretical and field research. While few parameters are traditionally used to characterize the water, most fail to predict the adverse consequences in terms of SAR_e or ESP likely to develop upon continuous use of irrigation water. SAR in spite of its limitations is widely used to assess the sodium hazard of the irrigation water. Considering the recent challenges in using recycled and municipal waste waters (Gupta and Gupta, 2014), polluted surface water, agricultural drainage water, and groundwater in irrigated areas that may have spiked concentrations of K and Mg, it may be desirable to switch over to CROSS. CROSS or $CROSS_{opt}$ are very similar but takes care of relative dispersive potential of K and relative flocculation potential of Mg. While there is enough evidence to suggest that Mg systems are dispersive (Curtin *et al.*, 1994; Qadir *et al.*, 2018; Zhang and Norton, 2002), recent studies also demonstrate that K systems are also quite dispersive at low concentrations of Na (Dang *et al.*, 2018, Zhu *et al.*, 2019). Clearly, CROSS resolves major argument against SAR or MCAR by giving due consideration to K and Mg. Besides what is stated, it may be added that the CROSS of the soil solution will not be equal to the CROSS of the irrigation water. There appears to be almost unanimity in using Ca_x instead of Ca in all the new equations to account for the precipitation of Ca in the soil on account of EC_{iw} and HCO_3/Ca ratio of the water and the estimated partial pressure of CO_2 in the surface few mm of the soil. Therefore, we recommend that the following equation which is more theoretically elegant should replace SAR, MCAR or adj R_{Na}.

$$CROSS = (Na + a\,K)/\ [(Ca_x + b\,Mg)/2]^{1/2} \quad \ldots(28)$$

To account for the concentration of the soil solution upon evaporation in the absence of exchange or other precipitation reactions, CROSS is likely to increase in proportion to the square root of the concentration factor.

$$CROSS_{sw} = n\,(Na + a\,K)/\ [n(Ca_x + b\,Mg)/2]^{1/2} = \sqrt{n}\,(Na + a\,K)/\ [(Ca_x + b\,Mg)/2]^{1/2} \quad \ldots(29)$$

Here $CROSS_{sw}$ is the CROSS of the soil water, a and b are constants both being less than 1.0 and n is the concentration factor. $CROSS_{sw}$ then can be used to derive the soil SAR/ESP values. As per the current knowledge, value of the constant a varies from 0.56 to 0.34 and b from 0.6 to 0.076. It is in the realm of future research as to the most appropriate values of a and b for a given combination of soil, water and agro-climatic conditions. Before, we conclude this issue; let us dwell upon the factor b using modified eq. (6) and eq. (5).

$$SAR = Na/[Ca_x^{1/2}(1+ bMg/Ca_x)/2]^{1/2} = Na/[Ca_x^{1/2}] \quad \ldots(30)$$

To maintain this equality as suggested by Gupta (1983), the value of b has to change with Mg/Ca ratio. It is 1.0 for Mg/Ca=1.0, 0.5 for Mg/Ca = 2.0 and 0.20 for Mg/Ca =5.0 and so on. This suggests another path of research to arrive at appropriate values of b of eq. (29). It may not be out of place to mention that the research on this issue is all the more important for Indian monsoonal climatic conditions. In conclusion, it is surmised that eq. (28) with a and b selected from any one of the two equation (eq. 7 or eq. 8) should be used to assess the sodium hazard of irrigation water until more research enlighten the scientific community on these parameters. Guidelines to classify water on this basis will remain the same as are prevalent for the parameter SAR.

In our opinion use of EDP in place of ESP can be quite helpful in understanding the resodification potential of sodic soils where waters of high Mg/Ca ratio are used. Such waters may have low RSC but still can cause soil dispersion because of the presence of Mg. Mg has a specific effect on the dispersion of illite, and is about 4-10% effective as an equivalent amount of exchangeable Na in causing the dispersion (Zhu *et al.*, 2019).

The current knowledge on RSC is limited but still better than SAR. Eaton's classification using RSC of irrigation waters even with its limitations is still useful as high RSC is a warning signal that SAR_e is likely to exceed the expected normal increase proportional to the square root of the concentration factor. In spite of this there is possibility of some improvement in the use of equations for calculating RSC. Considering that Ca is preferentially precipitated over Mg, Mg is not precipitated by HCO_3 and the reaction never goes to completion, we can modify the RSC equation using the same corollary as for SAR.

$$RSC = (CO_3+HCO_3) - Ca(1+b\,Mg/Ca) \quad \ldots(31)$$

The value of b is always equal to or less than 1.0. For waters having no or trace CO_3, value of b may be taken as zero so that it reduces to RSBC equation. Researchers may work out the values of b for various soil-water and agro-climatic combinations. Guidelines used to classify water on the basis of RSC can be used to classify water with the new equations except that the limit of 2.5 for heavy textured soils may be reduced. For this purpose, a critical review of the existing data on RSC and crop yields in heavy textured soils need to be examined to arrive at a reasonable value. For the remediation of high SAR and high RSC water, we recommend that gypsum requirement may be calculated both for SAR reduction as well as RSC reduction. The higher value out of the two should be the amendment requirement for the remediation of high SAR alkali water.

The role of Mg in soil flocculation is in between the two extremes given by Na on the one hand and Ca on the other. Therefore, excess quantities of Mg in the water may affect soil dispersion. There is an urgent need to modify the public policy agenda to include high magnesium waters and soils as problematic resources requiring appropriate reclamation efforts. We have proposed an equation to quantitatively estimate the gypsum requirement for water having varying Mg/Ca ratios. This may avoid any ambiguity on the amount of gypsum application to ameliorate the waters having high Mg/Ca ratio.

Conclusions

Conventionally used parameter SAR to assess the sodium hazard of water should be slowly phased out especially in view of the widespread use of recycled water for irrigation, which might have spiked concentrations of all the four major cations namely Na, K, Mg and Ca. All the 4 cations need to be considered while assessing the quality of such waters. Use of CROSS or $CROSS_{opt}$ after incorporating Ca_x for Ca to account for Ca precipitation as proposed by Suarez (1981) should begin in right earnest. Simultaneously, research efforts should be geared to finalize the values of constants a and b used in these equations. Separate equations for waters containing CO_3+ HCO_3 and only HCO_3 have been suggested for calculating RSC to assess the alkali hazard of irrigation water. Equations to calculate gypsum requirement for SAR to ameliorate high SAR alkali waters has been derived to quantitatively assess the requirement, which has been lacking so far. Similar equation for amendment required to reduce known Mg/Ca ratio to a desired value has also been proposed. Since many of the issues could not be conclusively addressed, research issues have been flagged so that water quality assessment for sodium and alkali hazards and their adverse impacts on soil properties can be made a science-based exercise.

References

Anonymous (1983) Coordinated Project on Management of Salt Affected Soils and Use of Saline Water in Agriculture. Ann. Rep. RBS College, Agra.

Arienzo M, Christen EW, Jayawardane NS and Quayle WC (2012) The relative effects of sodium and potassium on soil hydraulic conductivity and implications for winery wastewater management. *Geoderma* **173–174**: 303-310.

Ayers RS and Westcot DW (1976) Water Quality for Agriculture. FAO Irrig. Drain. **Pap. 29**, FAO Rome, Italy: 97p.

Ayers RS and Westcot DW (1985) Water Quality for Agriculture. FAO Irrig. Drain. **Pap. 29**, Rev.1. FAO Rome, Italy: 97p.

Bajwa MS, Hira GS and Singh NT (1983) Effect of sodium and bicarbonate irrigation waters on sodium accumulation and on maize and wheat yields in northern India. *Irrigation Science* **4**: 191-199.

Bennett, JMcL, Marchuk A, Marchuk S and Raine SR (2019). Towards predicting the soil-specific threshold electrolyte concentration of soil as a reduction in saturated hydraulic conductivity: The role of clay net negative charge. *Geoderma* **337**: 122-131.

Bhandari LM, Purohit AD, Bhargava TN and Gupta IC (1970) Potability classification of ground waters in the arid zone of western Rajasthan. *Annals of Arid Zone* **9 (4)**: 221-228.

Bhargava GP (1989) *Salt-affected Soils of India-a Reference Book*. Oxford & IBH Publishing, New Delhi. 261p.

Bhargava GP (2003) *Training Manual for Undertaking Studies on Genesis of Sodic Alkali Soils*. Central Soil Salinity Research Institute, Karnal. 111p.

Bohn HL, McNeal BL and O'onnor GA (2001) *Soil Chemistry*. John Wiley and Sons, Inc. 307p.

Bower CA (1961) Prediction of the effect of irrigation water on soil. Proc. Tehran Symp. on *Salinity Problems in Arid Zones*. 1-8.

Bresler E, McNeal BL, and Carter DL (1982) *Saline and Sodic Soils*. Springer-Verlag, Berlin, Germany. 236p.

Buelow MC, Steenwerth K and Parikh SJ.(2015) The effect of mineral-ion interactions on soil hydraulic conductivity. *Agricultural Water Management* **152**:277-85.

Bulakh A and Wenk, HR (2004) *Minerals: Their Constitution and Origin*. Cambridge University Press, UK. 646p.

Chaabra R (2004) Classification of salt-affected soils. *Arid Land Research and Management* **19**: 61-79.

Christopher SR, Lopez CJ, Navarro AR, Sahi N and Coleman M (2009) Inorganic synthesis of Fe-Ca-Mg carbonate at low temperature. *Geochimica Cosmochimica* **73 (8)**: 5361-5376.

Curtin D, Steppuhn H, and Selles F (1994) Effects of magnesium on cation selectivity and structural stability of sodic soils. *Soil Science Society of America Journal* **58 (3)**: 730-737.

Dang, A, Bennett, J McL, Marchuk A, Biggs A and Raine SR. (2018) Quantifying the aggregation-dispersion boundary condition in terms of saturated hydraulic conductivity reduction and the threshold electrolyte concentration. *Agricultural Water Management* **203**: 172-178.

Duan QY, Gupta VK and Sorooshian SS (1993) Complex evolution approach for effective and efficient global minimization. *Journal of Optimization Theory and Applications* **76 (3)**: 501-521.

Eaton FM (1950) Significance of carbonates in irrigation waters. *Soil Science* **69 (2)**: 123-133.

Girdhar IK and Yadav JSP (1981) Role of magnesium in varying quality of irrigation water in influencing soil properties and wheat yield. *Agrokemia Es Talajtan (Suuplementum)* **30 (sup)**: 148-157.

Girdhar IK and Yadav JSP (1982) Effect of different Mg/ Ca ratios and electrolyte concentrations in irrigation water on the nutrient content of wheat crop. *Plant Soil* **65 (1)**: 63–71.

Gupta IC (1979) *Use of Saline Water in Agriculture in Arid and Semi-arid Zones of India*. Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi. 210 p.

Gupta IC (1980) Effect of irrigation with high-sodium waters on soil properties and the growth of wheat. Intern. Symp. Salt. Affected Soils, Karnal, 287-288.

Gupta IC (1983). Quality of irrigation water and the concept of residual sodium carbonate. *Current Agriculture* **7**: 150-155.

Gupta IC (1984) Reassessment of irrigation water quality criteria and standards. *Current Agriculture* **8**: 113-126.

Gupta IC (1990) *Use of Saline Water in Agriculture in Arid and Semi-arid Zones of India*. Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi. 308p.

Gupta IC and Abichandani CT (1967) Seasonal variations in the composition of some saline irrigation waters of western Rajasthan. *Annals of Arid Zone* **6**: 109-116.

Gupta IC and Gupta SK (2001) *Use of Saline Water in Agriculture*. Scientific Publishers, Jodhpur. 297p.

Gupta IC, Gupta S K and Sharma DP (2007) *Alkali Wastelands, Environment and Reclamation*. MD Publications Pvt. Ltd. New Delhi. 411p.

Gupta SK (2015) Assessing the Hazards of High SAR and Alkali Water: A Critical Review. *Journal of Soil Salinity and Water Quality* **7**(1): 1-11.

Gupta SK and Gupta IC (1987) *Management of Saline Soils and Waters*. Oxford & IBH Publishing Co., New Delhi, 339p.

Gupta SK and Gupta IC (2014) *Management of Saline and Waste Water in Agriculture*. Scientific Publishers (India) Jodhpur. 316 p.

Gupta SK, Sharma PC and Chaudhari S.K. 2019. *Handbook of Saline and Alkali Soils: Diagnosis, Reclamation and Management*. Scientific Publishers, Jodhpur. 239 p.

Hassett JS (1970) *Magnesium Ion Inhibition of Calcium Carbonate Precipitation and its Relation to Water Quality*. All Graduate Theses and Dissertations 4574. 61p.

Keren R, Shainberg L and Shal-hevet J (1984) Potassium, magnesium, and boron in soils under saline and sodic conditions. *In: Soil Salinity under Irrigation: Processes and Management, Berlin, Germany*. Springer-Verlag. 77-99.

Khan M (1975) The effect of magnesium in classification of alkali soils. Proc. Intern. Conf. on Water Logging and Salinity, Lahore.

Laurenson S, Bolan NS, Smith E and McCarthy M (2012) Use of recycled wastewater. *Aust J Grape and Wine Res* **18 (1)**:1-10.

Levy GJ, Huang PM, Li Y, Sumner ME (2012) *Sodicity. In: Handbook of Soil Sciences*, 2nd ed. Boca Ratón, FL: CRC Press.

Levy GJ, and van Der Watt HVH (1990) Effect of exchangeable potassium on the hydraulic conductivity and infiltration rate of some South African soils. *Soil Sci*. **149 (2)**: 69-77.

Manchanda HR, Sharma SK and Singh JP (1985) Effect of increasing levels of residual sodium carbonate in irrigation water on the exchangeable sodium percentage of a sandy-loam soil and crop yield. *J. Indian Soc. Soil Sci*. **33 (2)**: 336-371.

Marchuk A and Rengasamy P (2012) Threshold electrolyte concentration and dispersive potential in relation to CROSS in dispersive soils. *Soil Research* **50 (6)**: 473-481.

Marchuk A, Rengasamy P, McNeill A and Kumar A (2013) Nature of the clay-cation bond affects soil structure as verified by X-ray computed tomography. *Soil Res*. **50 (50)**: 638-644.

Minhas PS and Sharma DR (2006) Predicability of existing indices and an alternative coefficient for estimating sodicity build-up using adj R_{Na} and permissible limits for crops grown on soils irrigated with waters having residual alkalinity. *Journal of the Indian Society of Soil Science* **54 (3)**: 331-338.

Naseem S, Hamz S and Bashir E (2010) Groundwater geochemistry of Winder agricultural farms, Balochistan, Pakistan and assessment for irrigation water quality. *European Water* **31**: 21-32.

Oelkers E, Scott J and Pokrovsky O (2003) The dissolution and precipitation rates of magnesite as a function of solution composition at 150! and implications for CO_2 sequestering. EGS- AGU-EUG Joint Assembly, Abstracts from the meeting held in Nice, France, 6-11 April 2003.

Oster JD and Sposito G (1980) The Gapon coefficient and the exchangeable sodium percentage-sodium adsorption ratio relation. *Soil Science Society of America Journal* **44 (2)**: 258-260.

Oster JD, Garrison S and Chris JS (2016) Accounting for potassium and magnesium in irrigation water quality assessment. *California Agriculture* **70 (2)**: 71-76.

Petersen GWG, Chesters, G and Lee GB (1966) Quantitative determination of calcite and dolomite in soil. *Journal of Soil Science* **17 (2)**: 328-338.

Pratt PF, Branson RL and Chapman HD (1960) Effect of crop, fertilizer and leaching on carbonate precipitation and sodium accumulation in soil irrigated with water containing bicarbonate. Trans. 7th Intern. Cong. Soil Sci. 2: 185-192.

Qadir,M, Schubert S, Oster, JD, Sposito G, Minhas PS, Cheraghi SAM, Murtaza G, Mirzabaev, A and Saqib,M (2018) High magnesium waters and soils: Emerging environmental and food security constraints. *Science of the Total Environment* **642 (15)**: 1108-1117.

Qadir M, Sposito G, Smith CJ and Oster JD (2021) Reassessing irrigation water quality guidelines for sodicity hazard. *Agricultural Water Management* **255**: 0.1016/j.agwat.2021.107054

Quirk JP (2001) The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. *Australian Journal of Soil Research* **39 (6)**: 1185-1217.

Quirk JP and Schofield RK (1955) The effect of electrolyte concentration on soil permeability. *Journal of Soil Science* **6 (2)**: 163-178.

Raghunath HM (1987) *Groundwater* Wiley Eastern Ltd., Delhi, 563 p.

Rengasamy P, Sumner ME and Naidu R (1998) *Processes involved in sodic behaviour. Sodic Soil: Distribution, Properties, Management and Environmental Consequences*. Oxford University Press, New York. 35-50.

Rengasamy P and Marchuk A (2011) Cation ratio of soils structural stability (CROSS). *Soil Research* **49 (3)**: 280-285.

Rosenbrock HH (1960) An automatic method for finding the greatest or least value of a function. *Computer Journal* **3 (3)**: 175-184.

Rhoades JD (1983) Using saline water for irrigation. *Proc. Intern. Workshop Salt Affected Soils of Latin America, Maracay, Venezuela*. 233-264.

Shafiek CS, Al-Kaysi A. and Al-Mamooree DS (2015) Evaluation of theoretical basis used to create residual sodium carbonate (RSC) equation and the possibility of mg-carbonate minerals precipitation in soil. *IOSR Journal of Agriculture and Veterinary Science* **8 (4)**: 66-71.

Shainberg I and Letey J (1984) Response of soil to sodic and saline conditions. *Hilgardia* **52 (2)**: 1-57.

Shainberg I and Levy GJ (2005) *Flocculation and Dispersion. In: Hillel, D. (Ed-in-chief). Encyclopedia of Soils in the Environment*. Elsevier Ltd., Oxford, U.K. 2: 27-34.

Sharma, DP and Rao KVGK (1998) Strategy for long term use of saline drainage water for irrigation in semi-arid regions. *Soil and Tillage Research* **48 (4)**: 287-295.

Singh, RB, Minhas PS, Chauhan CPS and Gupta RK. 1992. Effect of high salinity and SAR waters on salinization, sodication and yield of pearl-millet and wheat. *Agricultural Water Management* **21 (1-2)**: 93-105.

Singh V, and Singh UC (2008) Assessment of groundwater quality of parts of Gwalior (India) for agricultural purposes. *Indian Journal of Science and Technology* **1 (4)**: 1-5.

Smith CJ, Oster JD and Sposito G. (2015) Potassium and magnesium in irrigation water quality assessment. *Agricultural Water Management* **157 (C)**: 59-64.

Suarez DL (1975) Precipitation of magnesium carbonates. *Annual Report of the U.S. Salinity Laboratory. USDA, Riverside, California*.

Suarez DL (1981) Relation between pH_c and Sodium Adsorption Ratio (SAR) and an alternate method of estimating SAR of soil or drainage waters. *Soil Science Society of America Journal* **45 (3)**: 469-475.

Szabolcs I and Darab C (1964) The influence of irrigation water on high sodium carbonate content of soils. In: *Proc. of 8th Int. Congress of ISSS, Transaction II*: 804-812.

US Salinity Laboratory Staff (1954) Diagnosis and Improvement of Saline and Alkali Soils. *Handbook No. 60*. USDA, Washington, DC. 160p.

WAPDA (1974) Water quality and soil. A note on soil studies. Monitoring and Planning Organization, Water and Power Development Authority (WAPDA) Pakistan.

Wilcox LV, Blair GY and Bower CA (1954) Effect of bicarbonates on suitability of waters for irrigation. *Soil Science* **77 (4)**: 259-266.

Yan S, Zhang T, Zhang B, Feng H, and Siddique KHM (2024). Calibration of saline water quality assessment standard based on EC and CROSS considering soil water-salt transport and crack formation. *Journal of Hydrology* **633**, p. 130975.

Zhang XC and Norton LD (2002) Effect of exchangeable Mg on saturated hydraulic conductivity, disaggregation and clay dispersion of disturbed soils. *Journal of Hydrology* **260 (1-4)**: 194-205.

Zhu, Y, Ali A, Dang A,Wandel, AP and Bennett JM (2019) Re-examining the flocculating power of sodium, potassium, magnesium and calcium for a broad range of soils. *Geoderma* **352**: 422-428.

Received: October 10, 2024; Accepted: October 22, 2024

Journal of Soil Salinity and Water Quality 16(2), 207-218, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.157117

Crop Improvement Strategies for Addressing Waterlogging and Salinity in Coastal Ecosystems

Devika Sellathdurai[1]*, Dhiman Burman[1], Uttam Kumar Mandal[1], Tashi Dorjee Lama[1], NR Prakash[2], Lokeshkumar BM[2] and Sukanta K Sarangi[3]

[1]*ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town-743 329, West Bengal*
[2]*ICAR-Central Soil Salinity Research Institute, Karnal-132001, Haryana*
[3]*ICAR-Central Institute for Women in Agriculture, Bhubaneswar-751003, Odisha*
**Corresponding author's Email: devika.s@icar.gov.in*

Abstract

Rice is the predominant crop in coastal regions and serves as a vital source of livelihood and income security for millions of people residing in these areas. However, coastal regions are highly vulnerable to climate change and face numerous abiotic stresses, including soil and water salinity, erratic rainfall, saline mangroves, heavy rainfall, prolonged dry spells, saline water intrusion, cyclonic disturbances, high temperatures, and high humidity. These challenges expose rice crops to both biotic and abiotic stresses, with the unpredictable and dynamic nature of these threats amplifying their impact. Coastal ecosystems play a crucial role in agricultural production, but they are increasingly at risk due to waterlogging and salinity caused by rising sea levels, extreme weather events, and human interventions. Currently, nearly 200 million people live in coastal areas that are less than 5 meters above mean sea level (MSL), a number that is projected to rise due to the ongoing effects of climate change, including increasing soil salinity, seawater intrusion, soil pollution, and the use of low-quality water. By the end of this century, the population in coastal regions may reach 400-500 million. Since rice is often the only crop cultivated in these areas, providing a lifeline to millions of resource-poor farmers in stress-prone environments, it is essential that crop improvement efforts for rice in coastal regions be given higher priority. This review examines the crop improvement strategies aimed at addressing these challenges, with a focus on genetic, biotechnological, and management approaches. Advances in breeding for salt-tolerant and waterlogging-tolerant rice varieties, along with the use of molecular markers and gene-editing technologies, offer promising solutions. By integrating these strategies with sustainable agronomic practices, it is possible to enhance crop resilience and ensure food security in coastal regions affected by salinity and waterlogging stress.

Key words: water logging, salinity, Physiological strategy, Breeding strategy, Coastal region

Introduction

Coastal ecosystems, known for their fertile soils and favourable climates, are vital to agricultural production globally. However, these regions are increasingly facing threats from waterlogging and salinity, exacerbated by climate change, sea-level rise, and inadequate drainage systems. Such challenges diminish crop productivity and pose significant risks to the livelihoods of millions of farmers who rely on these ecosystems for their sustenance. Asian deltas, among the most densely populated areas worldwide, are particularly susceptible to these issues. Characterized by low elevations, high rainfall, and significant sediment deposition, these regions are experiencing pervasive salinization, which impacts both agriculture and ecosystem health (Rahman *et al.,* 2019). The Bengal Delta in Bangladesh serves as a critical case study, home to approximately 30 million people who are increasingly exposed to rising salinity levels in water and soil resources. This trend threatens essential ecosystem services and human welfare (Feist *et al.*, 2023; Rahman and Ahmad 2018). Recent studies indicate a stepwise increase in salinity within the tidal river channels characteristic of the Bengal Delta, particularly during the period from 2006 to 2007 (Sherin *et al.*, 2020). Projections suggest that this increase will continue, with saline water anticipated to penetrate further inland over the next century (Akter *et al.*, 2019). A survey conducted in 2009 revealed that approximately

10,560 km² of cultivable land is affected by salinisation, marking a 26% increase since 1973 (SRDI 2010). Furthermore, climate modeling predicts a 39% rise in salt accumulation by 2050 (Mainuddin *et al.*, 2021), which may lead to a decline in agricultural yields by 25 to 50% by 2098 (Clarke *et al.*, 2015). Given these alarming trends, the development of crop improvement strategies aimed at enhancing tolerance to waterlogging and salinity has become critical for sustainable agriculture in coastal regions. This review will explore the current strategies and advancements in crop improvement that address these pressing challenges, highlighting their potential to secure agricultural productivity and livelihoods in vulnerable coastal ecosystems.

Understanding waterlogging and salinity stress

Waterlogging stress

Waterlogging, caused by excessive soil moisture, leads to oxygen deficiency in the root zone, impairing root respiration, nutrient uptake, and overall plant growth. This condition is common in saline areas with shallow water tables or poor drainage systems (Saleh *et al.*, 2013). Under waterlogged conditions, the lack of oxygen leads to hypoxia, triggering the accumulation of ethylene and anaerobic metabolites. This reduction in oxygen significantly lowers ATP production in plant roots, dropping from 38 mol under aerobic conditions to just 2 mol in anaerobic conditions, thereby severely impairing plant metabolism (Armstrong and Drew, 2002). Waterlogged soils take several days to become fully hypoxic, during which plant growth and physiological processes are already disrupted. This results in reduced root and shoot development, increased root senescence, and impaired solute movement and membrane functions (Barrett-Lennard, 1983).

Waterlogging and salinity often coexist in coastal ecosystems, compounding stress on plants. Waterlogged soils can exacerbate salt stress by increasing Na^+ and Cl^- ion transport to plant shoots. This elevated ion concentration initially results from increased ion uptake but later from reduced shoot growth. High levels of Na+ and Cl^- negatively affect plant growth, survival, and productivity, making the management of salt-affected lands even more complex (Barrett-Lennard, 2003). Understanding these interactions is crucial for developing strategies to mitigate the combined effects of waterlogging and salinity, including the breeding of salt- and waterlogging-tolerant crops, and improving soil and water management in coastal regions.

Salinity stress arises from the accumulation of soluble salts in soil, impairing water uptake by plants due to osmotic stress and leading to ion toxicity and nutrient imbalances. Globally, over 1.1 billion hectares of land are affected by salinity, with the number increasing by 1.5 million hectares annually (Roy *et al.*, 2019). This issue affects over

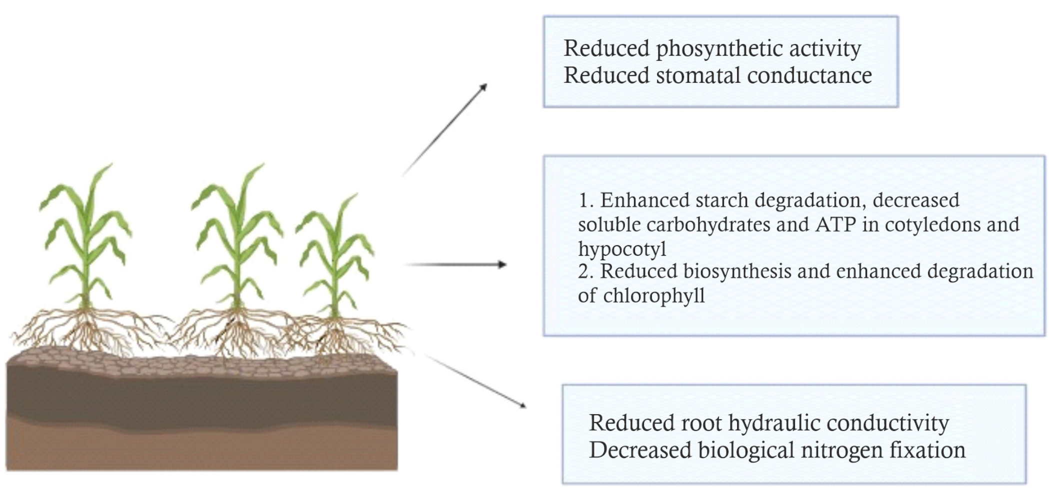

Fig. 1 The effect of water logging stress on plant growth and development

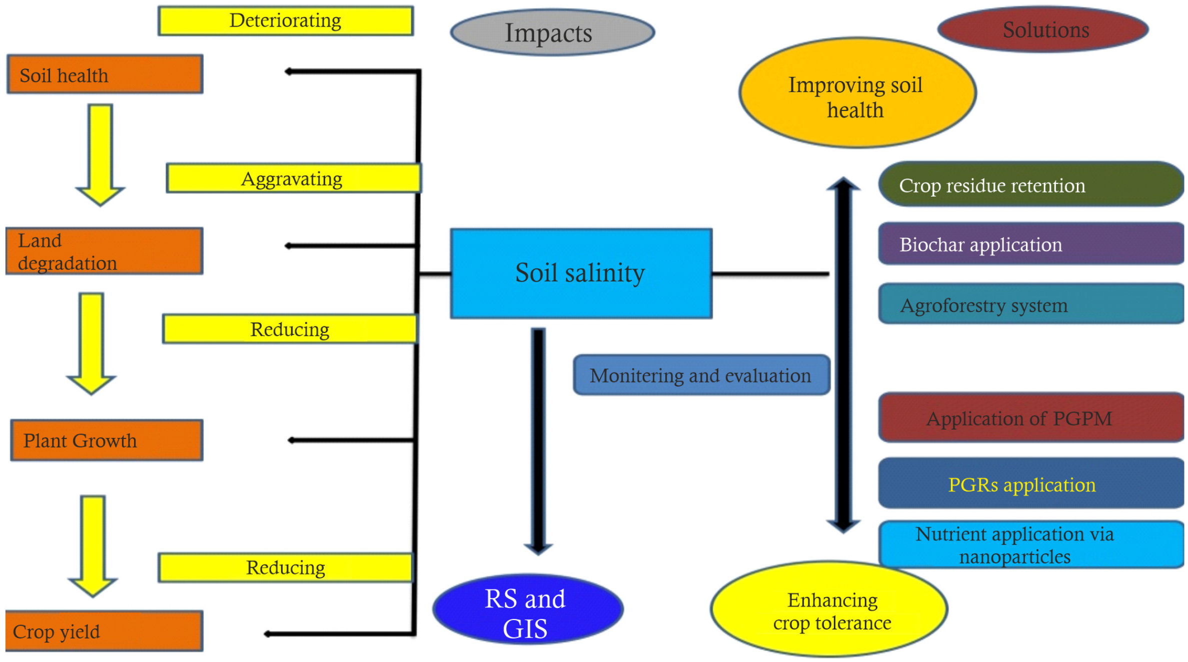

Fig. 2 Schematic representation of the effects of salinity stress

6% of the world's land area and 20% of irrigated croplands, with arid and semi-arid regions being particularly vulnerable (Parihar *et al.*, 2015). In India, around 7.5 million hectares are impacted, predominantly in northern, central, and northeastern regions (Kumar & Sharma, 2020). As the global population is projected to reach 9.7 billion by 2050, ensuring food security will require a 1.7-fold increase in crop yields (Yadav, 2020). Saline soils, rich in salts like sodium, magnesium, and calcium chlorides and sulfates, negatively impact plant growth by lowering water potential and inducing ion toxicity (Bharti *et al.*, 2016). These conditions disrupt germination, growth, photosynthesis, and nutrient uptake, reducing crop yields. The extent of damage varies depending on crop type, growth stage, and salinity tolerance (Qin *et al.*, 2016). Furthermore, soil microbial activity, crucial for processes like nitrogen transformation and residue decomposition, is impaired, leading to further declines in soil fertility (Ismayilov *et al.*, 2021). Plants employ adaptive mechanisms such as ion exclusion through selective root uptake and the synthesis of compatible solutes like proline and glycine betaine to maintain cellular homeostasis (Hossain *et al.*, 2011). Plant growth-promoting rhizobacteria (PGPR) also play a vital role in alleviating stress by improving nutrient uptake, supporting nitrogen fixation, and regulating stress-responsive genes (Timmusk *et al.*, 2014). Traditional methods like leaching and surface scraping are often impractical in water-scarce areas, making sustainable remediation strategies critical. Adding organic matter improves soil structure, aeration, and fertility, converting saline soils into more productive environments (Mahmoud *et al.*, 2011). Advances in crop breeding and biotechnology, including CRISPR and marker-assisted selection, offer promising solutions for developing salt-tolerant crop varieties, essential for future agricultural resilience.

Crop improvement strategies of water logging condition in coastal region

Nutrient application and waterlogging stress mitigation

Nutrient deficiency, a major consequence of waterlogging, leads to reduced photosynthesis, decreased carbon fixation, and a subsequent decline in plant growth and yield (Bange *et al.*, 2004). Applying essential nutrients, particularly nitrogen, can mitigate these effects and enhance productivity (Noreen *et al.*, 2018). Enhanced-efficiency nitrogen fertilizers like slow-release (SR) and controlled-release (CR) fertilizers are critical for supporting plant growth under waterlogged conditions by providing a steady nitrogen supply synchronized with crop demand, thereby maximizing nitrogen-use efficiency (NUE) (Trenkel, 2010; Varadachari and Goertz, 2010). Waterlogged soils restrict root growth and nutrient uptake by reducing oxygen availability, causing membrane potential loss and limiting the absorption of essential cations, such as potassium and ammonium (Gill *et al.*, 2018). Exogenous fertilizers, particularly SR/CR types, help plants recover under hypoxic conditions, improving yields in crops like barley, wheat, maize, and cotton (Pang *et al.*, 2007b; Zheng *et al.*, 2017; Rao *et al.*, 2002; Li *et al.*, 2013). Studies in Australia and India show that CR urea application significantly boosts wheat grain yield under waterlogged conditions (Robertson *et al.*, 2009; Mondal *et al.*, 2018), while polyolefin-coated urea in Colorado increased nitrogen recovery in barley (Saito *et al.*, 2001). These fertilizers extend canopy duration, boost photoassimilate production, and enhance the harvest index (Kisaakye *et al.*, 2017). Potassium and phosphorus applications further restore ionic balance and optimize yields, particularly in sugarcane, rapeseed, and flooded paddy fields (Ashraf *et al.*, 2011; Masunaga & Marques Fong, 2018). However, the widespread use of fertilizers to counter waterlogging is hindered by concerns about tissue toxicity—such as manganese toxicity—and nutrient imbalances that can disrupt soil ecology (Silva *et al.*, 2017; Jackson & Ricard, 2003). Unpredictable waterlogging events and the difficulty in estimating crop nitrogen demand also limit SR/CR fertilizer effectiveness. Pre-waterlogging nitrogen applications often lead to leaching losses, while post-waterlogging applications can be inefficient due to ongoing root damage (Robertson *et al.*, 2007). In crops like cotton, excessive nitrogen can cause vegetative overgrowth, complicating harvests (Najeeb *et al.*, 2015).

Plant growth regulators (PGRs) and waterlogging stress mitigation

Plant growth regulators (PGRs) play a significant role in mitigating waterlogging damage when applied at the correct growth stage (Nguyen *et al.*, 2018; Ren *et al.*, 2018). Auxins, such as 1-naphthaleneacetic acid (1-NAA), promote adventitious root development under hypoxic conditions, enhancing oxygen absorption in crops like barley (Pang *et al.*, 2007b). Cytokinins, like 6-benzyladenine (6-BA), have been shown to improve nutrient translocation and root growth, leading to higher yields in waterlogged maize (Ren *et al.*, 2016, 2018). Abscisic acid (ABA) enhances photosynthetic efficiency and water management, as demonstrated in cotton under pre-waterlogging conditions (Pandey *et al.*, 2002; Kim *et al.*, 2018). Triazoles, such as paclobutrazol and uniconazole, also mitigate oxidative stress and enhance chlorophyll content in canola and sweet potato (Lin *et al.*, 2006; Leul & Zhou, 1998, 1999). However, despite the potential of PGRs, their commercial application remains limited due to inconsistent results across different crop species and environmental conditions (Rademacher, 2015). Timing, dosage, and crop-specific responses significantly affect their effectiveness, and more research is needed to optimize these factors.

The combined application of fertilizers and PGRs offers a promising strategy for mitigating waterlogging damage. Fertilizers replenish depleted nutrients while PGRs alleviate physiological stress. For instance, combining 1% urea, 0.5% potassium chloride, and growth regulators like brassinolide and diethyl aminoethyl hexanoate significantly improved the growth and yield of waterlogged cotton (Li *et al.*, 2013). This dual approach addresses both nutrient deficiencies and hormonal imbalances, enhancing recovery from waterlogging stress. Anti-ethylene agents like 1-methylcyclopropene (1-MCP) and amino-ethoxyvinylglycine (AVG) reduce ethylene accumulation, which leads to premature fruit abscission in cotton (Shabala, 2011; Najeeb *et al.*, 2018). Studies show that 1-MCP and AVG improved seed and lint yields when applied during early reproductive phases (Brito *et al.*, 2013; Kawakami *et al.*, 2010). Hydrogen peroxide (H_2O_2) pre-treatment is emerging as another potential method for enhancing waterlogging tolerance by acting as a signaling molecule to manage oxidative stress, though more research is required to validate its effectiveness across different crops.

Use of tolerant species and varieties

Developing crop varieties with enhanced waterlogging tolerance offers a cost-effective and sustainable strategy to address the negative impacts of this stress (Zhou, 2010; Tewari & Mishra, 2018; Wani *et al.*, 2018). Genetic variation for waterlogging tolerance has been identified in crops like barley (Takeda & Fukuyama, 1986; Pang *et al.*, 2004; Zhang *et al.*, 2015) and wheat (Davies and Hillman, 1988; Herzog *et al.*, 2016; Nguyen T.N. *et al.*, 2018). However, waterlogging tolerance is a complex trait governed by multiple physiological and genetic mechanisms, including the formation of root aerenchyma, which facilitates oxygen transport under hypoxic conditions (Pujol and Wissuwa, 2018). Other mechanisms include ion homeostasis and the regulation of reactive oxygen species (ROS) to prevent oxidative damage (Gill *et al.*, 2018). Breeding programs aim to identify and pyramid quantitative trait loci (QTL) linked to these tolerance traits, such as improved root aerenchyma formation and ROS regulation, to develop waterlogging-tolerant cultivars. The polygenic nature of waterlogging tolerance presents a challenge, but advancements in molecular breeding techniques, such as marker-assisted selection (MAS) and genome editing, offer new opportunities to accelerate progress. MAS allows breeders to select plants with desirable tolerance traits by identifying molecular markers linked to QTLs, while genome editing tools like CRISPR-Cas9 provide precision in introducing waterlogging tolerance genes into commercial varieties (Gill *et al.*, 2018). These innovations hold significant potential for improving the resilience of staple crops, particularly in flood-prone regions, thereby contributing to increased yields and enhanced food security under changing climate conditions. Moving forward, research should focus on refining phenotyping methods and leveraging genome-editing tools to rapidly introduce waterlogging tolerance genes. With a stronger focus on genetic solutions, breeders can better equip agriculture to cope with waterlogging stress in the future.

Crop improvement strategies for salinity in coastal eco system

Possible physiological adaptations to the waterlogging/salinity interaction

Although the evidence is still emerging, the literature suggests several strategies that plants might adopt to regulate salt transport under the combined stress of waterlogging and salinity. First, plants can avoid hypoxia through the formation of aerenchyma, which facilitates oxygen transport to roots under waterlogged conditions, while the development of a well-formed endodermis helps to regulate ion uptake and transport, limiting salt intrusion (Pujol and Wissuwa, 2018). Additionally, plants can reduce stomatal conductance to minimize water loss and stress.

Table 1. The role of biochar in improving crop tolerance to salinity stress when applied alone or combination

Biochar treatment	Crop	Effect of biochar treatment on salt stress	Reference
Biochar as surface amendment	*Abuliton theophrast* and *prunella vulgaris*	Completely eliminated salt-induced mortality in both plants and significantly increased the biomass of *P. vulgaris* by 50% compared to untreated controls	Thomas *et al.* (2013)
Biochar	Potato	Enhanced shoot and root traits while decreasing Naz /Kz ratios in the xylem and lowering ABA concentrations in the leaves	Akhtar *et al.* (2015a)
Biochar with plant-growth stimulating endobacteria	Maize	Reduced Naz uptake and enhanced the nutrient status of the plants.	Akhtar *et al.* (2015)
Biochar poultry manure mix with pyroligneous fluid	Maize crop	Significant increases in carbon and nitrogen levels, both in bulk soil and rhizopheric soil, resulted from the application of the amendments.	Lu *et al.* (2015)
Biochar coupled with arbuscular mycorrhizae	Lettuce	Enhanced phosphorus (P) and manganese (Mn) uptake in lettuce through combined application	Hamner *et al.* (2015)

Finally, plants may implement salt removal strategies, such as salt exclusion, compartmentalization within vacuoles, or secretion through salt glands, to protect metabolic processes and mitigate ion toxicity.

Advanced approaches toward salinity management

One promising approach to managing salinity stress is the regulation of abscisic acid (ABA) and stomatal conductance. Increased stomatal conductance and reduced ABA levels have been correlated with biochar-mediated enhancement of plant growth under salt stress. Studies in crops like tomato and wheat have shown that biochar application improves stomatal conductance, likely due to its positive effects on soil structure and moisture retention (Akhtar *et al*., 2015b). Additionally, biochar application has been found to lower ABA levels, especially when combined with plant growth-promoting rhizobacteria (PGPR) under salinity stress, further promoting plant growth and development (Akhtar, 2015a; Hafez *et al*., 2019). However, these effects may vary depending on the soil type, highlighting the need for further research.

Improving ionic balance in the soil environment: Reduction in Na+ toxicity

Excess salt, particularly sodium (Na^+), disrupts the ionic balance in plants, leading to soil degradation and toxicity. Sodium ions replace essential calcium ions in soil, reducing cation exchange capacity (CEC) and negatively impacting soil aggregate stability, hydraulic conductivity, and surface permeability (Sun *et al*., 2020). This contributes to soil erosion and further stresses plant growth. Biochar, with its high CEC and salt sorption capacity, offers a cost-effective solution to mitigate soil salinity. When applied in proper doses and combinations, biochar can reduce Na+ uptake by plants, thereby alleviating toxicity (Liang *et al*., 2010; Kim *et al*., 2016). Studies have demonstrated biochar's effectiveness in improving soil structure and reducing Na^+ absorption in crops (Thomas *et al*., 2013; Lashari *et al*., 2015).

Effect on the properties of saline soil

Biochar not only mitigates the direct effects of salinity on plants but also enhances the overall physical and chemical properties of saline soils.

Table 2. Effect of salinity on various physiological, morphological traits and crop yield

Morpho-physiological traits	Experiment	Crop	Effect of salinity on the trait	Reference
Seeed germination	Peteri plates	Lasiurus scindicus	Seedling germination was completely inhibited at a NaCl concentration of 200 mM.	Mallik *et al*., 2023
Photosynthetic activity	Petri plates	Lasiurus scindicus	chlorophyll content decreased by 90% in the presence of a 150 mM NaCl solution and became almost undetectable at higher NaCl concentrations.	Malik *et al*., 2023
Plant growth	Pot experiment	Latuca sativa	After 21 days of exposure to 100 mM, 200 mM, and 500 mM NaCl treatments, there was a significant reduction in root length, shoot length, and leaf number.	Ahmend *et al*., 2022
Nutrient uptake	Laboratory study	Genotypes of rice (IR28, cheongmyeong, Nagdong	A significant reduction in the concentrations of key ions (K+, Ca2+, Zn, and Mg) was observed with the application of 150 mM NaCl, compared to MgCl2 and $CaCl_2$ at the same concentration	Farooq *et al*., 2022
Crop yield	Field study	Oryza sativa	The crop yield decreased by 50% at an electrical conductivity of 6 dS m^{-1} compared to 0 dS m^{-1}	Khan *et al*., 2022

By improving soil cation exchange capacity (CEC), enhancing soil structure, and fostering beneficial microbial communities, biochar plays a vital role in restoring soil health in salinity-affected regions. Additionally, it aids in sodium ion (Na^+) removal, creating a more favorable environment for crop growth under salinity stress (Sun *et al.*, 2016).

Furthermore, biochar has emerged as a promising soil amendment for alleviating salinity stress and promoting plant growth. One of its critical functions is the regulation of abscisic acid (ABA) and stomatal conductance. Studies indicate that biochar application improves stomatal conductance in crops such as tomato and wheat under salt stress, facilitating better gas exchange and water regulation (Akhtar *et al.*, 2015b). Biochar also reduces ABA levels, supporting root hydraulic conductivity and osmotic adjustment, which enables plants to cope with saline conditions. However, the efficacy of these effects can vary based on soil type, biochar properties, and its synergistic interactions with plant growth-promoting rhizobacteria (PGPR), further enhancing plant resilience under stress (Hafez *et al.*, 2019).

Additionally, biochar mitigates Na^+ toxicity by improving ionic balance in saline soils. Excess sodium ions can displace essential nutrients, degrade soil structure, and reduce hydraulic conductivity, ultimately leading to soil erosion and poor crop performance. Due to its high salt sorption capacity and ability to enhance CEC, biochar helps restore soil balance by limiting Naz uptake and maintaining nutrient availability for plants (Thomas *et al.*, 2013; Sun *et al.*, 2020). This process contributes to improved soil health and reduced salinity stress on crops. Moreover, biochar enhances soil properties by increasing organic matter content and enzymatic activities, particularly when combined with organic matter, compost, or fulvic acid. This combination not only improves soil structure and nutrient retention but also boosts water-holding capacity, fostering an environment conducive to robust plant growth even under saline conditions (Sun *et al.*, 2020). The effectiveness of biochar can be significantly enhanced when combined with other soil amendments, though it is crucial to optimize application rates and methods for maximum benefit.

Exogenous application of osmolytes, osmoprotectants, and PGRs

Osmoprotectants

Overproduction of compatible organic solutes, known as osmoprotectants, is a common adaptive response in plants subjected to various stressors, including salinity, drought, and heat (Serraj and Sinclair, 2002). These low molecular weight compounds, such as proline, sucrose, polyols, trehalose, and quaternary ammonium compounds like glycine betaine (GB), accumulate without disrupting cellular functions. They help plants manage stress by facilitating osmotic adjustment, neutralizing reactive oxygen species (ROS), protecting cellular membranes, and stabilizing proteins (Ashraf and Foolad, 2007; Bohnert and Jensen, 1996; Yancey *et al.*, 1982). Although genetic engineering to enhance osmoprotectant production has had limited success, the exogenous application of these solutes shows promise in improving stress tolerance across various crops. For instance, glycine betaine can mitigate the adverse effects of salt stress when applied externally, leading to improved plant growth and overall stress tolerance (Agboma *et al.*, 1997; Makela *et al.*, 1998a). Proline stabilizes cellular structures and scavenges free radicals during stress, contributing to enhanced resilience (Hare and Cress, 1997). Additionally, polyamines like spermidine stabilize subcellular components and membranes, further aiding in stress tolerance (Bouchereau *et al.*, 1999).

Plant growth regulators (PGRs)

Plant growth regulators such as salicylic acid (SA) has been shown to alleviate salt stress in crops like barley and wheat, enhancing their growth under saline conditions (El-Tayeb, 2005; Khodary, 2004). Other compounds, including jasmonic acid, thiamin, and 5-aminolevulinic acid (5-ALA), exhibit potential for improving stress tolerance. However, further research is required to elucidate their specific mechanisms of action and effectiveness (Tsonev *et al.*, 1998; Sayed and

Gadallah, 2002; Yoshida *et al*., 1996). Exogenous application methods, such as foliar sprays, are often practical and cost-effective for enhancing crop growth in saline environments. Nonetheless, optimal application strategies may vary by plant species, stress type, and environmental conditions.

Nutrient management

Effective nutrient management is critical in mitigating salt-induced growth inhibition, as nutrient uptake is controlled by membrane transporters, including Ca^{2+} -ATPases, K^+ channels, and transporters for nitrate, ammonium, and sulfate (Epstein and Bloom, 2005; Marschner, 1995; Tester and Davenport, 2003). Research indicates that salt-induced nutrient deficiencies may arise from Na-induced inhibition or reduced activity of essential transporters (Maathuis and Amtmann, 1999; Qi and Spalding, 2004; Rus *et al*., 2004; Tester and Davenport, 2003). These deficiencies can be countered by supplementing mineral nutrients in the growth medium. For example, nitrogen (N) supplementation has enhanced growth and yield in crops like maize (Ravikovitch, 1973), tomato (Papadopoulos and Rendig, 1983), grapes (Taylor *et al*., 1987), and apple (El-Siddig and Ludders, 1993). Champagnol (1979) reported that 34 out of 37 studies demonstrated increased crop growth and yield with phosphorus (P) addition to saline soils. In tomatoes, Awad *et al*. (1990) found that phosphorus addition improved salt tolerance across a range of salinity levels (10–100 mM NaCl). Calcium (Ca) is another essential nutrient that mitigates the effects of salinity by enhancing K^+/Na^+ selectivity (Hasegawa *et al*., 2000). Ebert *et al*. (2002) observed that root application of 10 mM Ca^{2+} as $Ca(NO_3)_2$, alleviated salt-induced growth inhibition by increasing leaf K^+ and Ca^{2+} concentrations while decreasing leaf Naz levels. Similarly, Arshi *et al*. (2006) reported that 10 mM Ca^{2+} supplementation improved photosynthetic capacity in *Cassia angustifolia* by regulating stomatal function.

Furthermore, potassium (K^+) supplementation can alleviate the adverse effects of salt stress in various crops such as tomato, maize, sunflower, and beans (Grattan and Grieve, 1999). These studies suggest that increasing macronutrient levels can be an effective strategy to mitigate the harmful effects of salt stress on plant growth.

Foliar application of micronutrients

While nitrogen (N), phosphorus (P), and potassium (K) are primarily absorbed through plant roots, they can also be absorbed through leaves, bypassing the cuticle barrier (Taiz & Zeiger, 2002). Foliar application is especially beneficial when soil conditions limit root nutrient uptake. Under saline conditions, the uptake of K^+, Ca^{2+}, and N through roots is often impaired, reducing plant growth. Foliar application can enhance nutrient absorption, alleviate physiological disorders, and improve growth and yield. The effectiveness of foliar fertilization depends on nutrient mobility within the plant. Nutrients like N, K, and magnesium (Mg) are more mobile in the phloem, making them more effective when applied to foliage, while calcium (Ca) and iron (Fe) are less mobile and less effective. Potassium is essential for many physiological functions, including enzyme activation, stomatal regulation, and photosynthesis, making foliar K^+ applications useful under salt stress. For example, KH_2PO_4 foliar spraying has been shown to correct P and K^+ deficiencies in salt-stressed crops like strawberries, tomatoes, and spinach, improving the K^+/Na^+ ratio and reducing salt-induced growth inhibition. Foliar application of KNO_3 has also been found to reduce salt toxicity in *Lagenaria siceraria*, increasing fruit yield by 76.9% per plant and enhancing growth in salt-stressed sunflower. Understanding how stress affects foliar nutrient levels and their role in stress resistance is critical. While nutrients can help mitigate stress, ion antagonism during nutrient uptake may reduce their effectiveness. For example, while foliar-applied K^+ did not enhance overall macronutrient accumulation under salt stress, it helped partition Na^+ to the roots, protecting photosynthetic tissues and improving chlorophyll levels and membrane permeability. Variability in K^+ accumulation may result from differences in nutrient sources, plant species, and application conditions.

Breeding for Salt Tolerance

Breeding for salt tolerance is essential for sustainable agriculture and food security, especially given the increasing challenges of climate change and soil salinity. Developing salt-tolerant crops involves complex molecular, biochemical, and physiological responses at various stages of plant development. Conventional breeding has made progress in identifying salt-tolerant lines; however, limited genetic variation within crop gene pools and challenges like reproductive barriers and unintended transfer of undesirable traits have hindered substantial advancements in salt tolerance (Ashraf, 1994a; Chinnusamy *et al.*, 2005). To overcome these challenges, utilizing wild relatives of crops to introduce salt tolerance genes shows potential but is complicated by reproductive barriers. Modern breeding techniques such as somaclonal variation, protoplast fusion, and mutation breeding provide promising alternatives when genetic variability for salt tolerance is lacking. For instance, gamma radiation-induced rice mutants at NIAB in Pakistan exhibited higher yields under saline conditions compared to their salt-tolerant parent varieties (Akhtar, 2015). In barley, studies of semidwarfing genes for salt tolerance revealed that the gamma-ray-induced mutant Golden Promise exhibited significant salt stress tolerance, while other mutants did not, indicating that salt tolerance is not a universal trait among semidwarfs but is specific to certain mutations (Forster, 2001). Researchers have successfully identified moderately salt-tolerant rice lines at the seedling stage from gamma-ray-mutagenized cultures in the M2 generation. Chemical mutagens have also proven effective; for example, Ashraf (1984) induced salt tolerance in the rice cultivar Taichung 65 using N-methyl-N-nitrosourea, resulting in two mutants with high survival rates in saline conditions. Additionally, insertional mutagenesis in Arabidopsis has been instrumental in studying genes regulating hormone responses like auxins and abscisic acid, which are critical for plant growth and development (Ahloowalia & Maluszynski, 2001). While insertional mutagenesis is resource-intensive, radiation and chemical mutagenesis offer more efficient alternatives, despite the randomness of the mutations. Genetic markers like RAPD, AFLP, and SSR can help identify and study valuable mutations, providing new opportunities to enhance crop yields in salt-affected regions (Lema-Ruminska *et al.*, 2004; Fageria *et al.*, 2012). Future research should focus on integrating genomic technologies and precision breeding methods to further improve salt tolerance in crops, addressing the growing challenges posed by salinity in agricultural systems.

Advancements in molecular breeding for salt tolerance

Over the past two decades, advancements in molecular marker technology have revolutionized crop improvement efforts, especially in developing stress-tolerant varieties to combat increasing soil salinity (Vinh & Paterson, 2005). DNA markers have become indispensable for identifying genotypes with enhanced stress tolerance traits, significantly accelerating the development of commercially viable cultivars. Given the complex nature of abiotic stress tolerance, quantitative trait locus (QTL) mapping has emerged as a critical tool. This technique uses DNA markers to isolate and evaluate the genetic contributions of specific loci, enabling a more precise assessment of stress tolerance traits across multiple crops. Several types of DNA markers, including restriction fragment length polymorphisms (RFLPs), random amplified polymorphic DNAs (RAPDs), amplified fragment length polymorphisms (AFLPs), simple sequence repeats (SSRs), and single nucleotide polymorphisms (SNPs), have been employed in the study of abiotic stress inheritance. These markers provide valuable insights into the genetic architecture underlying stress responses, facilitating the identification of key loci involved in stress tolerance. One notable advancement in this field is the development of "transposon display," a technique that offers near-complete genome coverage or chromosome-specific targeting, allowing researchers to capture a broader spectrum of genetic variation (Casa *et al.*, 2000). By combining DNA markers with QTL analysis, researchers are now better equipped to dissect complex traits, significantly improving the precision and efficiency of breeding programs aimed at enhancing stress tolerance in crops such as rice, wheat, and maize (Duncan & Carrow, 1999).

Molecular breeding for salt tolerant

QTL mapping and marker-assisted selection (MAS) offer significant advantages over traditional phenotypic screening methods by reducing the influence of environmental variability and enhancing the precision of genotype analysis. Salt tolerance is a highly complex trait influenced by both additive and dominance effects (Ashraf, 1994a; Batool, 2014). Studies have identified numerous QTLs associated with salt tolerance in crops such as citrus, rice, and barley. For instance, in rice, seven QTLs linked to seedling salt tolerance were identified, with four located on chromosome 6 (Prasad *et al.*, 2000a). Notably, QTLs associated with salt tolerance vary across different growth stages, further highlighting the complexity of breeding for this trait. MAS, enabled by advances in molecular biology, allows breeders to more effectively stack desirable traits, thus improving stress resilience. This precision breeding technique significantly reduces the time and resources required compared to conventional breeding approaches. However, due to the intricate nature of salt tolerance mechanisms, integrating QTL mapping with MAS continues to be an area of active research, particularly in crops like rice, wheat, and barley.

Improving crop salt tolerance through transgenic approaches

Transgenic crops, or genetically modified organisms (GMOs), are engineered to incorporate specific genes that enhance stress tolerance traits, such as salt tolerance. Improving this trait through genetic modification is challenging because of the multifaceted plant responses to salt stress. Salt tolerance mechanisms differ among plants, which are generally classified as halophytes (salt-tolerant) or glycophytes (salt-sensitive). Halophytes manage high salinity by accumulating salt in vacuoles and maintaining a favorable K^+/Na^+ ratio, whereas glycophytes focus on salt exclusion and osmotic balance (Munns & Tester, 2008; Flowers & Colmer, 2008). Recent advances have uncovered several key genes involved in plant stress responses, such as those encoding osmolytes (e.g., glycine betaine), transcription factors, antioxidants, and ion transport proteins (Zhang *et al.*, 2017; Shah *et al.*, 2020). For example, transgenic crops such as carrots and tomatoes expressing the betaine aldehyde dehydrogenase (BADH) gene have demonstrated enhanced salt tolerance (Zhou *et al.*, 2009). Similarly, rice plants overexpressing BADH showed improved ion selectivity under saline conditions (Wang *et al.*, 2015). Although the exact mechanisms by which glycine betaine regulates ion homeostasis remain under investigation, its role in improving K^+ retention and reducing salt-induced K^+ leakage is well-documented (Ashraf & Foolad, 2007). Further research suggests that exogenous application of glycine betaine can mitigate NaCl-induced stress by enhancing H^+ efflux, which contributes to a favorable pH gradient and supports cytosolic K^+ homeostasis (Tao *et al.*, 2020). This effect may be mediated by the activation of H^+-ATPase, an enzyme that regulates K^+ channels and maintains the electrochemical gradient needed for efficient ion transport (Zhao *et al.*, 2014). Additionally, salt stress has been shown to stimulate H^+-ATPase activity, thereby acidifying the external environment and facilitating Na^+ exclusion from the cytoplasm (Li *et al.*, 2017). These findings underscore the potential of transgenic and molecular approaches to enhance salt tolerance in crop species.

Conclusion

Crop improvement strategies for addressing waterlogging and salinity in coastal ecosystems have made considerable strides, but continued innovation and interdisciplinary collaboration are crucial. By integrating conventional breeding, biotechnological advances, and sustainable management practices, agriculture in coastal regions can be made more resilient, ensuring food security and sustainable livelihoods for millions of people dependent on these vulnerable ecosystems while significant progress has been made in developing stress-tolerant crops, challenges remain. The complex nature of waterlogging and salinity stress, coupled with the need for multi-stress tolerance, requires a holistic approach. Future research should focus on Multi-Disciplinary Collaboration: Collaboration between geneticists, agronomists, soil scientists, and environmentalists is essential for addressing the complex challenges of waterlogging and salinity. Climate-Smart Agriculture: Integrating climate-smart agricultural practices with crop improvement strategies can enhance the resilience of coastal agriculture to climate change-induced stresses. Farmer Participation: Engaging farmers in the development and dissemination of stress-tolerant varieties ensures the adoption of these technologies at the grassroots level.

References

Agboma P, Sinclair TR, Jokinen K, Peltonen-Sainio P and Pehu E (1997) An evaluation of the effect of exogenous glycine betaine on the growth and yield of soybean: timing of application, watering regimes and cultivars. *Field crops research* **54(1):** 51-64.

Ahloowalia BS, Maluszynski M, and Nichterlein K (2004) Global impact of mutation-derived varieties. *Euphytica* **135**: 187-204.

Ahmad R, and Jabeen R (2005) Foliar spray of mineral elements antagonistic to sodium-a technique to induce salt tolerance in plants growing under saline conditions. *Pakistan Journal of Botany* **37(4):** 913.

Ahmed HG, Zeng Y, Raza H, Muhammad D, Iqbal M, Uzair M, Sabagh A (2022) Characterization of wheat (Triticum aestivum L.) accessions using morpho-physiological traits under varying levels of salinity stress at seedling stage. *Frontiers in Plant Science* **13:** 953670.

Akhtar S, Niaz M, Zafar Iqbal M, Anwar Saeed M (2015) Comparison of wheat (triticum aestivum l.) some clones with their respective parents for salt tolerance. *Journal of Agricultural Research 53***(4):** *03681157.*

Akram NA, and Ashraf M (2011) Pattern of accumulation of inorganic elements in sunflower (Helianthus annuus L.) plants subjected to salt stress and exogenous application of 5-aminolevulinic acid. *Pakistan Journal of Botany* **43(1):** 521-530.

Akter R, Hasan N, Reza F, Asaduzzaman M, Begum K, and Shammi M (2023) Hydrobiology of saline agriculture ecosystem: A review of scenario change in south-west region of Bangladesh. *Hydrobiology* **2(1):** 162-180.

Anil VS, Krishnamurthy P, Kuruvilla S, Sucharitha K, Thomas G and Mathew MK (2005) Regulation of the uptake and distribution of Na+ in shoots of rice (Oryza sativa) variety Pokkali: role of Ca2+ in salt tolerance response. Physiologia Plantarum **124(4):** 451-64.

Arshi A, Abdin MZ, and Iqbal M (2006) Sennoside content and yield attributes of Cassia angustifolia Vahl. as affected by NaCl and CaCl2. *Scientia horticulturae* ***111*****(1):** 84-90.

Ashraf MF and Foolad MR (2007) Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environmental and Experimental Botany* **59(2):**206-216.

Awad AS, Edwards, DG and Campbell LC (1990) Phosphorus enhancement of salt tolerance of tomato. *Crop Science* **30(1):** 123-128.

Bang HW (2006) Nitrous oxide and methane in European coastal waters. *Estuarine, Coastal and Shelf Science* **70(3):** 361-374.

Bharti N, Pandey SS, Barnawal D, Patel VK and Kalra A (2016) Plant growth promoting rhizobacteria Dietzia natronolimnaea modulates the expression of stress responsive genes protecting wheat from salinity stress. *Scientific reports* **6(1):** 1-16.

Bohnert HJ, and Jensen RG. (1996) Strategies for engineering water-stress tolerance in plants. *Trends in biotechnology* **14(3):** 89-97.

Bonaglia S, Rütting T, Kononets M, Stigebrandt A Santos, IR and Hall PO (2022) High methane emissions from an anoxic fjord driven by mixing and oxygenation. *Limnology and Oceanography Letters* **7(5):** 392-400.

Bouchereau A, Aziz A, Larher F, Martin-Tanguy J (1999) Polyamines and environmental challenges: recent development. *Plant science* **140(2):** 103-125.

Cheng Z, Targolli J, Huang X, Wu, R (2002) Wheat LEA genes, PMA80 and PMA1959, enhance dehydration tolerance of transgenic rice (Oryza sativa L.). *Molecular Breeding* **10:** 71-82.

Chinnusamy V, Xiong L, & Zhu, J. K (2005) and Molecular Biology Approaches for Crop Improvement for Stress Environments. *Abiotic Stresses: Plant Resistance Through Breeding and Molecular Approaches* 1690.

Clarke D, Williams S, Jahiruddin M, Parks K, and Salehin M (2015) Projections of on-farm salinity in coastal Bangladesh. *Environmental Science: Processes & Impacts*. **17(6):** 1127-1136.

Cong P, Ouyang Z, Hou R and Han D (2017) Effects of application of microbial fertilizer on aggregation and aggregate-associated carbon in saline soils. *Soil and Tillage Research* **168:** 33-41.

Fageria NK, Stone LF, Santos ABD (2012) Breeding for salinity tolerance. *Plant breeding for abiotic stress tolerance.* 103-122.

Farooq F, Rashid N, Ibrar D, Hasnain Z, Ullah R, Nawaz M and Khan S (2022) Impact of varying levels of soil salinity on emergence, growth and biochemical attributes of four Moringa oleifera landraces. *PLoS One* **17(2):** 0263978.

Forster, B. P. (2001). Mutation genetics of salt tolerance in barley: an assessment of Golden Promise and other semi-dwarf mutants. *Euphytica* **120:** 317-328.

Huang M, Zhang Z, Sheng Z, Zhu C, Zhai Y, Lu, P, Brinkman, D (2019) Soil salinity and maize growth under cycle irrigation in coastal soils. *Agronomy Journal.* **111(5):** 2276-2286.

Kaur, G, Sanwal, SK, Sehrawat N, Kumar A, Kumar N, Mann, A (2022) Getting to the roots of Cicer arietinum L.(chickpea) to study the effect of salinity on morpho-physiological, biochemical and molecular traits. *Saudi Journal of Biological Sciences* **29(12):** 103464.

Kumar P, and Sharma PK (2020) Soil salinity and food security in India. *Frontiers in sustainable food systems*. **4:** 533781.

Mishra N, Jiang C, Chen, L, Paul A, Chatterjee A, Shen, G. (2023). Achieving abiotic stress tolerance in plants through antioxidative defense mechanisms. *Frontiers in Plant Science*.**14:** 1110622.

Misra, AN, Srivastava A, Strasser, R (2001) Utilization of fast chlorophyll a fluorescence technique in assessing the salt/ion sensitivity of mung bean and Brassica seedlings. *Journal of plant physiology*. **158(9):**1173-1181.

Munns R (2005) Genes and salt tolerance: bringing them together. *New phytologist*. **167(3):** 645-663.

Najib S, Fadili A, Mehdi K, Riss J, Makan A, Guessir, H (2016) Salinization process and coastal groundwater quality in Chaouia, Morocco. *Journal of African Earth Sciences*. **115:** 17-31.

Navarro JM, Martýìnez V, Carvajal M (2000) Ammonium, bicarbonate and calcium effects on tomato plants grown under saline conditions. *Plant Science*. **157(1):** 89-96.

Noreen S, Faiz S, Akhter MS, Shah KH (2019) Influence of foliar application of osmoprotectants to ameliorate salt stress in sunflower (Helianthus annuus L.). *Sarhad Journal ofAgriculture*. **35:** 1316-1325.

Oh DH, Lee SY, Bressan RA, Yun DJ, Bohnert HJ (2010) Intracellular consequences of SOS1 deficiency during salt stress. *Journal of Experimental Botany.* **61(4):** 1205-1213.

Ojja S, Kisaka S, Ediau M, Tuhebwe D, Kisakye AN, Halage AA, Mutyoba JN (2018) Prevalence, intensity and factors associated with soil-transmitted helminths infections among preschool-age children in Hoima district, rural western Uganda. *BMC infectious diseases*. **18:** 1-12.

Pang J, Cuin T, Shabala L, Zhou M, Mendham N, Shabala, S (2007) Effect of secondary metabolites associated with anaerobic soil conditions on ion fluxes and electrophysiology in barley roots. *Plant Physiology*. **145(1):** 66-276.

Panhwar NA, Buriro SA, Memon AH, Panhwar SA, Lahori AH (2021) Influence of salinity on germination and early seedling of five wheat (Triticum aestivum L) genotypes. *Pure and Applied Biology (PAB)*. **10(4):** 956-961.

Papadopoulos I, and Rendig VV (1983) Interactive effects of salinity and nitrogen on growth and yield of tomato plants. *Plant and Soil.* **7:** 47-57.

Prasad SR, Bagali PG, Hittalmani S, Shashidhar HE (2000) Molecular mapping of quantitative trait loci associated with seedling tolerance to salt stress in rice (Oryza sativa L.). *Current Science.* 162-164.

Qi Z and Spalding EP (2004) Protection of plasma membrane K+ transport by the salt overly sensitive1 Na+-H+ antiporter during salinity stress. *Plant Physiology*. **136(1):** 2548-2555.

Roy PR, Tahjib-Ul-Arif M, Polash MAS, Hossen MZ, Hossain MA (2019) Physiological mechanisms of exogenous calcium on alleviating salinity-induced stress in rice (Oryza sativa L.). *Physiology and Molecular Biology of Plants*. **25:** 611-624.

Zhang X, Fan Y, Shabala S, Koutoulis A, Shabala L, Johnson P, Zhou, M (2017) A new major-effect QTL for waterlogging tolerance in wild barley (H. spontaneum). *Theoretical and Applied Genetics*. **130:** 1559-1568.

Zhao C, Zhang Z, Xu J (2014) Betaine enhances H+-ATPase activity and K+ transport in wheat. *Plant Physiology and Biochemistry*. **84:** 87-95.

Zheng W, Xue D, Li, X, Deng, Y., Rui, J., Feng, K & Wang ZL (2017). The responses and adaptations of microbial communities to salinity in farmland soils: a molecular ecological network analysis. *Applied Soil Ecology*. **120:** 239-246.

Zhou M. (2010) Improvement of plant waterlogging tolerance. *Waterlogging signalling and tolerance in plants*, 267-285.

Zhou MX, Li HB Mendham NJ (2007) Combining ability of waterlogging tolerance in barley. *Crop Science*. **47(1):** 278-284.

Zhou S, Wang Z, Xu J (2009) Overexpression of the BADH gene in transgenic tomatoes enhances tolerance to salt stress. *Plant Cell Reports*. **28(7):** 927-934.

Received: September 25, 2024; Accepted: October 29, 2024

Journal of Soil Salinity and Water Quality 16(2), 219-233, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156476

Maneuvering Crop Wild Relatives to Revamp Salt Tolerance in Crops

Lokeshkumar BM[1#], Krishanu[1#], Anita Mann[1], Arvind Kumar[1], Ashwani Kumar[1], Satish Kumar Sanwal[1], Ravi Kiran KT[2], Sanchika Snehi[3], and Nitish Ranjan Prakash[1*]

[1]ICAR- Central Soil Salinity Research Institute, Karnal – 132001, Haryana, India
[2]ICAR-Central Soil Salinity Research Institute, RRS, Lucknow – 226002, Uttar Pradesh, India
[3]IAgS, Banaras Hindu University, Varanasi – 221005, Uttar Pradesh, India
**Corresponding author's E-mail: nitishranjan240@gmail.com*

Abstract

The increasing severity of soil salinization presents a major challenge to global agricultural productivity. Crop wild relatives (CWRs), as reservoirs of genetic diversity, offer a valuable source of salt tolerance traits that can be introgressed into cultivated crops. This review explores the potential of CWRs in improving salt tolerance through modern breeding techniques. It highlights recent advancements in marker-assisted selection (MAS), quantitative trait locus (QTL) mapping, and genome-wide association studies (GWAS) that have facilitated the identification of salt tolerance genes in CWRs. Technologies such as high-throughput sequencing, single-nucleotide polymorphism (SNP) platforms, and genome editing tools like CRISPR/Cas9 are discussed for their role in accelerating the discovery and integration of beneficial alleles from wild species. The review also addresses the barriers to CWR utilization, including the lack of comprehensive phenotypic and genotypic data, and outlines strategies for overcoming these challenges. With the growing availability of genomic resources and advanced biotechnological approaches, CWRs hold tremendous potential for enhancing salt tolerance and securing sustainable food production in saline environments.

Keywords: Salt-tolerant crops, Crop wild relatives, Salt-tolerant donors, Pre-breeding

Introduction

Soil salinization presents a formidable challenge to agriculture, particularly in arid and semi-arid regions where high salt concentrations significantly impact crop growth and yield. This issue is exacerbated by the often high costs and limited effectiveness of current soil management and remediation strategies, which frequently fail to provide a permanent solution to salinity problems (Munns and Tester, 2008). As a result, there has been a growing emphasis on understanding and enhancing the salt tolerance of crops through various genomic and breeding approaches. These approaches leverage both natural evolutionary adaptations and advances in agricultural science to improve crop performance under saline conditions. Recent extensive reviews of the salt tolerance literature reveal that most crops can tolerate salinity up to a certain threshold level while increasing level of salinity impacting various growth stages are becoming crucial in the era of climate change. Beyond this threshold, however, yields tend to decline linearly with increasing salt concentrations. This relationship between salinity levels and yield reduction has been quantified for a variety of crops, providing important benchmarks for evaluating and improving salt tolerance (Flowers and Yeo, 1995). For example, threshold salinity levels and the rate of yield decrease per unit increase in salinity have been estimated for numerous crops, offering a critical understanding of how different plants respond to saline stress (Munns, 2002).

Several factors influence a plant's ability to tolerate salt, including soil characteristics, water availability, and environmental conditions. Plant,

[#]both the authors have contributed equally and hence are first author.

soil, and water factors all play a role in determining how well a crop can withstand saline environments, making it crucial to consider these elements when developing strategies to enhance salt tolerance (Kramer and Boyer, 1995). Physiological and biochemical mechanisms underlying salt tolerance have provided insights into how plants cope with salt stress through mechanisms such as osmotic adjustment, ion homeostasis, and the production of stress-related proteins (Hasegawa *et al.,* 2000). Understanding these mechanisms allows for the development of more targeted approaches to improving crop resilience using crop wild relatives. By examining key factors and measurement techniques, modern phenomic tools, critical examination of traits, trait optimization, trait component analysis, and salt tolerance from crop wild relatives can be leveraged to tailor novel climate-smart salt-tolerant varieties. The present review aims to summarize the types and importance of crop wild relatives their use in trait mapping for salt stress at various growth stages, with their proper utilization in crop breeding using conventional as well as genomic-assisted breeding approaches.

Crop Wild Relatives (CWRs): Importance and Types

CWRs are wild plant species closely related to domesticated crops. These wild species belong to the same genus or family as the cultivated crops and often share a common gene pool (Table 1). CWRs are significant because they serve as a reservoir of genetic diversity that can be utilized to enhance the traits of cultivated crops, particularly in adapting to challenging environmental conditions. This genetic diversity is essential for breeding programs aimed at developing crops with enhanced traits such as disease resistance, drought tolerance, and salt tolerance (Harlan and de Wet, 1971). CWRs have evolved in natural environments and thus possess unique adaptations that enable them to survive under conditions that are often detrimental to cultivated crops. CWRs can be a source of novel alleles that confer resistance to pests and diseases or tolerance to abiotic stresses such as salinity and drought (Fowler and Mooney, 1990). These traits are increasingly valuable as climate change and other environmental pressures threaten global food security. The mapping of salt-tolerant gene(s) from CWRs and their incorporation into cultivated varieties can enhance their ability to withstand salt stress, thereby improving agricultural sustainability and productivity. Moreover, by conserving these wild relatives, we protect not only the genetic resources they provide but also the ecosystems they inhabit. This biodiversity is crucial for maintaining ecological balance and resilience (Maxted *et al.,* 2006). CWRs can be categorized based on their genetic relationship to cultivated crops and their ecological characteristics:

- *Immediate Progenitors:* These are wild species/ wild relatives that are the direct ancestors of cultivated crops. For example, several accessions of *Triticum timopheevi*, *T. turgidum*, *Aegilopes tauschii* and *T. Urartu* (the wild progenitor of wheat), are known to be valuable source of salt-tolerance in wheat improvement (Khan *et al.,* 2000; Colmer *et al.,* 2006; Kotula *et al.,* 2024). These species are closely related to cultivated crops and often share many genetic traits.
- *Close Relatives:* These are wild species that are closely related to cultivated crops but are not direct ancestors. They belong to the same genus or family and can contribute valuable genetic traits. For instance, *Solanum pennellii*, a wild relative of the tomato, provides genes for drought tolerance and disease resistance (Rick, 1988). Similarly, Dhani grass (*Oryza coarctacta*) can contribute to salt tolerance in rice (Tamanna *et al.,* 2024).
- *Remote Relatives:* These are wild species that are more distantly related to cultivated crops. While they may not be as closely related as immediate or close relatives, they can still offer unique traits that are not present in domesticated varieties. An example is the use of wild species from different genera to introduce new traits into crops through genetic engineering or hybridization. For example, Sea barley grass (*Hordeum marinum*) have better salt tolerance than wheat (Smith *et al.,* 2005; Colmer *et al.,* 2006)

Table 1. Crop Wild Relatives (CWRs) of different crops, which are the wild species genetically related to cultivated crops and can impart salt-tolerance

Cultivated Crop	Wild relatives for salt-tolerance
Rice (*Oryza sativa*)	*Oryza rufipogon*, *Oryza nivara*, *Oryza coarctata*, *Oryza latifolia*, *Oryza australiensis*, and *Oryza alta*
Wheat (*Triticum aestivum*)	*Aegilopes tauschii*, *Triticum boeoticum*, *Triticum dicoccoides*
Maize (*Zea mays* ssp. *mays*)	*Zea diploperennis*
Barley (*Hordeum vulgare)*	*Hordeum spontaneum*, *Hordeum brevisubulatum*, and *Hordeum marinum*
Sorghum (*Sorghum bicolor*)	*Sorghum arundinaceum*, *Sorghum halepense*
Potato (*Solanum tuberosum)*	*Solanum juzepczukii, Solanum demissum, Solanum acaule, Solanum bulbocastnum, S. chacoense,*
Tomato (*Solanum lycopersicum*)	*Solanum pimpinellifolium*, *S. pennellii; S. chilense, S. peruvianum, S. cheesmani, S. hirsutum,*
Brinjal (*Solanum melongena*)	*Solanum linnaeanum, S. aethiopicum*
Banana (*Musa spp*.)	*Musa balbisiana*, *Musa acuminata*
Sugarcane (*Saccharum officinarum*)	*Saccharum spontaneum*, *Saccharum robustum*
Soybean (*Glycine max*)	*Glycine soja*, *Glycine tomentella*
Chickpea (Cicer arietinum)	*Cicer reticulatum, Cicer echinospermum*
Peanut (*Arachis hypogaea*)	*Arachis duranensis*, *Arachis ipaensis*
Cotton (*Gossypium hirsutum*)	*Gossypium raimondii*, *Gossypium arboreum*
Sunflower (*Helianthus annuus*)	*Helianthus argophyllus*, *Helianthus petiolaris*
Apple (*Malus domestica*)	*Malus sieversii*, *Malus orientalis*

The utilization of CWRs in crop improvement involves several strategies such as (1) Traditional Breeding (By crossbreeding cultivated crops with CWRs, breeders can introduce beneficial traits from the wild relatives into the cultivated varieties, successfully enhancing traits such as disease resistance and stress tolerance (Miller *et al.,* 2001); (2) Molecular Breeding (Advances in genomics allow for the direct transfer of specific genes from CWRs into cultivated crops, can accelerate the process of incorporating desirable traits and is particularly useful for traits controlled by single genes, editing of domestication related genes for accelerated domestication; Huang *et al.,* 2014); (3) Conservation and Management (Effective conservation strategies are essential to ensure the preservation of CWRs and their habitats, includes establishing gene banks, protecting natural habitats, and conducting research to understand their genetic resources; Dempewolf *et al.,* 2014). Understanding and utilizing CWRs is essential for developing crops that can adapt to the challenges of climate change and other environmental stresses.

Salt-Tolerant Wild Relatives

Salt stress is a significant abiotic factor affecting global agriculture, particularly in the context of rice, wheat, maize, barley, soybean, and other crops. The development of salt-tolerant crop varieties is crucial for maintaining yield and ensuring food security. Wild relatives of cultivated crops offer a promising source of genetic diversity that can be harnessed to improve salinity tolerance. Various crops and their wild relatives which can be used to impart salt tolerance are given below.

Rice

Rice is highly sensitive to salinity, which restricts its cultivation in saline-affected areas. Wild rice species, such as *Oryza rufipogon*, *Oryza nivara*, *Oryza coarctata*, *Oryza latifolia*, and *Oryza alta* have been identified as valuable sources of salt tolerance genes. *Oryza coarctata*, in particular, thrives in extreme salinity conditions, withstanding NaCl concentrations up to 450 mM (Solis *et al.,* 2020). This species is a halophyte growing wildly on the coastal seashore and can be used to confer salt tolerance into cultivated rice using *Oryza australiensis* as bridge species (Mammadov *et al.,* 2018). The greater salinity tolerance of *Oryza rufipogon* and *Oryza nivara*, the ancestors of farmed rice (*Oryza sativa*), is well known. This wild rice species is a useful donor for breeding initiatives aimed at improving salt tolerance qualities in cultivated rice since it possesses mechanisms that enable it to flourish in salinized environments

(Padmavathi *et al.,* 2024). Studies on *Oryza rufipogon* have demonstrated its potential for introducing salinity tolerance traits into cultivated rice varieties. For instance, accessions *of O. rufipogon* have shown superior salt tolerance compared to modern cultivars, with reduced Na^+ accumulation in leaves and improved K^+/Na^+ ratios (Schachtman *et al.,* 1991). These two species are very important as it is easily crossable to cultivated rice and have been used in development of salt-tolerant rice varieties, Jarava and Chinsura Nona 2 (Gosaba-6) in India (Padmavathi *et al.,* 2024). The genetic complexity of salinity tolerance in rice, governed by minor genes and high genotype × environment interactions, poses challenges for breeding programs (Prusty *et al.,* 2018). However, wild rice species offer a reservoir of genetic diversity that can be exploited to overcome these challenges by providing novel alleles and mechanisms for salt tolerance. Advances in genomic tools, such as whole genome sequencing, have facilitated the identification of QTLs associated with salinity tolerance, providing valuable insights for breeding programs (Stein *et al.,* 2018).

Wheat

In wheat, the D genome progenitor *Aegilopes tauschii* has been identified as a critical source of salt tolerance. Studies demonstrated that *A. tauschii* exhibits lower Na^+ concentrations and higher K^+/Na^+ ratios compared to durum wheat, suggesting a significant role in Na^+ exclusion mechanisms (Gorham *et al.,* 1987, 1990b). This trait is vital for developing bread wheat varieties that can tolerate saline conditions. Variability in Na^+ accumulation within *A. tauschii* accessions highlights the potential for selecting genotypes with enhanced salt tolerance (Schachtman *et al.,* 1992). Synthetic hexaploid wheat, incorporating *A. tauschii* genetic material, has shown promise in improving salt tolerance in bread wheat (Schachtman *et al.,* 1991). Apart from this some accessions of *Triticum dicoccoides* have been identified to confer salt tolerance (Pour-Aboughadareh *et al.,* 2021). Using these species will rely on bridge species and utilization of modern genetic engineering tools to improve salt tolerance in wheat. Salt tolerance in wheat can be further refined by focusing on the best sources of Na^+ exclusion and integrating them into breeding programs for modern wheat varieties.

Maize and Barley

Maize and barley are also affected by salt stress, but wild relatives offer promising avenues for improvement. Wild maize species, such as *Zea diploperennis*, exhibit higher tolerance to salt stress compared to cultivated varieties (Wang *et al.,* 2012). Barley is generally more tolerant to salt stress than other cereals, however variations occur in terms of tolerance to salinity in different wild relatives of Barley (Colmer *et al.,* 2006). Wild barley species, *Hordeum spontaneum*, *Hordeum brevisubulatum*, and *Hordeum marinum* show superior salt tolerance traits that can be used to enhance modern cultivars (Colmer *et al.,* 2006; Khan *et al.,* 2021). Wild relatives such as *Hordeum marinum* and *H. brevisubulatum* can regulate the contents of Na^+ and Cl^- in their leaves under high salinities by optimizing membrane transport and sequestration, accumulating osmolytes, and reducing energy expenditure (Isayenkov, 2021). Other salt-tolerant wild relatives of barley often possess unique physiological mechanisms, such as enhanced ion compartmentalization and osmotic adjustment, which can be beneficial for breeding programs.

Legume crops

Wild relatives of soybean, such as *Glycine soja*, offer valuable genetic traits for improving salinity tolerance. *Glycine soja* can maintain higher levels of K^+ and lower Na^+ concentrations under saline conditions compared to cultivated soybean (Hernandez *et al.,* 2020). *Cicer reticulatum*, the progenitor of chickpea, exhibit enhanced salt tolerance traits that can be leveraged for crop improvement (Kumar *et al.,* 2021). *Cicer echinospermum* also offers a valuable source of genetic diversity for improving salinity tolerance. These wild species maintain higher K^+/Na^+ ratios under saline conditions, which is essential for preserving cellular function and ensuring plant growth (Upadhyaya *et al.,* 2011). Additionally, *Cicer reticulatum* has been found to possess deeper root systems and better osmotic adjustment capabilities, enabling it to withstand high salinity levels more effectively (Varshney *et al.,* 2013). The integration of these traits into cultivated chickpea varieties can significantly enhance their resilience to salinity. Modern breeding techniques, including the use of genomic tools and biotechnological interventions, have made it possible to identify and transfer salt tolerance genes from wild chickpea relatives into elite cultivars (Varshney *et al.,* 2019). These advances are crucial for developing chickpea varieties that can thrive in saline environments, thereby contributing to food security and sustainable agriculture in salt-affected regions.

Mustard

Wild relatives of mustard, such as *Brassica rapa* (field mustard) and *Brassica oleracea* (wild cabbage), have shown potential in providing genetic material for improving salinity tolerance in cultivated mustard varieties. Studies have demonstrated that these wild relatives possess adaptive traits such as enhanced osmotic adjustment, better ion compartmentalization, and efficient Na^+ exclusion mechanisms, which are crucial for surviving in saline environments (Ashraf and McNeilly, 2004). For example, *Brassica rapa* exhibits a more robust root system and higher proline accumulation under salt stress, which helps in maintaining cellular homeostasis and reducing salt-induced damage (Ashraf, 2009). These adaptive traits can be introgressed into cultivated mustard through breeding programs, thereby enhancing the crop's ability to tolerate saline conditions. Advances in molecular breeding techniques, such as marker-assisted selection and genomic selection, have facilitated the identification of QTLs associated with salinity tolerance in wild mustard relatives, providing a roadmap for developing salt-tolerant mustard varieties (Shahbaz *et al.,* 2013).

Fruits and Vegetables

Wild relatives of fruits and vegetables also provide a source of salinity tolerance genes. For example, wild tomatoes (*Solanum pennellii*) have demonstrated higher tolerance to salt stress compared to cultivated varieties, with better ion homeostasis and reduced water deficit under saline conditions (Solis *et al.,* 2020). Some accessions of *S. pimpinellifolium*, such as 'PI365967' can provide salt tolerance in tomato (Guo *et al.,* 2022). *Solanum juzepczukii* is a salt tolerant species related to potato (Chourasia *et al.,* 2021). Similarly, wild relatives of cucumber and melon exhibit traits that can be useful for developing salt-tolerant cultivars (Zhang *et al.,* 2022).

Genomics Assisted Breeding Approaches with Wild Relatives

Breeding with crop wild relatives (CWR) has become increasingly easy due to advances in marker-assisted selection (MAS), genomics, and genome editing technologies. These approaches leverage the genetic diversity found in wild species to enhance crop traits, improve resilience, and broaden genetic bases. A common approach towards utilizing crop wild relatives in crop breeding for salt tolerance is given in Fig.1.

Genes, QTLs and Marker Assisted Selection for Salt Tolerance

Several QTL mapping studies were performed to identify genomic loci governing seedling stage salinity tolerance in *Oryza rufipogon*. Wang *et al*. (2017) mapped ten unique QTLs governing seedling stage salinity tolerance in introgression lines of *O. rufipogon* into rice cultivar 93-11. They mapped QTLs on chromosomes 1, 5, 7, 9, 10, 11, and 12, with individual QTLs explaining 2–8% of phenotypic variance. Using introgression lines Tian *et al*. (2011) mapped 15 QTLs belonging to 4 different traits on chromosomes 1, 2, 3, 6, 7, 9, and 10 explaining 8–26% of the phenotypic variance. Abbas *et al*. (2021) reported that the expression level of genes *AeHKT1;4* and *AeNHX1* were significantly increased under salinity in tolerant accessions of *Aegilopes tauschii*, a progenitor of wheat. Similarly, other crop wild relatives can be used to generate introgression lines for mapping of candidate genes or genomic regions governing salinity tolerance.

MAS has significantly advanced the integration of traits from CWRs into domesticated crops, particularly for improving salt tolerance.

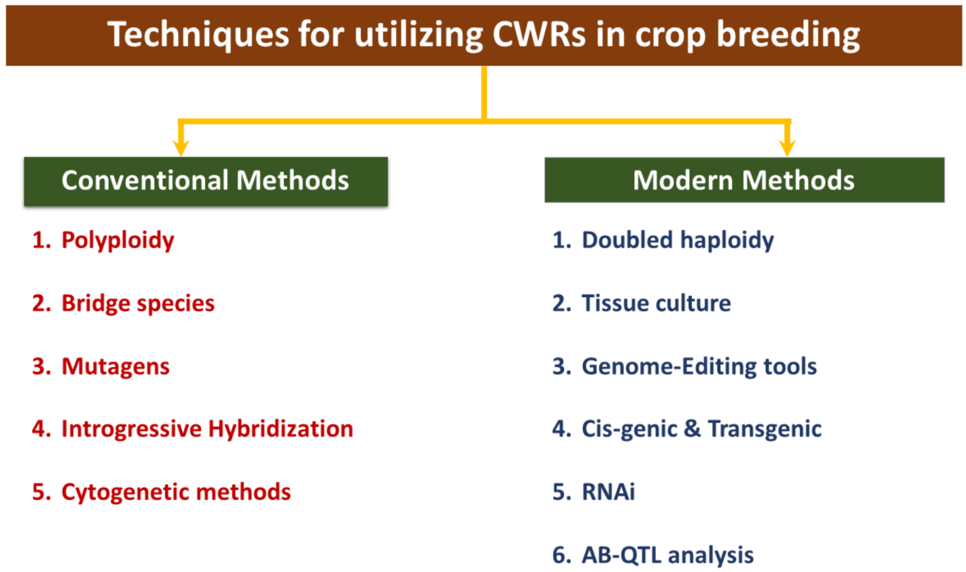

Fig. 1 Different approaches for utilization of crop wild relatives in crop breeding for salt tolerance

This approach uses molecular markers to link desirable traits to specific genetic regions, thereby enhancing breeding efficiency. The process typically begins with genetic mapping, which correlates genotypes with phenotypes through techniques like genome-wide association studies (GWAS) or quantitative trait locus (QTL) mapping (Takeda and Matsuoka, 2008; Morrell *et al.,* 2012). In several crops, QTLs related to salt tolerance have been identified in their wild relatives. For example, in rice, *Oryza rufipogon*, a wild ancestor of *Oryza sativa*, has been a key source of salt tolerance genes. Similarly, in barley, wild barley (*Hordeum spontaneum*) has contributed salt tolerance traits to cultivated varieties (*Hordeum vulgare*) and *Hordeum marinum* can be employed to map QTLs and for transfer of genes governing salt tolerance. QTLs responsible for ionic balance and osmotic adjustment under salt stress were mapped in wild barley and then introgressed into elite cultivars, improving their performance in saline soils (Mano and Takeda, 1997). In soybean, a significant breakthrough was the discovery of the *GmCHX1* gene, an ion transporter gene from wild soybean (*Glycine soja*), which is linked to enhanced salt tolerance. This gene helps the plant maintain ion homeostasis under saline conditions, and its introgression has improved salt tolerance in domesticated soybean (*Glycine max*) (Qi *et al.,* 2014). In tomato, wild species such as *Solanum pimpinellifolium* and *Solanum cheesmaniae* have been used to introduce salt tolerance traits. QTL mapping and introgression lines derived from these wild species have enabled the development of salt-tolerant tomato varieties, which show improved growth and fruit yield under salinity stress (Frary *et al.,* 2010).

These examples highlight the importance of utilizing CWR in breeding programs through MAS to improve crop resilience to salinity. Recent advances in genomics and sequencing technologies, such as SNP chip platforms and high-throughput sequencing methods (e.g Restriction Site-Associated DNA Sequencing, GBS stands for Genotyping-by-Sequencing), have further facilitated the identification and introgression of salt tolerance genes from wild relatives into domesticated crops (Baxter *et al.,* 2011; Elshire *et al.,* 2011). The availability of draft reference genomes for wild species has accelerated this process, enabling more precise characterization of genetic diversity (Consortium *et al.,* 2014; Brozynska *et al.,* 2016).

Advanced Backcross Quantitative Trait Locus Analysis

AB-QTL analysis is particularly advantageous because it combines the strengths of traditional backcrossing with modern quantitative trait loci (QTL) mapping to identify and introgress beneficial alleles from wild relatives or exotic germplasm into elite crop varieties. This approach is essential for improving traits that are difficult to enhance through conventional breeding methods alone, such as resistance to biotic and abiotic stresses. These traits, often lost during domestication and modern breeding due to the bottleneck effect, can be reintroduced into cultivated crops through AB-QTL analysis. By leveraging the genetic diversity present in wild species, breeders can not only incorporate valuable traits into cultivated lines but also pinpoint the specific genomic regions (QTLs) associated with these traits. This makes AB-QTL analysis a powerful strategy for developing superior crop varieties with enhanced resilience and productivity.

- *Enables the Utilization of Exotic Germplasm:* Wild relatives and landraces often possess alleles that confer resistance to diseases, pests, and environmental stresses. These alleles are often absent in modern cultivars due to the genetic narrowing that occurs during domestication. AB-QTL analysis allows for the effective utilization of these untapped genetic resources by integrating them into breeding programs (Tanksley and Nelson, 1996).
- *Improves Complex Traits:* Traits such as yield, drought tolerance, and salinity resistance are typically governed by multiple genes, making them challenging to improve through traditional breeding. AB-QTL analysis facilitates the identification of multiple QTLs associated with these complex traits, enabling a more comprehensive approach to trait improvement (Tanksley and McCouch, 1997).
- *Accelerate the Breeding Process:* By combining backcrossing with QTL mapping, AB-QTL analysis accelerates the breeding process. This method allows breeders to rapidly introgress desirable traits while simultaneously selecting against undesirable ones, making it an efficient strategy for crop improvement (Eshed and Zamir, 1995).

AB-QTL analysis involves several key steps (Fig. 2):

- *Selection of Parental Lines:* The process begins with the selection of an elite, high-yielding cultivar as the recurrent parent and a wild or exotic accession as the donor parent. The donor parent is chosen based on the presence of desirable traits not found in the elite cultivar.
- *Backcrossing:* The donor parent is crossed with the recurrent parent to produce a hybrid, which is then backcrossed with the recurrent parent over several generations (e.g., BC1, BC2). This process enriches the progeny for the recurrent parent's genome while retaining segments of the donor parent's genome that may harbor beneficial QTLs.
- *Phenotyping and QTL Mapping:* The progeny from the advanced backcross generations are evaluated for the traits of interest (phenotyping). Concurrently, molecular markers are used to construct a genetic map and identify the QTLs associated with the desirable traits inherited from the donor parent. This step involves correlating specific genomic regions with phenotypic variation to pinpoint the location of beneficial QTLs (Fulton *et al.,* 1997).
- *Marker-Assisted Selection (MAS):* Once QTLs are identified, marker-assisted selection is employed to track and select individuals carrying the beneficial alleles in subsequent generations. This approach ensures that the advantageous traits are retained while undesirable donor traits are minimized.
- *Development of Improved Varieties:* The final step involves the selection of progeny that combine the desirable traits from both the recurrent and donor parents. These progeny are then evaluated for agronomic performance, and those that meet breeding objectives are advanced to the next stages of development, ultimately leading to the release of improved crop varieties.

AB-QTL Analysis for Salt Tolerance in Various Crops

- *Tomato:* Salt tolerance has been a significant target in tomato breeding. By using AB-QTL analysis, researchers introgressed salt

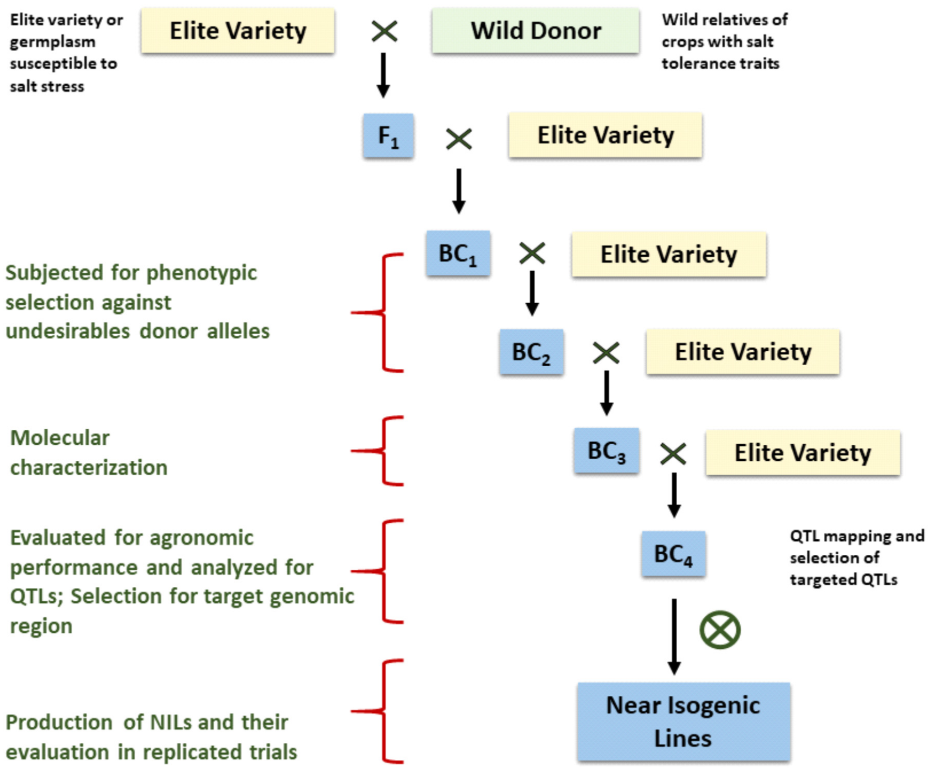

Fig. 2 Different steps in Advanced Backcross-QTL analysis for utilizing crop wild relatives in improving salt stress

tolerance alleles from wild tomato species (such as *Solanum pennellii*) into cultivated tomato. This has led to the identification of QTLs responsible for enhanced salt tolerance, improving the ability of cultivated tomatoes to survive and produce in saline soils (Frary *et al.,* 2010).

- *Rice:* In rice, AB-QTL analysis has been successfully used to identify QTLs related to salt tolerance. One notable study involved using wild rice (*Oryza rufipogon*) to identify QTLs associated with improved salinity tolerance. This led to the development of rice lines capable of maintaining yield under saline conditions by improving traits like sodium exclusion and osmotic adjustment (Thomson *et al.,* 2010).
- *Wheat:* For wheat, AB-QTL analysis has focused on introgressing salt tolerance genes from wild relatives such as *Aegilops cylindrica*. The QTLs identified are linked to better salt tolerance through mechanisms such as ion regulation and improved water use efficiency. This has resulted in wheat lines that are more resistant to salinity, an important trait for regions with salt-affected soils (Munns *et al.,* 2012).
- *Barley:* Barley is known for its inherent tolerance to harsh environments, and AB-QTL analysis has further enhanced this trait by introgressing salt tolerance QTLs from wild species like *Hordeum spontaneum*. The identified QTLs are linked to traits such as improved osmotic adjustment and ion homeostasis, which help in maintaining growth under saline conditions (Mano *et al.,* 2011).
- *Sorghum:* AB-QTL analysis in sorghum has been employed to improve salt tolerance by introgressing beneficial alleles from wild sorghum species. The QTLs identified control mechanisms like sodium exclusion and osmotic balance, contributing to the development of sorghum lines that perform well under saline conditions (Krishnamurthy *et al.,* 2013).
- *Maize:* In maize, AB-QTL analysis has been used to introgress salt tolerance genes from wild relatives like *Zea mays* ssp. *mexicana*. The

identified QTLs are linked to traits such as improved water use efficiency and ion regulation, resulting in maize lines with better growth and productivity in saline soils (Landi *et al.,* 2007).

- *Soybean:* AB-QTL analysis in soybean has led to the identification of QTLs related to salt tolerance by introgressing alleles from wild relatives like *Glycine soja*. These QTLs enhance traits like sodium exclusion and chlorophyll retention, improving soybean's ability to tolerate high salinity (Chen *et al.,* 2008).
- *Cotton:* Cotton, particularly *Gossypium hirsutum*, has benefited from AB-QTL analysis for salt tolerance by introgressing beneficial alleles from wild cotton species such as *Gossypium barbadense*. QTLs associated with better ion regulation, water use efficiency, and osmotic adjustment have been identified, resulting in salt-tolerant cotton lines (Zhang *et al.,* 2011).

De-novo Domestication

De novo domestication is an emerging breeding approach that seeks to domesticate wild species or CWRs by directly modifying key domestication traits, such as salt tolerance, to create new crops better suited to modern agricultural challenges. Unlike traditional breeding, which often involves years of crossing wild relatives with domesticated crops, *de novo* domestication utilizes precise genome editing technologies to accelerate the development of crops with enhanced traits. Later these domesticated forms of wild plants can be used in breeding program. A list of domestication traits and their target genes in some crops are mentioned in Table 2. One of the key benefits of *de novo* domestication is the ability to bypass some of the genetic bottlenecks that have occurred during traditional domestication. These bottlenecks have limited the genetic diversity of modern crops, making them more vulnerable to environmental stresses like salinity (Dempewolf *et al.,* 2017). By targeting genes in CWRs that control both domestication traits and stress tolerance, such as salt tolerance, breeders can quickly develop crops that are not only more resilient but also retain the agronomic qualities required for cultivation. Recent advancements in genome editing technologies, such as CRISPR/Cas9, have made *de novo* domestication increasingly feasible. These tools allow for the precise modification of key genes associated with traits like salt tolerance, enabling the creation of new crop varieties that can thrive in saline environments (Chen *et al.,* 2020). For instance, the *de novo* domestication of wild tomato species using CRISPR/Cas9 has successfully introduced traits such as improved yield, fruit size, and stress tolerance (Li *et al.,* 2018). Similar strategies could be applied to other salt tolerant CWRs to develop new crop varieties suited for saline conditions. CWRs often possess a wealth of untapped genetic variation for abiotic stress tolerance, including salinity resistance, but their agronomic traits are typically not suitable for large scale agriculture (Fernie and Yan, 2019). By selectively editing genes in wild species that control domestication related traits, such as plant architecture or seed dispersal, breeders can create crops that combine the wild relative's stress tolerance with the desirable traits of modern cultivars. Despite its potential, several challenges remain for *de novo* domestication. The functional validation of target genes in wild species, as well as the regulatory landscape surrounding genome editing, requires careful consideration. Furthermore, while *de novo*

Table 2. List of crops along with domestication genes that can be targeted in their wild relatives for *de novo* domestication

Wild relatives	Crops	Target traits	*Genes*
Teosinte	Maize	Barnching, inflorescence architecture	*tb1*, *tga1*, *gt1*
Wild rice	Rice	Shattering resistance, compact panicle	*Sh4*, *qSH1*, *Rc*, *Sdr4*
Wild wheat	Wheat	Less Branching, shattering resistance, crossability barriers	*Q, Br*
Wild tomato	Tomato	Fruit size,	*Style2.1, fw2.2, fas*
Wild barley	Barley	Shattering	*Btr1, Vsr1*
Wild sorghum	Sorghum	Shattering resistance	*SbSh1*

domestication can accelerate crop improvement, it also relies heavily on detailed knowledge of the genetic basis of domestication and stress tolerance traits, which may still be incomplete for many species (Zsögön *et al.,* 2018).

Genome Editing

Genome editing technologies, such as CRISPR/Cas9, represent a transformative advancement in crop breeding. These methods allow for precise modifications of the genome without introducing foreign DNA, potentially offering significant efficiency gains in crop improvement (Voytas, 2013; Bortesi and Fischer, 2015). While still in their early stages, genome editing technologies are increasingly capable of modifying larger genomic regions and multiple genes simultaneously (Lowder *et al.,* 2015; Ma *et al.,* 2015). These tools may further enhance the use of CWR by enabling the incorporation of allelic diversity from more distantly related or cross-incompatible species (Nogué *et al.,* 2016; Spindel and McCouch, 2016). Despite these advances, several barriers hinder the increased use of CWR. A major challenge is the lack of comprehensive phenotypic and genotypic data for many CWR accessions and, the absence of robust tissue culture-based regeneration protocols. Approximately 7 million crop accessions are stored in gene banks, yet significant gaps remain in the characterization of these materials (Commission on Genetic Resources for Food and Agriculture, 2010). Addressing these gaps involves improving documentation practices, using standardized systems for accession identification, and enhancing data collection on environmental factors and genetic diversity (Alercia *et al.,* 2015).

Rootstock Breeding

One promising approach to mitigating the effects of salinity on crops is through the development of salt-tolerant rootstocks. Rootstock breeding focuses on selecting and breeding root systems that can better manage saline conditions, providing a vital mechanism for enhancing overall plant resilience and productivity under salt stress. Rootstocks play a crucial role in determining the ability of a plant to tolerate salinity. They influence the plant's water and nutrient uptake, ion transport, and overall vigour. By selecting rootstocks that possess inherent salt tolerance, it is possible to confer these traits to the grafted scion, thereby improving the salinity tolerance of the entire plant. This approach is particularly valuable for perennial crops like fruit trees and grapevines, where the rootstock and scion are often from different genetic backgrounds. The development of salt-tolerant rootstocks involves several breeding strategies, including traditional selection, hybridization, and modern molecular techniques. These strategies aim to combine desirable traits from various parent lines to produce rootstocks that can thrive under saline conditions.

- *Traditional Breeding and Selection:* Traditional breeding methods involve selecting rootstock genotypes that demonstrate superior performance under saline conditions. This process includes screening large populations of rootstocks in saline environments and selecting individuals with the best salt tolerance traits. For example, in grapevine rootstock breeding, rootstocks like 1103 Paulsen have been identified for their ability to perform well under saline conditions (Steppuhn *et al.,* 2005).
- *Hybridization:* Crossbreeding salt-tolerant rootstock varieties with other rootstocks that have desirable agronomic traits (e.g., disease resistance, vigor) can produce hybrids with enhanced salt tolerance. For example, in tomato, breeding programs have successfully developed rootstocks that combine salt tolerance with resistance to soil-borne pathogens, resulting in more resilient plants (Martínez-Andújar *et al.,* 2016).
- *Molecular Breeding and Genomics:* Advances in molecular biology and genomics have enabled the identification of specific genes and QTLs associated with salt tolerance in rootstocks. Marker-assisted selection (MAS) and genomic selection are now used to accelerate the breeding process by targeting these genetic markers in breeding programs. For instance, QTLs associated with Na^+ exclusion have been identified in grapevine rootstocks, providing valuable targets for breeding efforts (Zhang *et al.,* 2018).

- *Biotechnological Approaches:* Genetic engineering and biotechnological interventions offer new possibilities for enhancing salt tolerance in rootstocks. Techniques such as CRISPR/Cas9 gene editing can be used to directly modify genes involved in salt tolerance, potentially creating rootstocks with superior resilience to salinity. However, the adoption of these technologies in rootstock breeding is still in its early stages and is subjected to regulatory and public acceptance considerations (Zhu *et al.,* 2016).

Conclusions and Future Perspectives

The integration of crop wild relatives (CWR) into modern breeding programs represents a significant advancement in agricultural science. Leveraging the genetic diversity of CWR has proven crucial for enhancing crop resilience, improving yield, and expanding genetic bases. The application of advanced breeding techniques, such as marker-assisted selection (MAS), introgression lines, and genomics, has facilitated the precise incorporation of desirable traits from wild species into cultivated crops. Technologies like high-throughput sequencing and SNP chip platforms have revolutionized the way genetic information is utilized, allowing for detailed and efficient trait mapping and genetic analyses. Marker-assisted selection and introgression lines have made it possible to systematically integrate beneficial traits from CWR, improving traits such as drought and heat tolerance. Recent advances in genomics, including reduced representation sequencing methods and the development of draft reference genomes, have provided powerful tools for identifying and characterizing genetic diversity in CWR. Landscape genomics further supports the targeted collection and conservation of valuable alleles by correlating genetic information with environmental factors. The emergence of genome editing technologies, such as CRISPR/Cas9, offers unprecedented precision in modifying plant genomes, potentially accelerating the incorporation of wild genetic material into crops. These technologies, while still evolving, promise significant improvements in crop breeding efficiency and effectiveness. However, the regulatory landscape and the current understanding of complex trait genetics pose ongoing challenges. Despite these advancements, several barriers remain. The most pressing issue is the lack of comprehensive phenotypic and genotypic data for many CWR accessions. With approximately 7 million crop accessions in gene banks, the gap in detailed characterization and documentation limits the utility of these resources. Addressing these gaps requires enhanced data management practices, standardized documentation systems, and improved collection strategies to capture the full spectrum of genetic diversity. Looking ahead, future efforts should focus on the following key areas:

- *Enhanced Data Collection and Management:* Developing standardized protocols for documenting CWR accessions and improving data sharing will be essential for maximizing the utility of genetic resources. Integration of genomic data with environmental information can further refine the selection of valuable traits and guide conservation efforts.
- *Advancements in Genomics and Sequencing:* Continued innovation in genomics, including the refinement of sequencing technologies and the expansion of reference genomes, will provide deeper insights into the genetic diversity of CWR. This will enable more precise mapping of traits and facilitate the identification of novel alleles.
- *Expansion of Genome Editing Applications:* As genome editing technologies advance, they will offer new opportunities for utilizing CWR genetic material in crop improvement. Continued research into the genetic basis of complex traits will enhance the effectiveness of these tools.
- *Integration of CWR into Breeding Programs:* To fully realize the potential of CWR, breeding programs must increasingly incorporate wild genetic material. This includes overcoming challenges related to genetic incompatibility and ensuring that the benefits of CWR are effectively harnessed.
- *Strengthening Conservation Efforts:* Protecting and conserving the genetic diversity of CWR

is critical. Prioritizing the collection of underrepresented diversity and focusing on areas of extreme climates will help safeguard valuable genetic resources for future use.

In summary, the use of CWR in crop breeding is poised for transformative growth, driven by technological advancements and a deeper understanding of genetic diversity. By addressing current challenges and leveraging emerging tools and approaches, the agricultural community can harness the full potential of CWR to enhance crop resilience and productivity.

Acknowledgements

Authors are thankful to the Director, ICAR-CSSRI, Karnal for supporting the research on rice breeding for salinity tolerance.

References

Abbas A, Yu H, Cui H and Li X (2021) Genetic diversity and synergistic modulation of salinity tolerance genes in *Aegilops tauschii* Coss. *Plants* **10(7)**:1393.

Alercia A, Diulgheroff S, and Mackay M (2015) FAO/bioversity multi-crop passport descriptors version 2.1. Food and Agricultural Organization, Rome, Italy.

Anderson DG, Kvie K S, Davydov V N, and Røed K H (2017) Maintaining genetic integrity of coexisting wild and domestic populations: Genetic differentiation between wild and domestic Rangifer with long traditions of intentional interbreeding. *Ecology and Evolution* **7(17)**: 6790-6802.

Ashraf, M F M R, and Foolad M R (2007) Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environmental and Experimental Botany* **59(2)**: 206-216.

Baxter SW, Davey JW, Johnston JS, Shelton AM, Heckel DG, Jiggins CD, and Blaxter ML (2011) Linkage mapping and comparative genomics using next-generation RAD sequencing of a non-model organism. *PloS One* **6(4)**: e19315.

Bortesi L and Fischer R (2015) The CRISPR/Cas9 system for plant genome editing and beyond. *Biotechnology Advances* **33(1)**: 41-52.

Brozynska M, Furtado A, and Henry RJ (2016) Genomics of crop wild relatives: expanding the gene pool for crop improvement. *Plant Biotechnology Journal* **14(4)**: 1070-1085.

Cavanagh C, Morell M, Mackay I, and Powell W, (2008) From mutations to MAGIC: resources for gene discovery, validation and delivery in crop plants. *Current Opinion in Plant Biology* **11(2)**: 215-221.

Chen K, Wang Y, Zhang R, Zhang H and Gao, C (2020) CRISPR/Cas genome editing and precision plant breeding in agriculture. *Annual Review of Plant Biology* **71**: 535–560

Chourasia KN, Lal MK, Tiwari RK, Dev D, Kardile HB, Patil VU, Kumar Amarjeeet Vanishree Girimala, Kumar Dharmendra, Bhardwaj Vinay, Meena Jitendra, Mangal Vikas, Shelake Rahul, Kim Jae, Paramanik dibyajyoti and Pramanik, D (2021) Salinity stress in potato: Understanding physiological, biochemical and molecular responses. *Life* **11(6)**: 545.

Colmer TD, Flowers TJ and Munns R (2006) Use of wild relatives to improve salt tolerance in wheat. *Journal of Experimental Botany* **57(5)**: 1059-1078.

Comadran J, Kilian B, Russell J, Ramsay L, Stein N, Ganal M, and Waugh R (2012) Natural variation in a homolog of Antirrhinum CENTRORADIALIS contributed to spring growth habit and environmental adaptation in cultivated barley. *Nature Genetics* **44(12)**: 1388-1392.

Dempewolf H, Baute GJ, Anderson J, Kilian B, Smith C, and Guarino L (2017) Past and future use of wild relatives in crop breeding. *Crop Science* **57(3)**: 1070–1082

Elshire RJ, Glaubitz, JC, Sun Q, Poland JA, Kawamoto K, Buckler ES, and Mitchell SE (2011), A robust, simple genotyping-by-sequencing (GBS) approach for high diversity species. *PloS One* **6(5)**: e19379.

Eshed Y, and Zamir D (1995) An introgression line population of *Lycopersicon pennellii* in the cultivated tomato enables the identification and fine mapping of yield-associated QTL. *Genetics* **141(3)**: 1147-1162.

Fernie AR, and Yan J (2019) De novo domestication: An alternative route toward new crops for the future. *Molecular Plant* **12(5)**: 615–631.

Flowers TJ and Yeo AR (1995) Breeding for salinity resistance in crop plants: *Functional Plant Biology* **22(6)**: 875-884.

Fowler C and Mooney PR (1990) *Shattering: Food, Politics, and the Loss of Genetic Diversity* University of Arizona Press.

Frary Anne, Deniz Göl, Davut Keleþ, Bilal Ökmen, Hasan Pýnar, Hasan Ö Þýðva, Ahmet Yemenicioðlu and Sami Doðanlar (2010) Salt tolerance in *Solanum pennellii*: antioxidant response and related QTL. *BMC Plant Biology* **10**: 1-16.

Fulton TM, Beck-Bunn T, Emmatty D, Eshed Y, Lopez J, Petiard V, and Tanksley SD (1997) QTL analysis of an advanced backcross of *Lycopersicon peruvianum* to the cultivated tomato and comparisons with QTLs found in other wild species. *Theoretical and Applied Genetics* **95**: 881-894.

Garcia A, Senadhira D, Flowers TJ, and Yeo AR (1995) the effects of selection for sodium transport and of selection for agronomic characteristics upon salt resistance in rice

(*Oryza sativa* L). *Theoretical and Applied Genetics* **90**: 1106-1111.

Gorham JUCO, Hardy C, Wyn Jones RG, Joppa LR, and Law CN (1987) Chromosomal location of a K/Na discrimination character in the D genome of wheat. *Theoretical and Applied Genetics* **74**: 584-588.

Gorham J, Bristol A, Young EM, JONESH RW, and Kashour G (1990) Salt tolerance in the Triticeae: K/Na discrimination in barley. *Journal of Experimental Botany* **41(9)**: 1095-1101.

Guo M, Wang XS, Guo HD, Bai SY, Khan A, Wang XM, ... and Li JS (2022) Tomato salt tolerance mechanisms and their potential applications for fighting salinity: A review. *Frontiers in Plant Science* **13**: 949541.

Harlan JR and de Wet JM (1971) Toward a rational classification of cultivated plants. *Taxon* **20(4)**: 509-517.

Hasegawa PM, Bressan RA, Zhu JK, and Bohnert HJ (2000) Plant cellular and molecular responses to high salinity. *Annual Review of Plant Biology* **51(1)**: 463-499.

Huang X, Huang S, Han B, and Li J (2022) The integrated genomics of crop domestication and breeding. *Cell* **185(15)**: 2828-2839.

Isayenkov S (2021) Wild Barley Relatives–Potential Donors of Salinity Tolerance for Cereal Crops In *Multiple Abiotic Stress Tolerances in Higher Plants* CRC Press. pp 75-90

Jaleel CA, Manivannan P, Sankar B, Kishorekumar A, Gopi R, Somasundaram R, and Panneerselvam R (2007) Water deficit stress mitigation by calcium chloride in *Catharanthus roseus*: Effects on oxidative stress, proline metabolism and indole alkaloid accumulation Colloids and surfaces B: *Biointerfaces* **60(1)**: 110-116.

Khan AG, Kuek C, Chaudhry TM, Khoo CS, and Hayes WJ (2000) Role of plants, mycorrhizae and phytochelators in heavy metal contaminated land remediation. *Chemosphere* **41(1-2)**: 197-207.

Khan A, Khan SR, Leventhal RM, and Brown WA (2001) Symptom reduction and suicide risk in patients treated with placebo in antidepressant clinical trials: a replication analysis of the Food and Drug Administration Database. *International Journal of Neuropsychopharmacology* **4(2)**: 113-118.

Khan I, Iqbal B, Khan AA, Inamullah, Rehman A, Fayyaz A, and Wang LX (2022) the interactive impact of straw mulch and biochar application positively enhanced the growth indexes of maize (*Zea mays* L) crop. *Agronomy* **12(10)**: 2584.

Kobayashi T, and Mano G (2011) The Schrödinger model for the minimal representation of the indefinite orthogonal group *O* (*p*, *q*) (Vol 213, No 1000) American Mathematical Society.

Kotula L, Zahra N, Farooq M, Shabala S and Siddique KH (2024) Making wheat salt tolerant: The Crop Journal.

Kramer PJ and Boyer JS (1995) *Water Relations of Plants and Soils*. Academic press, Cambridge, Massachusetts, United States of America.

Krishnamurthy L, Dinakaran E, Kumar AA, and Reddy BVS (2014) Field technique and traits to assess reproductive stage cold tolerance in Sorghum (*Sorghum bicolor* (L) Moench). *Plant Production Science* **17(3)**: 218-227

Kumar V, Vats S, Kumawat S, Bisht A, Bhatt V, Shivaraj S M, and Sonah H (2021) Omics advances and integrative approaches for the simultaneous improvement of seed oil and protein content in soybean (*Glycine max* L). *Critical Reviews in Plant Sciences* **40(5)**: 398-421.

Landi P, Sanguineti M C, Liu C, Li Y, Wang T Y, Giuliani S, and Tuberosa, R (2007) Root-ABA1 QTL affects root lodging, grain yield, and other agronomic traits in maize grown under well-watered and water-stressed conditions. *Journal of Experimental Botany* **58(2)**: 319-326.

Li T, Liu B, Spalding M H, Weeks D P, and Yang B (2018) High-efficiency TALEN-based gene editing produces disease-resistant rice. *Nature Biotechnology* **30**: 390–392

Lowder LG, Zhang D, Baltes NJ, Paul III JW, Tang X, Zheng X, and Qi Y (2015) A CRISPR/Cas9 toolbox for multiplexed plant genome editing and transcriptional regulation. *Plant Physiology* **169(2)**: 971-985.

Ma X, Zhang Q, Zhu Q, Liu W, Chen Y, Qiu R, and Liu Y G (2015) A robust CRISPR/Cas9 system for convenient, high-efficiency multiplex genome editing in monocot and dicot plants. *Molecular Plant* **8(8)**: 1274-1284.

Mammadov J, Buyyarapu R, Guttikonda SK, Parliament K, Abdurakhmonov IY and Kumpatla, SP (2018) Wild relatives of maize, rice, cotton, and soybean: treasure troves for tolerance to biotic and abiotic stresses. *Frontiers in Plant Science* **9**: 886.

Mano Y, and Takeda K (1997) Mapping quantitative trait loci for salt tolerance at germination and the seedling stage in barley. (*Hordeum vulgare* L) *Euphytica* **94***:* 263-272.

Martínez-Andújar C, Albacete A, Martínez-Pérez A, Pérez-Pérez JM, Asins MJ, and Pérez-Alfocea F (2016) Root-to-shoot hormonal communication in contrasting rootstocks suggests an important role for the ethylene precursor aminocyclopropane-1-carboxylic acid in mediating plant growth under low-potassium nutrition in tomato. *Frontiers in Plant Science* **7**: 1782.

Maxted N, Ford-Lloyd BV, Jury S, Kell S, and Scholten M (2006) Towards a definition of a crop wild relative. *Biodiversity and Conservation* **15**: 2673-2685.

Morrell PL, Buckler ES, and Ross-Ibarra J (2012) Crop genomics: advances and applications. *Nature Reviews Genetics* **13(2)**: 85-96.

Munns R (2002) Comparative physiology of salt and water stress *Plant, Cell and Environment* **25(2)**: 239-250.

Munns R and Tester M (2008) Mechanisms of salinity tolerance *Annu Rev Plant Biol* **59(1)**: 651-681.

Munns R, Husain S, Rivelli AR, James RA, Condon AT, Lindsay MP, and Hare RA (2002) Avenues for increasing salt tolerance of crops, and the role of physiologically based selection traits In *Progress in Plant Nutrition: Plenary Lecture*s of the XIV International Plant Nutrition Colloquium: Food Security and Sustainability of Agro-ecosystems through Basic and Applied Research (pp 93-105). Springer Netherlands.

Munns R, James RA, Xu B, Athman A, Conn SJ, Jordans C, and Gilliham M (2012) Wheat grain yield on saline soils is improved by an ancestral Na+ transporter gene. *Nature Biotechnology* **30(4)**: 360-364.

Nogué F, Mara K, Collonnier C, and Casacuberta JM (2016) Genome engineering and plant breeding: impact on trait discovery and development. *Plant Cell Reports* **35**: 1475-1486.

Padmavathi G, Bangale U, Rao KN, Balakrishnan D, Arun MN, Singh RK, and Sundaram RM (2024) Progress and prospects in harnessing wild relatives for genetic enhancement of salt tolerance in rice. *Frontiers in Plant Science* **14**: 1253726.

Pour-Aboughadareh, A., Kianersi, F., Poczai, P., & Moradkhani, H. (2021). Potential of wild relatives of wheat: ideal genetic resources for future breeding programs. Agronomy, **11(8)**: 1656.

Pour-Aboughadareh A, Sanjani S, Nikkhah-Chamanabad H, Mehrvar M R, Asadi A, and Amini A (2021) Identification of salt-tolerant barley genotypes using multiple-traits index and yield performance at the early growth and maturity stages. *Bulletin of the National Research Centre* **45(1)**: 117.

Prusty MR, Kim SR, Vinarao R, Entila F, Egdane J, Diaz M G, and Jena KK (2018) Newly identified wild rice accessions conferring high salt tolerance might use a tissue tolerance mechanism in leaf. *Frontiers in Plant Science* **9**: 417.

Qi X, Li MW, Xie M, Liu X, Ni M, Shao G, and Lam HM (2014) Identification of a novel salt tolerance gene in wild soybean by whole-genome sequencing. *Nature Communications* **5(1)**: 4340.

Rick CM (1988) Tomato-like nightshades: affinities, autoecology, and breeders' opportunities. *Economic Botany* **42(2)**: 145-154.

Roa Solís C, Delgado Orellana A, Fuller D Q, and Capparelli A (2024) Wild foods, woodland fuels, and cultivation through the Ceramic and Early Historical periods in Araucanía, Southern Chile (400–1850 ce). *Vegetation History and Archaeobotany* **33(1)**: 169-183.

Schachtman DP, and Munns R (1992) Sodium accumulation in leaves of *Triticum* species that differ in salt tolerance. *Functional Plant Biology* **19(3)**: 331-340.

Schachtman DP, Munns R, and Whitecross MI (1991) Variation in sodium exclusion and salt tolerance in *Triticum tauschii. Crop Science* **31(4)**: 992-997.

Schachtman DP, Tyerman SD, and Terry BR (1991) The K+/Na+ selectivity of a cation channel in the plasma membrane of root cells does not differ in salt-tolerant and salt-sensitive wheat species. *Plant Physiology* **97(2)**: 598-605.

Solis CA, Yong MT, Venkataraman G, Milham P, Zhou M, Shabala L and Chen ZH (2021) Sodium sequestration confers salinity tolerance in an ancestral wild rice. *Physiologia Plantarum* **172(3)**: 1594-1608.

Solis M (2020) Racial equity in planning organizations. *Journal of the American Planning Association* **86(3)**: 297-303.

Spindel JE, and McCouch SR (2016) When more is better: how data sharing would accelerate genomic selection of crop plants. *New Phytologist* **212(4)**: 814-826.

Spindel JE, Begum H, Akdemir D, Collard B, Redoña E, Jannink JL, and McCouch S (2016) Genome-wide prediction models that incorporate de novo GWAS are a powerful new tool for tropical rice improvement. *Heredity* **116(4)**: 395-408.

Stein JC, Yu Y, Copetti D, Zwickl DJ, Zhang L, Zhang C, and Wing RA (2018) Genomes of 13 domesticated and wild rice relatives highlight genetic conservation, turnover and innovation across the genus Oryza. *Nature Genetics* **50(2)**: 285-296.

Steppuhn H, Van Genuchten MT, and Grieve CM (2005) Root zone salinity: I Selecting a product–yield index and response function for crop tolerance. *Crop Science* **45(1)**: 209-220.

Takeda S, and Matsuoka M (2008) Genetic approaches to crop improvement: responding to environmental and population changes. *Nature Reviews Genetics* **9(6)**: 444-457.

Tamanna N, Mojumder A, Azim T, Iqbal MI, Alam MNU, Rahma A, and Seraj ZI (2024) Comparative metabolite profiling of salt sensitive Oryza sativa and the halophytic wild rice Oryza coarctata under salt stress. *Plant Environment Interactions* **5(3)**: e10155.

Tanksley SD, and McCouch SR (1997) Seed banks and molecular maps: unlocking genetic potential from the wild. *Science* **277(5329)**: 1063-1066.

Tanksley SD, and Nelson JC (1996) Advanced backcross QTL analysis: a method for the simultaneous discovery and transfer of valuable QTLs from unadapted germplasm into elite breeding lines. *Theoretical and Applied Genetics* **92**: 191-203.

Thormann I, Endresen DTF, Rubio-Teso ML, Iriondo MJ, Maxted N and Parra-Quijano M (2014) Predictive characterization of crop wild relatives and landraces: Technical guidelines version 1.

Tian L, Tan L, Liu F, Cai H, and Sun C (2011) Identification of quantitative trait loci associated with salt tolerance at seedling stage from *Oryza rufipogon. Journal of Genetics and Genomics* **38(12)**: 593-601.

Voytas DF (2013) Plant genome engineering with sequence-specific nucleases *Annual Review of Plant Biology* **64(1)**: 327-350.

Wang S, Cao M, Ma X, Chen W, Zhao J, Sun C, and Liu F (2017) Integrated RNA sequencing and QTL mapping to identify candidate genes from *Oryza rufipogon* associated with salt tolerance at the seedling stage. *Frontiers in Plant Science* **8**: 1427.

Wang S, Wong D, Forrest K, Allen A, Chao S, Huang BE, and Akhunov E (2014) Characterization of polyploid wheat genomic diversity using a high density 90 000 single nucleotide polymorphism array. *Plant Biotechnology Journal* **12(6)**: 787-796.

Wright E M, and Kelly J D (2011) Mapping QTL for seed yield and canning quality following processing of black bean. (*Phaseolus vulgaris* L) *Euphytica* **179**: 471-484.

Xiao J, Li J, Grandillo S, Ahn S N, Yuan L, Tanksley S D, and McCouch SR (1998) Identification of trait-improving quantitative trait loci alleles from a wild rice relative, *Oryza rufipogon. Genetics* **150(2)**: 899-909.

Xu Y, Wang R, Tong Y, Zhao H, Xie Q, Liu D and An D (2014) Mapping QTLs for yield and nitrogen-related traits in wheat: influence of nitrogen and phosphorus fertilization on QTL expression. *Theoretical and Applied Genetics* **127**: 59-72.

Zhu JK (2002) Salt and drought stress signal transduction in plants. *Annual Review of Plant Biology* **53(1)**: 247-273.

Zhu JK (2016) Abiotic stress signaling and responses in plants. *Cell* **167(2)**: 313-324.

Zsögön A, Èermák T, Naves ER, Notini MM, Edel KH, Weinl S, and Fernie AR (2018) De novo domestication of wild tomato using genome editing. *Nature Biotechnology* **36(12)**: 1211–1216.

Received: September 12, 2024; Accepted: October 14, 2024

Journal of Soil Salinity and Water Quality 16(2), 234-248, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156583

Second Generation Bio-Ethanol Production from Agroforestry Practices in Salt-affected Landscapes in India: A Review

R Banyal[1]*, Manish Kumar[1], Raj Kumar[1], Arvind Kumar Rai[1], Gajender Yadav[1] and Rajkumar[2]

[1]Department of Soil and Crop Management, ICAR-Central Soil Salinity Research Institute, Karnal-132 001, Haryana, India
[2]Department of Social Science Research, ICAR-Central Soil Salinity Research Institute, Karnal-132 001, Haryana, India
**Corresponding author's E-mail: drbanyal08@gmail.com*

Abstract

World's dependency on fossil fuels have caused adverse effects on the environment and their availability is under threat. This has prompted significant interest in sustainable and environmental friendly bio-fuels to cater the energy demand. It is obtained from diverse renewable materials enriched with carbohydrate that can be hydrolysed to fermentable sugars and altered into ethanol. Second generation bio-ethanol production shows its betterness over first generation because it sourced from non-edible feedstock from forestry and agriculture wastes. This paper critically and analytically reviews the current status of second generation bio-ethanol significance, production methodologies, and agroforestry options in salt-affected landscapes in production of lingo-cellulosic biomass. Bio-ethanol production from ligno-cellulosic biomass is exceedingly challenging and due focus was given on technological, energy balance and efficiency, economic viability, environmental impacts, logistic and supply chain issues and government policies and subsidies for generating the understanding for their solutions. The discussions in this paper are also oriented towards the point that no direct information of the biomass obtained from the agroforestry practices put to direct use for second generation bio-ethanol production exacting to salt affected landscapes but the eventual possibilities are there in the future. Area under agroforestry in salt-affected soils is 7.02 m ha, accounts for 27.7 per cent coverage out of the total 25.3 m ha in the country. Possible viable agroforestry models (silvo-pastoral, agri-horticulture, agri-silviculture, and specialized models-multipurpose woodlots and energy forestry) are also discussed in length with its components and possible combinations for production of ligno-cellulosic biomass from marginal landscapes (salt-affected soils) which are not so fit to produce the food crops, directly.

Key words: Agroforestry, Salt-affected soils, Bio-ethanol, Biomass, Ligno-cellulose, Bio-energy, Emission

Introduction

Globally, alternate energy sources, sustainable, environmental friendly, renewable in nature, and economically viable are the need of the present time. Fossil fuels aremain source for energy generation in all the sectors, contributing 80 per cent of the energy demand. Global energy demand is predicted to increase by 48 per cent in the coming twenty years owing to the impulsive increase in global population. Finite nature of fossil fuel with environmental concerns, are forcing us to explore other alternative sources. Depletion in fossil fuel reserves coupled with environmental vagaries has impelled significant interest in sustainable and environmental friendly bio-fuels. The transportation sector is responsible for 60 per cent of the global consumption of fossil fuels, which significantly contributes to the extensive pollution affecting the environment (IEA, 2008). The transport sector contributes 19.0 per cent of global CO_2 emissions (around 8 kg of CO_2 per gallon of gasoline) and over 70 per cent of carbon monoxide emission (Balat and Balat, 2009). Due to these impacts, there is a growing interest in alternative fuels, such as bio-fuels, to reduce dependence on petroleum, cut trade deficits, and minimize air pollution and carbon emissions. This will support the change towards carbon-neutral bio-economy. Bio-diesel and bio-ethanol are particularly promising; bio-diesel can replace diesel, while bio-ethanol serves as a substitute for petrol (Aditiya *et al.,* 2016). However, research on second-generation bio-ethanol remains limited compared to bio-diesel (Silitonga *et al.,* 2013; Ong *et al.,* 2013).

Bio-ethanol is renewable fuel produced via fermentation of carbohydrates from ligno-cellulosic biomass, utilizing complex enzymatic processes.Ethanol has been blended with gasoline to enhance air quality, reduce carbon emissions, increase energy independence, lower fuel prices, and maintain vehicle performance. It reduces greenhouse gas emissions by 44 to52 per cent compared to gasoline. In 2023, ethanol in gasoline reduced CO-equivalent emissions by 56.5 million metric tons (Association, 2024). Bio-ethanol is particularly suitable for internal combustion engines, as it has a high antiknock value and effectively prevents engine knocking and premature ignition (Balat and Balat, 2009; Demirbas, 2009). Despite its lower energy content compared to gasoline (about 68.0% less), bio-ethanol's high oxygen content leads to cleaner combustion and reduced emissions of harmful substances. It has the potential to lower CO_2 emissions up to 80 per cent compared to gasoline, stimulating cleaner environment (Krylova *et al.,* 2008).

Since last one decade, interest in the second-generation bio-ethanol production from non-food ligno-cellulosic biomass rapidly increased owing to its abundance,low cost,andrenewability. Ligno-cellulosic biomass is equally distributed on the earth, than the fossil-fuel resources, which provides safetyin supplying domestic energy sources. It can be got from diverse residues or may be directly harvested from forest areas and its price is generally lower than of sugar or starch containing feed stocks. Bio-ethanol production straightway fits into zero waste circular economy, and using ethanol as substitute fuel which gives chance for world economy to turn into independent of the petro-chemical industry, providing energy safety and environmental security. Commercial production of cellulosic ethanol is still in infancy stage, being troubled by towering cost of research and development, and fabulous efforts are being required to convert it into more widespread and profitable spheres. Production of bio-ethanol from materials that have lingo-cellulose is pretty and sustainable due its renewable nature and no direct competition to edible crops (food).

This review article summarizes an overview of the bio-ethanol significance, extraction process, options of agroforestry systems with ligno-cellulosic trees and companion crops prevalent on salt affected landscapes of the country being used to produce second-generation bio-ethanol,as alternative to petroleum in the transport industry. As such no direct information of the biomass obtained from the agroforestry practices put to direct use for second generation bio-ethanol production exacting to salt affected landscapes but the eventual possibilities are there in the future.

Bio-ethanol: Future Global Fuel

The world is forced to shift towards renewable source of energy (bio-fuels) because of doubts on the availability and fluctuating prices of fossil fuels (Bhaskar and Pandey, 2015) supplemented with environmental concerns. Bio-fuels, derived from organic materials, are categorized into primary and secondary types. Primary bio-fuels, like fuel wood, are used directly for heating, cooking, or electricity generation, while secondary bio-fuels, such as bio-diesel and bio-ethanol, are processed from biomass and used in vehicles and numerous industries. Modern society relies heavily on fossil fuels for transportation and petrochemical needs, but this dependency has amplified greenhouse gas emissions and raised environmental concerns (Barua *et al.,* 2023; Sharma *et al.,*2020). With depleting fossil reserves and growing energy demands, the search for eco-friendly, bio-degradable, and cost-effective alternatives has been intensified. Bio-fuels produced from renewable resources, like bio-ethanol, offer promising solutions for reducing greenhouse gas emissions, reducing dependence on foreign oil, enhancing energy security, and promoting the sustainability of the global transportation sector (Demirbas, 2009).

Traditionally, bioethanol is made from sucrose and starch-rich feedstocks, also known as first-generation bio-ethanol. However, these feedstocks conflict with food and feed production systems. As a more sustainable alternative, cellulosic bio-ethanol production focuses on ligno-cellulosic materials, which include agricultural residues (such as straw,bagasse, and stover), forest trees, energy crops, and industrial wastes. These materials are abundant, inexpensive, and don't compete with food crops, making them viable feedstock for bio-ethanol production (Sharma and Sharma, 2018; Aditiya *et al.,* 2016; Sharma *et al.,* 2016).

Bio-ethanol can be produced from a diverse renewable materials enriched in carbohydrate that can behydrolysed into fermentable sugars and changedinto ethanol. Mainly, three types of feedstocks are used for bio-ethanol production: first-generation bio-ethanol from sucrose and starch crops like cereals, corn,sugarcane and other similar materials; second-generation bio-ethanol from ligno-cellulosic biomass (Robak and Balcerek, 2020; Aditiya *et al.,* 2016), and third-generation bio-ethanol from microalgae (Jambo *et al.,* 2016). First-generation bio-ethanol accounts for most global production, with over 27 billion gallons produced worldwide as per the estimated data in 2021, primarily in the United States of America (USA) and Brazil, which contribute around 85 per cent of the total output from sugarcane and corn (Association, 2024). However, the sustainability of first-generation bio-ethanol is under scrutiny due to concerns about its impact on the food security, land and the water resources and soil contamination, prompting research into second and third-generation bio-ethanol production methodologies (Bhatia *et al.,* 2017; Sharma *et al.,* 2020). Second-generation bio-ethanol utilizes non-food ligno-cellulosic biomass, offering more sustainable and economically viable solutions to meet energy demands (Devi *et al.,* 2022). Ligno-cellulosic biomass is the potential source to address the global energy crisis by producing second-generation bio-fuels without sacrificing the global food security (Zoghlami and Paes, 2019). This biomass production is from the agricultural and forestry sectors such as crop residue or by-products of wood processing industries (Maroua *et. al.,* 2019).

Bio-fuels are categorized based on their feedstock sources and production processes, which impact their sustainability and environmental footprint. First-generation bio-ethanol is derived from edible materials (food crops) enriched in sugars or starches, such as sugarcane, wheat and corn (Muktham *et al.,* 2016). This type of bio-ethanol benefits from well-established production processes and infrastructure, making it more commercially viable. However, it raises concerns regarding food security and environmental degradation due to its reliance on edible crops (Werpy *et al.,* 2004).In contrast, second-generation bio-ethanol is derived from non-edible material, including ligno-cellulosic materials like agricultural (e.g.: corn-stover, wheat-straw) and forest residues and, energy-crops (e.g.:miscanthus and switch grass) and industrial waste (Bhatia *et al.,* 2017; Sharma and Sharma, 2018; Barua *et al.,* 2023). This type of bio-ethanol is considered more sustainable as it does not compete with food production and utilizes waste materials. Nevertheless, it faces significant technological, cost, and process efficiency challenges that hinder its large-scale adoption (Muktham *et al.,* 2016).

The third-generation bio-fuels are derived from aquatic biomass such as algae, which offer an alternative energy source that overcomes the limitations of the first and second-generation bio-fuels (Nigam and Singh, 2011). Microalgae produces 15 to 300 times more bio-diesel per unit area basis compared to traditional crops, offering a promising solution for future energy needs without the drawbacks associated with earlier bio-fuel generations (Nigam and Singh, 2011). As technological advances, second and third-generation bio-fuels are expected to play more protruding roles in sustenance of energy driven scenario. Recently, the one more advanced bio-fuel has been recognisedis fourth-generation bio-fuel which are derived from engineered modified plants and micro-organisms (Bhaskar and Pandey, 2015).

Converting Ligno-cellulose Biomass to Bio-ethanol

The conversion of ligno-cellulosic biomass to bio-ethanol is complex and long process which involves steps right from raw material sourcing, transportation, pre-treatment of biomass,

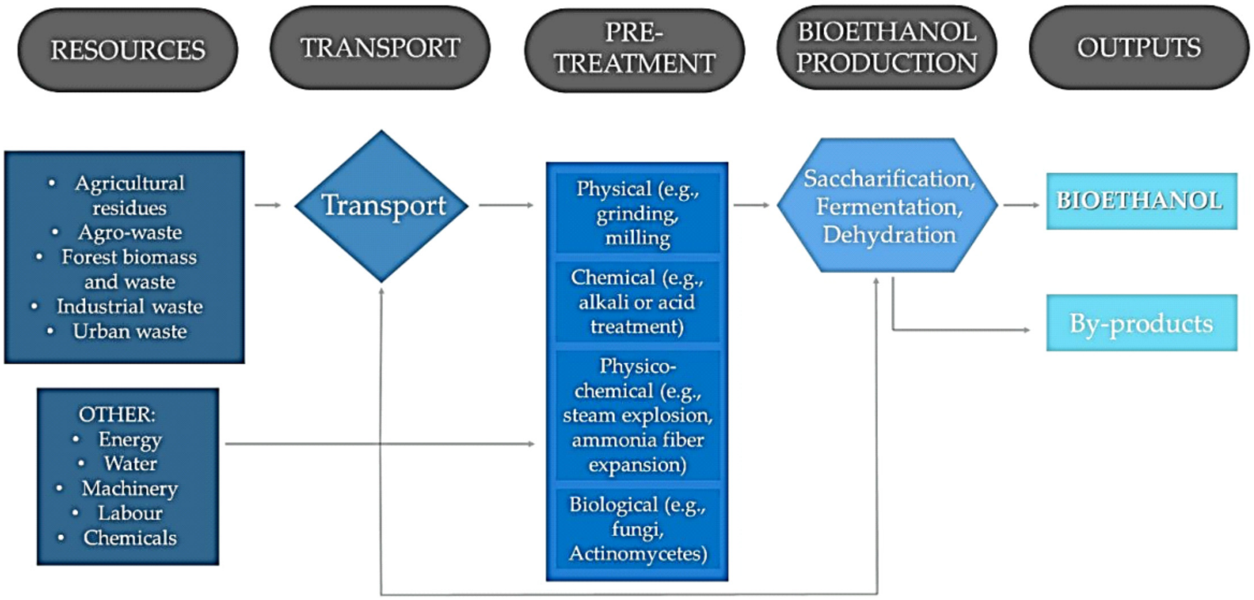

Fig. 1 Steps of bio-ethanol production (Source: Broda *et. al.,* 2022)

saccharification, fermentation, dehydration, products and by-products management including other requisite inputs of labour, machinery and chemicals (Fig. 1) (Broda *et. al.,* 2022). The steps like transportation of biomass, use of other inputs viz. energy, labour, chemical, water and machinery are of utmost significance but here in this review article, the focus is only on processes directly linked for converting complex structure of ligno-cellulosic biomass into bio-ethanol, namely pre-treatment, enzymatic-hydrolysis, fermentation and distillation (bio-ethanol release) and by-products recovery as described below:

Pre-treatment

The pre-treatment step intends to make cellulose and hemi-cellulose easily accessible to enzymatic-hydrolysis by disrupting the lignin and crystalline cellulose structures. This process is responsible to separate carbohydrates from lignin by breaking down the hydrogen-bonds of cellulose chains (Haghighi *et al.*, 2013; Das *et al.*, 2021; Awogbemi *et al.,* 2022). Pre-treatment methods can be physical (milling, grinding), chemical (acid, alkaline, steam explosion), or biological (using fungi or other microorganisms) (Sun and Cheng 2002; Kumar *et al.,* 2009; Mankar *et al*., 2021). Each method is chosen based on the biomass type and desired outcome, with the objective of increasing the yield of fermentable sugars.It is also there that no universal pre-treatment for all biomasses for satisfactory results are available. Therefore, specific technique with respect to available biomass for pre-treatment is still a subject of concern for the researchers which needs due attention in the current and future time (Das *et al*., 2021; Hasan *et al.,* 2018; Haghighi *et al*., 2013). Chipping, grinding and milling techniques are under physical pre-treatment for crushing of ligno-cellulosic biomass. The ultimate particle size is up to 10-30 mm or 0.2-2.0 mm based on the employed method. Contrary to this, chemical pre-treatment is done through the application of the various chemicals like alkalis (dilute solutions NaOH, KOH, $Ca(OH)_2$ and ammonia), acids (HCL and H_2SO_4), gases, salts, ionic liquids, oxidising agents and organic solvents (acetone, alcohols, propionic acid, phenols, amines, esters, formaldehydes), to make ligno-cellulosic biomass more susceptible to hydrolysis (enzymatic) (Haghighi *et al*., 2013; Safarian *et al*., 2018). Sometimes, both physical and chemical methods are being used for effective pre-treatment. Ligninolytic microorganisms (bacteria and fungi) or their enzymes enhance accessibility of ligno-cellulosic biomass for hydrolysis ensuing bio-ethanol production. White rot-fungi are most effective and main among four industrially significant species are *Trametes versicolor, Phanerochaete chrysosporium*, *Ceriporiopsis* *subvermispora* and *Pleurotusos treatus*. The commonly used bacterial-strains are species of *Clostridium*, *Cellulomonas*, *Bacillus*, *Thermomonospora* and *Streptomyces*. However, this method is driven by some drawbacks including higher space requirement, slow occurring rate of the process and need of unremitting check of microbial growth and activity (Das *et al.*, 2021; Rezania *et al.*, 2020; Ummalyma *et al.*, 2019; Vasco-Correa *et al.*, 2016).

Hydrolysis

Enzymatic hydrolysis is done to obtainsimple sugars (glucose, pentoses, hexoses and xylose) from the polysaccharides exist in the pre-treated ligno-cellulosic biomass (cellulose and hemicellulose) (Pandey, 2015). The effectiveness of this stage depends on pre-treatment efficiency, enzyme concentration, and reaction conditions. Enzymes used as catalyst in hydrolysis of xylan (cellulose and hemi-cellulose) with equal weightage of acids and alkalis (Robok and Balcerek, 2020; Tsai and Meyer, 2014). More accessible amorphous structure of hemi-cellulose is responsible for easy hydrolysis than cellulose. Cellulose driven with more diverse composition and structure with side chains of numerous sugar types, requires complex arrays of enzymes for complete hydrolysis. The most key attributes in hydrolysis are solid loading, sugar concentration, enzyme-loading, shaking-speed, hydrolysis-time, inhibitors concentration and the additives (Robok and Balcerek, 2020; Abdou *et al.,* 2020)

Ethanol fermentation

In ligno-cellulosic biomass hexoses (glucose, fructose and sucrose) and pentoses (xylose, mannose, galactose and arabinose) being responsible for the ethanol fermentation. In glucose fermentation, *Zymomonas mobilis* and *Saccharomyces cerevisiae* strains are main in use, because of high ethanol production and resistance to the high ethanol concentration (up to 120.0 g/L). They are also unableto ferment pentoses, hampering ethanol production from ligno-cellulosic biomass. The examples of natural fermenting pentoses are yeast *Candida shehatae*, *Pichia stipitis* and *Scheffersomyces stipites*. In pentose fermenting yeasts, large scale use is subdued by their sensitivity to higher ethanol-concentration (>40 gL^{-1}) and in able for fermenting xylose at lower pH levels (Robok and Balcerek, 2020). Key challenges in ethanol fermentation is efficiently fermenting both six-carbon (hexose) and five-carbon (pentose) sugars, as many microorganisms do not naturally ferment pentoses (Kumar *et al.,* 2009; Mankar *et al.,* 2021).

Distillation and dehydration

Both steps are vivacious in getting fuel grade ethanol from ligno-cellulosic biomass. Ethanol obtained from fermentation is mixed with water and other by-products. Distillation allows the separation of ethanol from the miscible liquid mixture via consecutive evaporation and condensation processes (Kang *et al.,* 2019). The water content in the post-mixture is quite high, oftenly more than 80.0 per cent of dry weight (Haghighi *et al.*, 2013). Finally, it is purified through distillation to separate the ethanol from the water, followed by dehydration processes (using molecular sieves) to achieve better quality dry-product, holds minimum 99.5 per centethanol by volume (Pan *et al.,* 2005; Robok and Balcerek, 2020). Separation of ethanol from fermented broth is done through various methods like adsorption, distillation, membrane processes, azeotropic distillation, diffusion distillation, extractive distillation, pervaporation, vacuum distillation and chemical dehydration, but amongst them only membrane distillation and pervaporation are most effective and economical (Broda *et al.,* 2022; Aditiya *et al.*, 2016).

Co-product recovery

Lignin by-product can be utilized for energy production or as a raw material in producing chemicals and other materials of significance.

Second-Generation Bio-ethanol Production Options in India

Second-generation bio-ethanol in India offers the promising solution for sustainable fuel production by utilizing agricultural and industrial waste instead of food crops. While ethanolblended petrol, such as E20 (20% ethanol), is considered a viable alternative fuel for transportation, concerns remain over the use of food resources like molasses, rice, and maize for ethanol production, which raises the issue of "food v/s fuel" (Jain, 2022). The Indian government plans to achieve 20.0 per cent ethanol blending in petrol by 2025, requiring approximately 1,016 crore litres of ethanol annually, according to the Ministry of Petroleum and Natural Gas (MoP&NG). Currently, India produces around 684 crore litres of ethanol from sugarcane-derived molasses and surplus grains, with a target of increasing it to 1,500 crore litres by 2025. This expansion would require significant quantities of grains and sugar, potentially heightening concerns about food security and water usage (Jain, 2022).However, second-generation (2G) bio-ethanol technology could help in addressing these challenges by converting agricultural waste such as rice straw, wheat straw, cotton stalks, and corn residuesinto ethanol. This approach not only reduces the environmental impact of stubble burning but could also cut approximately 3,20,000 metric tonnes of CO_2 emissions annually, enhancing both economic and environmental sustainability in India's bio-fuel sector (Jain, 2022).

Agroforestry Options in Bio-ethanol Production from Salt-affected Landscapes

Agroforestry is a land-use system that includes socially and ecologically acceptable mixing of trees with agricultural-crops and/or animals in simultaneously and/or sequentially pattern on same unit of land to get higher returns on sustainable wayparticularly under low levels of technological backups that too in marginal lands (viz. salt-affected lands). It has been recognized as the science of designing and evolving integrated self-sustainable land management models, involving introduction and/or retention of woody components (trees, shrubs, bamboos, canes, palms) with agronomical-crops including pasture and/or animals, concurrently or sequentially on the same unit of land and time, to cater the ecological and socio-economic needs of the populace. Agroforestry catersnearly half of the demand of fuel wood, 2/3rdof the small-timber, 70-80 per cent wood for plywood, 60 per cent raw material for paper-pulp and 9.0 to 11.0 per cent of the green-fodder requirement of livestock (Dhyani *et al.,* 2009). Agroforestry offers significant advantages over conventional agriculture and forestry, including improved soil health, greater biodiversity, better water management, and enhanced climate resilience. Furthermore, by providing fuelwood, agroforestry reduces pressure on natural forests and mitigates forest degradation caused by activities like charcoal production (Ouya, 2013). Agroforestry is particularly noted for its potential in producing second-generation bio-ethanol from ligno-cellulosic biomass, especially in silvo-pastoral systems, bio-energy/multipurpose wood lots forestry, that too in salt affected landscapes, a sustainable alternative to first-generation bio-fuels that rely on food crops. Some other agroforestry systems like agri-silviculture, agri-silvi-horticulture is also equally competent to produce second-generation bio-fuel i.e. bio-ethanol.

Extent of Area for Bio-ethanol Production from Ligno-cellulosic Biomass in Salt-affected Landscapes

Seventeen Indian states (Andhra Pradesh, Telangana, Bihar, Jharkhand, Gujarat, Haryana, Punjab, Karnataka, Kerala, Maharashtra, Madhya Pradesh, Chhattisgarh, Odisha, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal) and two union territories (Andaman & Nikobar and Lakshadweep) have salt- affected areas to the tune of 7 m ha. The major (14.2%) chunk of salt-affected region is found in Gujarat Plains & Hills region followed by East Coast Plains & Hills region (13.7%), Upper Gangetic Plains (12.6%), Trans-Gangetic Plains (11.3%), Central Plateau & Hills region (10.7%), Southern Plateau & Hills region (7.90%), Middle Gangetic Plains (7.00%) with lowest 0.50 per cent in Eastern Plateau. As per one of the estimate that semi-arid and arid regions have the minimum (1.20%) and maximum (26.9%) coverage under un-suitable category for farming practices (Firoz *et al.,* 2019).

The possible agroforestry systems in salt-affected landscapes are summarised in table 1.0 along with classes/groups of salt affected soils, distribution and covered area.Indo-Gangetic plains (IGP) spreads over an area of 43.7 m ha and is rich in prominent agroforestry systems of silvo-pastoral system, silvi-agriculture system, conventional/traditional systems, energy plantation systems, horti-agri-system, etc. Such agroforestry systems cover an area of 2.50 m ha and contributing about 10 per cent of the total area under agroforestry in India. Arid and semi-arid zones of India covering about 127 million ha and accounts 52.8 percent of the total geographical area (Kalsi, 2007) encompasses different agroforestry systems ranging from permanent (silvi-pastoral) to highly specialized system of homestead gardening. Khejri (*Prosopis cineraria*) based silvi-agriculture system is prevalent in arid region of the north-western India. Salt-affected soils in arid and humid region of deltaic coastal areas cover the low lying and flood plains areas of Gujarat, West Bengal, Odisha, Andhra Pradesh, Tamil Nadu and Andaman & Nicobar. Deltaic coastal areas are predominant with mangroves and associated halophytes besides other natural vegetation of evergreen, semi-evergreen and deciduous forests on uplands and grazing lands in pockets. Agroforestry practices apparently ranged from simple forms of shifting cultivation to the sophisticated hedgerow farming of sparse stands of trees to high density, complex home-gardens of lowland.

The estimated area covered under agroforestry in India is 25.3 m ha which spreads to 8.28 per cent of the total geographical area of the country. On an average 14.2 per cent of total cultivated land has agroforestry in one or the other form, which includes 11.2 per cent in irrigated and 16.5 per cent in rainfed areas (Dhyani *et al.*, 2013). The area under agroforestry in salt-affected soils is 7.02 m ha out of the total 25.3 m ha in the country. About 27.7 per cent area under agroforestry is in the salt- affected soils which is of significance and will have the edge to expand further in near future.

Diverse Flora (Trees and Grasses) in Salt-affected Landscapes for Ligno-cellulosic Biomass Production

However, the kitty of flora is not so diverse with respect to the salt affected lands across the country contrary to the good soils. But, few of them have a good potential to rehabilitate the salt-affected landscapes with the additional benefit of giving ligno-cellulosic biomass while growing in some form of agroforestry fashion. The flora is categorised into highly tolerant, moderately tolerant and less tolerant depending upon the tolerance limit of salinity and alkalinity. Very efficient and productive agroforestry systems existed in less salt affected soils and their efficiency is declined with increase in the salt load in the soil. But, in the present context (bio-ethanol production) ligno-cellulosic biomass can be produced efficiently from the highly sodic and highly saline soils with low inputs. Tree species such as Simarouba (*Simarouba glauca*), sugar palm (*Arenga pinnata*), and nypa palm (*Nypa fruticans*) are recognized for their suitability in bio-ethanol production (Sharma *et. al.,* 2016). Although the technology for converting ligno-cellulosic biomass to second-generation bio-ethanol is still developing, agroforestry systems are expected to play a more prominent role in global bio-ethanol production with the advancement in these technologies. In addition to bio-ethanol, bio-diesel production from tree species like oil palm (*Elaeis guineensis*) and jatropha (*Jatropha curcas*) offers further opportunities. Oil palm has demonstrated great promise for producing multiple products, including bio-diesel (Chew and Bhatia, 2008). However, challenges in realizing the full potential of jatropha suggest a need for better agronomic practices (Pandey *et al.,* 2011; Behera *et al.,* 2010). The integration of bio-fuel production into agroforestry could significantly reduce the carbon footprint, provided that these systems are designed to sustainable biomass production without affecting food security (Sharma *et al.,* 2016). Additionally, residues from bio-fuel production, such as oilseed cakes, can enhance biogas production and reduce greenhouse gas emissions when used as renewable alternatives to fossil fuels (Weiland, 2010).

Some prominent tree species suitable to salt affected lands in agroforestry systems are *Acacia tortilis* (Israeli babool), *Prosopis juliflora* (Vilayati babool), *Prosopis cineraria* (Khejri), *Azadirachta indica* (Neem), *Albizzia Iebbek* (Siris), *Acacia. senegal* (Kumat), *Dichrostachys glomerata*, *Cassia siamea* (Kala siris), *Tamarix articulata* (Farash), *Holoptelia integrifolia* (Churel), *Colophosper mummopane*, *Zizyphus nummularia* (Bordi), *Dalbergia sissoo* (Shishum), *Butea monosperma,* (Dhak), *Eucalyptus spp., Leucaena leucocephala, Melia composita and M.*

Table 1. Grouping of salt-affected areas of Indian states with existing prominent agroforestry systems and area coverage

S. No.	Groups/classes of salt affected soils	Indian states	Prominent agroforestry systems	Area under agroforestry (million ha)
1.	Sodic soils of Indo-Gangetic plains	Uttar Pradesh, Haryana, Punjab, Bihar, Madhya Pradesh and Rajasthan	• Silvo-pastoral system • Silvi-agriculture system with halophyte trees • Conventional/traditional systems • Energy plantation systems • Horti-agri-system	2.50
2.	Salt-affected soils (saline and sodic) in arid and semi-arid regions	Punjab, Haryana, Rajasthan, Andhra Pradesh, Karnataka, Maharashtra, Tamil Nadu and Uttar Pradesh	• Permanent agroforestry (Silvo-pastoral system) • Agri-silviculture system • Bio-drainage systems (boundary and block) with salt tolerant phreatophytes tree species • Multi-purpose trees on croplands (Scattered trees in agriculture fields followed by block energy and boundary plantations especially shelter-belts, wind breaks and hedges) in arid regions. • Alley cropping system	1.00
3.	Salt-affected soils in areas of medium and deep black soils	Karnataka, Madhya Pradesh, Maharashtra and Gujarat	• Alley cropping system • Agri-silviculture system • Silvi-pastoral system • Protein banks (Growing of protein rich tree fodder on farm/rangelands)	1.42
4.	Salt affected soils in arid region of coastal areas	Gujarat	• Silvo-pastoral system • Alley cropping • Home gardens • Taungya • Forest farming • Live fence (Shelter belts, wind breaks)	0.71
	Salt affected soils in humid region of deltaic coastal areas	West Bengal, Odisha, Andhra Pradesh, Tamil Nadu, Andaman & Nikobar	• Alley cropping • Home gardens • Alley cropping • Silvi-pastoral • Horti-silvi-pastoral • Live fence (Shelter belts, wind breaks) • Wood lots	1.39
			Total area	7.02
			Total area under agroforestry in India	25.3
			%age of agroforestry area to the total recorded geographical area in India	8.28
			%age of agroforestry in salt affected areas to the total area under agroforestry in India	27.7

Sources: (Dhyani *et al.,* 2013, 2014, Dagar *et al.*, 2014; Vasave *et al.*, 2015)

dubia, Salix spp., Pongamia pinnata, Syzygium cuminii, *Emblica officinalis*, *Tecomella spp., Salvadora persica, S. oleoides*, *Pithocellubium dulce*, *Capparis decidua*, etc. may be useful for bio-ethanol production. In addition to trees, halophytic grasses are very significant that too in silvo-pastoral systems in highly sodic soils in arid and semi-arid region of the country. List of few potential halophytic grasses and some other plants with their partitioning percentage of cellulose, hemi-cellulose and lignin is appended in Table 2.

Eventual Agroforestry Models for Second Generation Bio-ethanol Production in Salt-affected Landscapes

Agroforestry production models integrate trees with crops/grasses to create systems that offer multiple benefits, such as improved soil fertility, increased biomass for bio-energy. Some practical examples of agroforestry production models for bio-ethanol production using tree species on salt - affected landscapes are as:

Table 2. Halophytic grasses and some other plants primarily grown in salt-affected soils for ligno-cellulosic biomass production

S. No.	Grass name	Family	%age of cellulose and lignin			Reference
			Cellulose	Hemi-cellulose	Lignin	
1	*Panicum virgatum*	*Poaceae*	45.0	31.0	12.0	McLaughin and Kszos, 2005
2.	*Phragmites australis*	*Poaceae*	50.0	-	17.0	Yan *et al.*, 2010
3.	*Aeluropuslagopoides*	*Poaceae*	26.7	29.3	7.67	Abideen *et al.,* 2011
4.	*Aervajavanica*	*Amaranthaceae*	15.7	13.3	6.33	Abideen *et al.*, 2011
5.	*Arthrocnemumindicum*	*Amaranthaceae*	11.3	13.0	7.00	Abideen *et al.*, 2011
7	*Cenchrusciliaris*	*Poaceae*	22.7	23.2	7.00	Abideen *et al.*, 2011
8.	*Cholorisbarbata*	*Poaceae*	25.3	23.0	8.33	Abideen *et al.,* 2011
9.	*Desmostachyabipinnata*	*Poaceae*	26.7	24.7	6.67	Abideen *et al.,* 2011
0.	*Dicanthiumannulatum*	*Poaceae*	19.0	24.3	7.00	Abideen *et al.,* 2011
11.	*Eleusine indica*	*Poaceae*	22.0	29.7	7.00	Abideen *et al.,* 2011
12.	*Halopyrummucronatum*	*Poaceae*	37.0	28.7	5.00	Abideen *et al.,* 2011
14.	*Lasirusscindicus*	*Poaceae*	24.7	29.7	6.00	Abideen *et al.,* 2011
15.	*Panicum turgidum*	*Poaceae*	28.0	27.9	6.00	Abideen *et al.*, 2011
16.	*Paspalampaspaloides*	*Poaceae*	20.3	33.0	2.33	Abideen *et al.*, 2011
17.	*Phragmiteskarka*	*Poaceae*	26.0	29.0	10.3	Abideen *et al.*, 2011
20.	*Sporobolusioclados*	*Poaceae*	15.3	30.7	2.00	Abideen *et al.*, 2011
21.	*Suaedamonoica*	*Amaranthaceae*	10.7	11.3	2.33	Abideen *et al.*, 2011
22.	*Suedafruuticosa*	*Amaranthaceae*	8.67	21.0	4.67	Abideen *et al.*, 2011
24.	*Typhadomingensis*	*Poaceae*	26.3	38.7	4.67	Abideen *et al.*, 2011
25.	*Urochondrasetulosa*	*Poaceae*	25.3	25.0	6.33	Abideen *et al.*, 2011
26.	*Miscanthus spp.*	*Poaceae*	40-60	20-40	10-30	Abideen *et al.*, 2011
27.	*Achnatherumsplendens*	*Poaceae*	-	-	16.7	Xian-zhao *et al.,* 2012

Silvo-pastoral systems

Promising salt tolerant multi-purpose trees (MPTs) along with grasses are grown under this system of agroforestry. Most suitable tree species for reclamation of alkali soils are *Prosopis juliflora*, *Vachelia nilotica*, *Casuarina equisetifolia*, *Terminalia arjuna*, *Tamarix articulata*, and *Pongamia pinnata.* Similarly, grass species are *Leptochloa fusca*, *Chloris gayana*, *Brachiaria mutica* and *Sporobolus* spp. In waterlogged saline areas, various grasses namely such as *Leptochloa fusca* (Karnal grass), and species of *Aeluropus*, *Eragrostis*, *Sporobolus*, *Chloris*, *Panicum*, *Bracharia* can be successfully cultivated and/or grown along with salt tolerant trees for viable and sustainable silvo-pastoral systems to sustain livestock productivity (Dagar, 2014). *Aeluropus lagopoides*, *Sporobolus helvolus*, *Cynodon dactylon*, *Brachiaria ramosa*, *Paspalum* spp., *Echinochloa colonum*, *E. crusgalli*, *Dichanthium annulatum*, *Vetiveria zizanioides*, and *Eragrostis* sp. are important grasses which are adapted in both salinity and waterlogging situations and are suitable to grow in this systems. *Ziziphus*, *Atriplex*, *Kochia*, *Suaeda*, *Salsola*, *Haloxylon* and *Salvadora* are other prominent forage shrubs of saline regions and browsed by camel, sheep and goat have the potential to grow in such marginal landmasses (Dagar, 2014). In another type of system, developed for Indo-Gangetic plains (semi-arid region) *Acacia nilotica+ Chloris gayana* based silvo-pastoral system was found to be highly efficient, productive and viable option for reclaiming sodic soils over silviculture (pure woodlot) and fallow land use for ligno-cellulosic biomass production. For the economic utilization of saline soil, it is necessary to adopt tree based use systems inducting trees such as *Atriplex amnicola, Tamarix aphylla*, *Phoenix dactilifera*, *Prosopis spp.*, *Casuarina spp.*, etc. along with the grasses.Silvo-pastoral systems combine tree species, like *Sesbania sesban* and *Calliandra calothyrsus*, with pasture grasses and livestock. These trees produce woody biomass suitable for bioethanol production (Singh, 2009; Dagar *et al.,* 2014). *Prosopis juliflora+Leptochloa* silvo-pastoral system gave better production with biological reclamation benefits in alkali soils and an option for bio-ethanol production (Singh *et al.,* 2014). On the basis of biomass production and improvement in soil health due to tree + grass systems, silvi-pastoral system could be adopted for reclamation of alkali soils in central Indo-Gangetic plains. *Dalbergia sissoo* based silvo-pastoral system with grasses like *Pennisetum purpurium, Bracharia mutica* and *Panicum maximum* as intercrops is also viable option for sodic soils to have ligno-cellulosic biomass (Parihar and Saxena, 2016).

Agri-horticulture systems

Various fruit trees based agroforestry systems were developed and are commonly practiced by the farming communities at large in normal soils and sporadically in salt affected soils. Dagar *et al*. (2016) developed low-water intensive, salt-tolerant fruit trees based agroforestry systems with saline irrigation in semi-arid regions of the country. Fruit trees (*Carissa carandas*-(karonda), *Emblica officinalis* (Aonla) and *Aegle marmelos* (Bael)) and the intercrops (*Hordeum vulgare* (barley), *Brassica juncea* (mustard), *Cyamopsis tetragonoloba* (cluster bean) and *Pennisetum typhoides* (Pearl millet)) were grown in the interspaces. This biomass can be the option for second generation bio-ethanol production. *Casuarina* and guava based agri-slivi-horticulture system developed for sodic soils in central India (Parihar and Saxena, 2016). Olive is also one of the promising fruit trees suitable in saline environments, which is a glycophytic species that avoids salinity stress essentially (Gucci and Tattini, 1997). A systematic investigation on screening and evaluation of potential Olive germplasm to alkalinity (upto pH 9.0) and salinity (upto 10 dS m^{-1}) tolerance was done at ICAR-CSSRI, Karnal, Haryana wherein *Arbequina* cultivar emerged as best performer with respect to biometric, physiological and biochemical responses than other cultivars (CSSRI, 2020). Olive cultivars (Arbequina, Koroneiki and Barnea) can be potential option for ethanol production. Olive pomace is one of the main substrate for meeting out the 4.37 per cent energy requirement of the transport sector in Algeria along with cereal straw (Maroua *et al*., 2019).

Agri-silviculture system

Eucalyptus-based agri-silvicultural systems identified for inland waterlogged saline soils of semi-arid ecosystem by Ram *et al.*, (2011), Dagar *et al*. (2016) and Banyal *et al*. (2019) have the possibility to contribute in production of ligno-cellulosic biomass for generating second generation bio-ethanol from waterlogged saline areas. For shallow saline situations, *Eucalyptus* (*Eucalyptus tereticornis*) and Melia (*Melia composita*)-based agri-silviculture systems developed with mustard and pearl millet as intercrops which can be also be seen as potential contributor to ligno-cellulosic biomass (Banyal *et al*., 2018; CSSRI, 2020).

Specialized agroforestry systems

Multipurpose woodlot systems (trees)

Special location specific multipurpose trees (MPTs) are grown in mixed or sole plantation for benefitting in supplying fuelwood, fodder, soil protection, soil amelioration, etc. But, now one more merit is associated about the production of second generation bio-ethanol production. Woodlot systems involve planting of all MPTs based on the prime objective. *Prosopis juliflora* woodlots have been established to produce biomass for energy. It is one of the promising MPTs for reclamation of saline-sodic lands which reduces the ECe and ESP and increased organic carbon (%) considerably. Although, initially considered invasive, its management as a woodlot species has provided substantial biomass for bio-ethanol production and contributed to soil restoration efforts.

Energy forestry systems

Energy plantation models can be visualized as potential alternative system in salt affected soils to produce second-generation bio-ethanol. This is of great significance because of its carbon neutral mode. It is equally significant to feed the fuelwood for domestic consumption with environmental and social benefits (Banyal, 2013; Banyal *et al.,* 2019). The suitable tree species for energy forestry in salt-affected soils are *Prosopis juliflora*, *Vachelia nilotica*, *Albizia lebbeck*, *Eucalyptus* *spp*., *Parkinsonia aculeata*, *Prosopis cineraria*, *Tamarix articulata*, *Leucaena leucocephala*, *Salix tetrasperma*, *Melia spp*. (*composita, azedarach and dubia*), Bamboo, *Terminalia arjuna*, *Salvadora spp*., *Azadirachta indica*, *Acacia auriculiformis, Ceiba pentandra, Calophyllum inophyllum, Pongamia pinnata* almost in all the agro-ecological regions of the country.

Challenges and Considerations in Second Generation Bio-ethanol Production

Production of bio-ethanol from ligno-cellulosic biomass is exceedingly challenging because of complexity and recalcitrance in the diversity of source of biomass. Several steps are required to separate the energy laden carbohydrates from the ligno-cellulosic substrate to have the final usable product bio-ethanol. Pre-treatment, hydrolysis, fermentation and distillation are the main steps which have some unique holdups in the complete production process, affecting its effectiveness and supplemented with higher working costs. Intensive research to develop new economically viable and environmentally efficient technologies for bio-ethanol extraction from ligno-cellulosic biomass is the need of the hour. Some of the pertinent challenges in second-generation bio-ethanol production are as follows:

Technological challenges

- Second and thirdgeneration bio-fuels face technological and scalability challenges.
- Efficiency of each step of production process, particularly pre-treatment and enzymatic hydrolysis, plays a crucial role in the overall yield and cost-effectiveness of the bio-ethanol production process. The selection of suitable strategy that should not impede with the overall efficiency of each extraction step, is still a millionaire question.
- In the second generation bio-ethanol production, specialized equipmentsare needed, making it expensive compared to first-generation bio-ethanol production.
- Inadequate carbohydrate degradation and inhibitors presence compromised the yield of bio-ethanol during pre-treatment stage, is a major challenge in the entire process. Compounds released during pretreatment (such as furfural, acetic acid, and phenolic compounds) can inhibit fermentation, requiring additional detoxification steps.
- Reduction in use of toxic chemicals, water and energy.
- Use of novel bio-catalyst for augmenting the proficiency of saccharification.
- Increase in the efficacy of enzymes specific to the activity (thermal stability, inhibitors).
- Downsizing the footprints of the complete process in addressing the climatic issues.
- Need to have the complete know-how about the structure and composition of different ligno-cellulosic biomass with effect on individual pre-treatment at macro and micro (molecular) levels.
- Lack of understanding about the interactions between ligno-cellulosic biomass, micro-organisms, products and by-products generated during the entire process of extraction of bio-ethanol fuel.
- Existing knowledge is quite broad but still there is need to bring the process of bio-ethanol generation, a profitable venture, when we talk about its commercial use.
- Some bio-fuels may require modifications to existing engines or fuel distribution infrastructure, which can be costly and limit their adoption.

Energy balance and efficiency

- Bio-fuels, especially first-generation bio-fuels, have lower energy yields compared to fossil fuels.
- Inefficient conversion processes can reduce net energy gains from bio-fuel production.

Economic viability

- Bio-fuels can be expensive to produce, especially second-generation bio-fuels made from non-food sources.
- Market competition with fossil fuels can be challenging in periods of low oil prices.

Environmental impact

- Bio-fuel production can lead to indirect land-use changes and soil degradation.

Logistical and supply chain issues

- Bio-fuel feedstocks can be bulky and expensive to transport.
- Seasonal availability of bio-fuel crops can make continuous bio-fuel production challenging.

Government policies and subsidies

- Policy uncertainty and varying environmental standards and regulations can hinder investment in bio-fuel technologies.

Conclusions

Second generation bio-ethanol production is a promising solution to address the energy and environmental crisis not only at country level but also globally. Fossil fuels are finite, catering 80 per cent of energy demand but with costing of environment. It's cause of concern for everyone that forced to explore the alternate environment friendly with sustenance bio-energy sources. Ligno-cellulosic biomass, a renewable and extensively available resource from agriculture and forestry waste, is being seen as the option to produce second-generation bio-ethanol. However, there are holdups in its conversion to bio-ethanol which needs research to get rid of them. As per an estimate, 27.7 per cent area (7.02 m ha) under agroforestry is in the salt affected soils in the country.Numerous trees and grass species have been shown their potential for ligno-cellulosic biomass from salt affected landscapes and can be promising in generating second-generation bio-ethanol. Agroforestry is particularly noted for its potential in producing second-generation bio-ethanol from ligno-cellulosic biomass, especially in silvo-pastoral systems, bio-energy/ multipurpose wood lots forestry, that too in salt-affected landscapes. Some other agroforestry systems like agri-silviculture, agri-silvi-horticulture is also equally competent for second-generation bio-ethanol production. Production of bio-ethanol from ligno-cellulosic biomass is exceedingly challenging with some due considerations namely technological, energy balance and efficiency, economic viability, environmental impacts, logistic and supply chain issues and government policies and subsidies to bring the second-generation bio-ethanol production at commercial level. The possible options agroforestry practices in-tune with salt affected soils has unique abilities to produce ligno-cellulosic biomass for bio-ethanol production. Development in second-generation bio-ethanol production is not as advanced as the first-generation production. However, in future looking at the possibility of feedstock's availability from marginal landmasses, it holds a massive potential if dedicatedly implemented at national and global level.

References

Abdou Alio M, Tugui OC, Rusu L, Pons A and Vial C (2020) Hydrolysis and Fermentation Steps of a Pre-treated Sawmill Mixed Feedstock for Bioethanol Production in a Wood Biorefinery. *Bioresource Technology*:310.

Abideen Z, Ansari R and Khan MA (2011) Halophytes: potential source of ligno-cellulosic biomass for ethanol production. *Biomass Bioenergy* **35**: 1818–1822.

Aditiya HB, Mahlia TMI, Chong WT, Nur H and Sebayang AH (2016) Second Generation Bioethanol Production: A Critical Review. *Renewable Sustainable Energy Review* **66**: 631–653.

Association RF (2024) Why is Ethanol Important? Renewable Fuels Association. https://ethanolrfa.org/ethanol-101/why-is-ethanol-important.

Awogbemi O and Von Kallon DV (2022) Pre-treatment Techniques for Agricultural Waste. Case Stud. *Chemical Environment Engineering* **6**.

Balat M and Balat H (2009) Recent trends in global production and utilization of bio-ethanol fuel. *Applied Energy* **86(11)**: 2273–2282.

Banyal R (2013) Short rotation culture with willows in hill farming systems, Book of Proceedings National Seminar on Indian Agriculture: Present Situation, Challenges, Remedies and Road map (Ed: Adarsh Kumar, Y.S. Dhaliwal; T.R. Sharma; R.K. Kapila; Pawan K. Sharma and J.D. Sharma*)*, Rachna publications, Pushpanjali Complex, Rajpur, Palampur, HP: 82-85.

Banyal R, Bhardwaj AK, Singh RK, Gajender, Pathan Aslam, Chander, Jagdish and Bhatia, VK (2019) Impact of Eucalyptus plantations on waterlogged saline ecologies in Indo-Gangetic plains, *Project Report*, ICAR-CSSRI, Karnal, Haryana: 84.

Banyal R, Yadav RK, Sheoran Parvender, Bhardwaj AK, Parveen Kumar, Raj Kumar and Tolia Rahul (2018)

Managing Saline Soils of Indo-Gangetic Plains with *Eucalyptus* and *Melia* based Agroforestry Systems, *Indian Journal of Ecology* **45(4)**: 841-849.

Barua S, Sahu D, Sultana F, Baruah S and Mahapatra S (2023) Bio-ethanol, internal combustion engines and the development of zero-waste bio-refineries: An approach towards sustainable motor spirit. *RSC Sustainability* **1(5)**: 1065–1084.

Behera SK, Srivastava P, Tripathi R, Singh JP and Singh N (2010) Evaluation of plant performance of *Jatropha curcas* L. under different agro-practices for optimizing biomass – A case study, *Biomass and Bioenergy* **34(1)**: 30–41.

Bhaskar Thallada and Pandey Ashok (2015) Advances in thermochemical conversion of biomass-introduction, In: Recent advances in thermos-chemical conversion of biomass. Elsevier, 3-30. https://doi.org/10.1016/B978-0-444-63289-0.00001-6.

Bhatia SK, Kim SH, Yoon JJ and Yang YH (2017) Current status and strategies for second generation bio-fuel production using microbial systems. *Energy Conversion and Management* **148**: 1142–1156.

Broda Magdalena, Yelle J Daniel and Serwanska Katarzyna (2022) Bioethanol Production from Ligno-cellulosic Biomass-Challenges and Solutions, *Molecules* **27**: 8717.

Chew TL and Bhatia S (2008) Catalytic processes towards the production of bio-fuels in a palm oil and oil palm biomass-based bio-refinery. *Bio-resource Technology* **99(17)**: 7911–7922.

CSSRI, (2020) *Annual Report 2019-2020*. ICAR-Central Soil Salinity Research Institute, Karnal, Haryana-132 001, India.

Dagar JC, Lal Khajanchi, Jeet R, Mukesh K, Chaudhary SK, Yadav RK, Sharif A, Singh G and Kaur A (2016) *Eucalyptus* geometry in agroforestry on waterlogged saline soils influences plant and soil traits in North-West India. *Agriculture, Ecosystem & Environment* **233**:33-42.

Dagar JC, Pandey CB and Chaturvedi CS (2014) Agroforestry: A Way Forward for Sustaining Fragile Coastal and Island Agro-Ecosystems. In: *Agroforestry Systems in India: Livelihood Security & Ecosystem Services, Advances in Agroforestry,* Ed. J.C. Dagar, *Springer Nature* Singapore: 185-232.

Das N, Jena PK, Padhi D, Kumar Mohanty M and Sahoo GA (2021) Comprehensive Review of Characterization, Pre-treatment and Its Applications on Different Lignocellulosic Biomass for Bio-ethanol Production. *Biomass Conversion Biorefinery* **82**: 1–25.

Demirbas A (2011) Competitive liquid biofuels from biomass, *Applied Energy* **88**(1): 17–28.

Demirbas MF (2009) Bio-refineries for bio-fuel upgrading: A critical review. *Applied Energy* **86**: S151–S161.

Devi A, Bajar S, Kour H, Kothari R, Pant D and Singh A (2022) Ligno-cellulosic Biomass Valorization for Bioethanol Production: A Circular Bio-economy Approach. *Bio-Energy Research* **15(4)**: 1820–1841.

Dhyani SK (2014) National Agroforestry Policy 2014 and the need for area estimation under agroforestry. *Current Science* **107**: 9-10.

Dhyani SK, Handa AK and Uma (2013) Area under agroforestry in India: an assessment for present status and future perspective. *Indian Journal of Agroforestry* **15(1)**: 1–11.

Dhyani SK, Kareemulla K, Ajit and Handa AK (2009) Agroforestry potential and scope for development across agro-climatic zones in India, *Indian Journal of Forestry* **32**: 181-190.

Firoz Ahmad Md, Meraj Uddin and Laxmi Goparaju (2019) Agroforestry suitability mapping of India: geospatial approach based on FAO guidelines, *Agroforest Systems* **93**: 1319–1336.

Gucci R and Tattini M (1997) Salinity tolerance in Olive. *Horticultural Reviews* **21**: 177–214.

Haghighi Mood S, Hossein Golfeshan A, Tabatabaei M, Salehi Jouzani G, Najafi GH, Gholami M and Ardjmand M (2013) Lignocellulosic Biomass to Bioethanol, a Comprehensive Review with a Focus on Pre-treatment. *Renewable Sustainable Energy Review* **27**: 77–93.

Hassan SS, Williams GA and Jaiswal AK (2018) Emerging Technologies for the Pre-treatment of Lignocellulosic Biomass. *Bio-resource Technology* **262**: 310–318.

IEA (2008) Key world energy statistics. Paris.

Jain R (2022) India's green push for second-generation bioethanol. Down to Earth. *https://www.downtoearth.org.in/energy/india-s-green-push-for-second-generation-bioethanol-85472*

Jambo SA, Abdulla R, Mohd Azhar SH, Marbawi H, Gansau JA and Ravindra P (2016) A review on third generation bio-ethanol feedstock. *Renewable and Sustainable Energy Reviews* **65**: 756–769.

Kalsi Rajiv S (2007) Status, distribution and management of Galliformes in arid and semi-arid zones of India. In Galliformes of India. ENVIS Bulletin: Wildlife and Protected Areas (Sathyakumar, S. and Sivakumar, K. (Eds.). vol. 10 (1). Wildlife Institute of India, Dehradun, India: 101-104.

Kang KE, Jeong JS, Kim Y, Min J and Moon SK (2019) Development and Economic Analysis of Bio-ethanol Production Facilities Using Ligno-cellulosic Biomass. *Journal Bio-science Bioenergy*. **128**: 475–479.

Krylova AYu, Kozyukov EA and Lapidus AL (2008) Ethanol and diesel fuel from plant raw materials: A review. *Solid Fuel Chemistry* **42(6)**: 358–364.

Kumar P, Barrett DM, Delwiche MJ and Stroeve P (2009) Methods for Pre-treatment of Lignocellulosic Biomass for Efficient Hydrolysis and Biofuel Production. *Industrial & Engineering Chemistry Research* **48(8)**: 3713–3729.

Mankar AR, Pandey A, Modak A and Pant KK (2021) Pre-treatment of ligno-cellulosic biomass: A review on recent advances. *Bio-resource Technology* **334**: 125-135.

Maroua Gares, Serge Hiligsmann, Noreddine Kacem and Chaouche (2019) Lignocellulosic biomass and industrial bioprocesses for the productionof second generation bio ethanol, does it have a future in Algeria? *SN Applied Science*, Springer Nature Switzerland AG.

McLaughlin SB and Kszos LA (2005) Development of Switchgrass (*Panicum virgatum*) as a Bioenergy Feedstock in the United States. *Biomass and Bioenergy* **28**: 515-535.

Muktham R, Bhargava SK, Bankupalli S and Ball AS (2016) A Review on 1st and 2nd Generation Bioethanol Production-Recent Progress. *Journal of Sustainable Bioenergy Systems* **6(3)**.

Nigam PS and Singh A (2011) Production of liquid biofuels from renewable resources. *Progress in Energy and Combustion Science* **37(1)**: 52–68.

Ong HC, Silitonga AS, Masjuki HH, Mahlia TMI, Chong WT and Boosroh MH (2013) Production and comparative fuel properties of biodiesel from non-edible oils: *Jatropha curcas*, *Sterculia foetida* and *Ceiba pentandra*. *Energy Conversion and Management* **73**: 245–255.

Ouya D (2013) Unpacking the evidence on firewood and charcoal in Africa (Agroforestry World Blog). World Agroforestry Centre. Available (online): *http://blog.worldagroforestry.org/index.php/2013/10/03/*.

Pan X, Arato C, Gilkes N, Gregg D, Mabee W, Pye K, Xiao Z, Zhang X and Saddler J (2005) Bio-refining of softwoods using ethanol organosolv pulping: Preliminary evaluation of process streams for manufacture of fuel-grade ethanol and co-products. *Biotechnology and Bioengineering* **90(4)**: 473–481.

Pandey KK, Pragya N and Sahoo PK (2011) Life cycle assessment of small-scale high-input Jatropha biodiesel production in India. *Applied Energy*, *88*(12), 4831–4839.

Pandey S (2015) Cellulases in conversion of lignocellulosic waste into second-generation biofuel. *International Journal of Advanced Research* **3(7)**: 392–399.

Parihar AKS and Saxena AK (2016) Agri-silvi-horticulture system for sodic lands. In Agroforestry technologies for different agro-climatic zones of the country (Eds.: Chaturvedi, O.P., Sikka, A.K., Handa, A.K. and Bajpai, C.K.), AICRP on AF, ICAR-CAFRI, Jhansi: 42-43.

Ram J, Dagar JC, Lal Khajanchi Singh G, Toky OP, Verma Tanwar, Dar SR and Chauhan MK (2011) Bio-drainage to combat waterlogging increase farm productivity and sequester carbon in canal command areas of North West India. *Current Science* **100 (11)**: 1-8.

Rezania S, Oryani B, Cho J, Talaiekhozani A, Sabbagh F, Hashemi B, Rupani PF and Mohammadi AA (2020) Different Pre-treatmentTechnologies of Ligno-cellulosic Biomass for Bioethanol Production: An Overview. *Energy* **199**.

Robak K and Balcerek M (2020) Current State-of-the-Art in Ethanol Production from Ligno-cellulosic Feed stocks. *Microbiological Research* **240**.

Safarian S and Unnthorsson R (2018) An Assessment of the Sustainability of Ligno-cellulosic Bioethanol Production fromWastes in Iceland. *Energy* **11**: 1493.

Sharma B, Larroche C and Dussap CG (2020) Comprehensive assessment of 2G bio-ethanol production. *Bio-resource Technology* **313**.

Sharma N and Sharma N (2018) Second Generation Bio-ethanol Production from Ligno-cellulosic Waste and Its Future Perspectives: A Review. *International Journal of Current Microbiology and Applied Sciences* **7(05)**: 1285–1290.

Sharma N, Bohra B, Pragya N, Ciannella R, Dobie P and Lehmann S (2016) Bio-energy from agroforestry can lead to improved food security, climate change, soil quality, and rural development. *Food and Energy Security* **5(3)**: 165–183.

Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Ong, H. C., Chong, W. T., & Boosroh, M. H. (2013). Overview properties of biodiesel diesel blends from edible and non-edible feedstock. *Renewable and Sustainable Energy Reviews* **22**: 346–360.

Singh G (2009) Comparative productivity of *P. cineraria* and *Tecomella undulata* based agroforestry systems in degraded lands of Indian Desert. *Journal of Forestry Research* **20(2)**:144-150.

Singh YP, Singh G and Sharma DK (2014) Bio-amelioration of alkali soils through agroforestry systems in central Indo-Gangetic plains of India. *Journal of Forestry Research* **25**: 887–896.

Sun Y and Cheng J (2002) Hydrolysis of ligno-cellulosic materials for ethanol production: A review. *Bio-resource Technology* **83(1)**: 1–11.

Tsai CT and Meyer AS (2014) Enzymatic Cellulose Hydrolysis: Enzyme Reusability and Visualization of Glucosidase Immobilized in Calcium Alginate. *Molecules* **19**: 19390–19406.

Ummalyma SB, Supriya RD, Sindhu R, Binod P, Nair RB, Pandey A and Gnansounou E (2019) Biological Pre-treatment of Ligno-cellulosic Biomass-Current Trends and Future Perspectives. In: *Second and Third Generation of Feed stocks*; Basile, A Dalena, F., Eds.; Elsevier: Amsterdam, The Netherlands: 197–212.

Vasave JB, Deshmukh SP and Usadadia VP (2015) Management of Salt affected soil by Agro-Forestry System: 1-7. *www.academia.edu*.

Vasco-Correa J, Ge X and Li Y (2016) Biological Pretreatment of Lignocellulosic Biomass. In: Biomass Fractionation Technologies for a Ligno-cellulosic Feedstock Based Bio-refinery; Mussatto, S.I., Ed.; Elsevier: Amsterdam, The Netherlands: 561–585.

Weiland P (2010) Bio-gas production: Current state and perspectives. *Applied Microbiology and Biotechnology* **85(4)**: 849–860.

Werpy T, and Petersen G (2004) Top Value Added Chemicals from Biomass: Volume-I Results of Screening for Potential Candidates from Sugars and Synthesis Gas, (*DOE/GO-102004-1992, 15008859*).

Xian-zhao L, Chun-zhi W, Qing S and Chao-kui L (2012) The potential resource of halophytes for developing bio-energy in China coastal zone. *Journal of Agricultural Science and Food Research* **1**: 044–051.

Yan M, Pan GX, Li LQ and Zou JW (2010) An overview of the potential role of reed (*Phragmites australis*) wetlands in terrestrial carbon sequestration of China. *Chinese Agricultural Science Bulletin* **26**: 320–323.

Zoghlami A and Paës G (2019) Ligno-cellulosic biomass: understanding recalcitrance and predicting hydrolysis. *Frontier Chemicals. doi: 10.3389/fchem.2019.00874.*

Received: September 14, 2024; Accepted: October 14, 2024

Journal of Soil Salinity and Water Quality 16(2), 249-256, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.158405

Rapid Assessment and Mapping of Soil Salinity in Subsurface Drainage Project using Electromagnetic Induction and Geostatistical Analysis

Sagar D. Vibhute[1]*, SK Kamra[1], Aslam L Pathan[1], DS Bundela[1], R Abhishek[2], Satyendra Kumar[1] and Jitendra Kumar[1]

[1]*Division of Irrigation and Drainage Engineering, ICAR-CSSRI, Karnal-132001, Haryana*
[2]*Agricultural Engineering, SGT University, Gurugram-122505, , Haryana*
**Corresponding author's E-mail: Sagar.Vibhute@icar.gov.in*

Abstract

Assessment of soil salinity is essential in subsurface drainage (SSD) projects not only for identifying suitable locations for SSD installation but to monitor its performance in reducing soil salinity. A study was undertaken in Katwara SSD site of Rohtak district of Haryana using EM 38 and surfer tool for rapid assessment and mapping of soil salinity. An EM38 survey was conducted in a block of 36 ha and values of apparent electrical conductivity (EC_a) of soil were recorded in vertical (EC_{av}) and horizontal (EC_{ah}) positions at 91 locations. Simultaneously soil samples with auger were collected at 9 locations (10% of the EM38 locations) to develop a multiple regression (MLR) equation for converting EC_a values to EC_e. The equations were developed for 0-30, 30-60, 60-90 and 0-90 cm soil depths with R^2 0.68, 0.89, 0.94 and 0.70, respectively. This shows that the combination of EM38 and MLR equation are effective in rapid assessment of soil salinity in subsurface drainage project. Furthermore, to convert this point data of EM values in spatial variability maps, krigging method was applied using surfer tool. The developed maps depicted spatial variation in soil salinity in drainage block for different soil depths. The scatter plot of predicted and measured EC_e values was closer to 1:1 line and this indicated better prediction accuracy. The methodology used for assessment of initial soil salinity can be further used for monitoring salt movement throughout the drainage block.

Key words: Soil salinity, Electrical Conductivity, Subsurface drainage, Electromagnetic induction

Introduction

Land degradation is major threat to food security and more than one third of the total geographic area (120.72 million ha) of India is affected by the one or another type of degradation (Maji, 2007). This mainly includes water erosion, soil salinity, wind erosion, waterlogging (permanent surface inundation) and mining etc. Soil salinity is major threat in irrigated areas and majority of the canal command areas in the country are facing problem of secondary soil salinization (Vibhute *et al.*, 2016). The area under salt affected soils in the country is 6.72 million ha and out of this 2.96 million ha comes under saline and costal saline soils (Sharma and Singh, 2015). The reclamation of salt affected soils by lowering soil EC/ESP below permissible limit is highly imperative for enhancing crop growth so that sustainable crop production can be achieved on these soils (Gheyi *et al.*, 2022). The reclamation of saline soils which needs leaching and subsequent disposal of soluble salts can be carried out using subsurface drainage (SSD) technology and states like Haryana, Rajasthan, Punjab, Maharashtra and Karnataka have successfully implemented SSD system (Raju *et al.*, 2022, Kamra *et al.*, 2019, Vineeth *et al.*, 2023, Kad *et al.*, 2022). Apart farm removing excess water from crop rootzone, the system improves physico-chemical conditions of the rhizosphere (Kumar *et al*, 2022). However, regular assessment of soil and groundwater salinity levels need to be carried out before installation and at periodic interval after installation period to ensure efficient working of SSD projects (Chinchmalatpure *et al.*, 2020).

The extensive soil sampling is required to quantify desalinization of soil profile by subsurface drainage system. Further, measurement of different soil and ground water parameters like EC, pH, cations and anions is required to know the degree of soil salinity in the area. The conventional method of EC measurement comprises collection of soil samples followed by laboratory analysis. But this method is time consuming and labour intensive. The electromagnetic induction based instruments like EM 38 are found very helpful in assessing the soil salinity through measurement of apparent soil electrical conductivity (EC_a) values (Narjary *et al.*, 2017). The technology has been effectively used across different soil types by the various researchers for prediction of soil salinity (Heil and Schmidhalter, 2017; Petsetidi and Kargas, 2023; Khongnawang *et al.*, 2021; Paz *et al.*, 2020). Once the data of EC_a is collected from the field using EM38, suitable conversion method needs to be applied for correlating this data with EC_e values. The Multiple linear regression methods found simple yet effective techniques for this conversion. Narjay *et al.* (2017) predicted soil salinity with MLR with very good R^2 of 0.77 whereas Waghaye *et al.* (2018) found that soil moisture based MLR models gave R^2 as high as 0.99.

Once the point data of a soil property across the different locations in an area is collected, appropriate interpolation techniques can be used to draw the spatial variability maps. Tools like surfer, ArcGIS etc. has ability to develop such spatial variability maps. The Surfer tool was effectively used in the past for spatial variability mapping of soil fertility, salinity, soil moisture etc. (Ramzan *et al.*, 2017) Therefore, present study was undertaken at newly installed SSD site at Katwara village of Rohtak district and non-destructive soil salinity assessment method of electromagnetic conduction based EM-38 survey was used to measure apparent soil conductivity in the area. Subsequently surfer tool was used to draw spatial variability maps of soil salinity at different depths.

Materials and Methods

Study area

The study site is located in Katwara village of Rohtak district of Haryana and it comes under Sonepat – III project site of Haryana Operational Pilot Project (HOPP). The project site comprises of 12 blocks and out of these, block number 3 having net area of 36 ha was selected in this study. The site is located between 76°33'36" to 76°34' 1.2" E longitude and 29°2'52.8" to 29°3'36" N latitude. The soil texture of the site is sandy loam in nature. The climate of the area is subtropical monsoonal with mild & dry winter and hot summer. The normal annual rainfall is about 592 mm. The location of study area is given in the Fig.1. The study was initiated immediately after the installation of sub surface drainage.

The composite SSD system consisting of network of lateral and connector pipes were installed at the site. The lateral, collector and open drains are shown in black, red and blue lines, respectively whereas sump is shown with green circle as shown in Fig.1. The lateral drains collect water from every corner of field and discharge it into the collector drain, which further conveys it to the outlet for its disposal in open drains. The corrugated flexible PVC pipe of 80 mm diameter covered with polypropylene filter material was used for lateral pipes and installed at either 60 or 67 m spacing depending upon the field orientation. For collector pipe, corrugated flexible PVC pipe

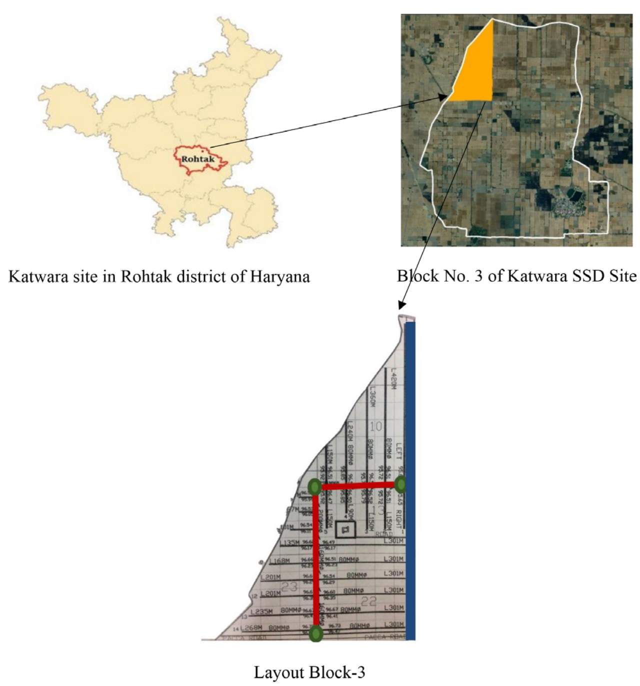

Fig. 1 Location of the study area

of 160 mm, 200 mm and 294 mm diameter wrapped in nylon socks was used. Three sumps, were installed in the area.

EM38 survey and soil sample collection

EM38 works on the principle of electromagnetic induction and used for measurement of the apparent electrical conductivity (EC_a) of soils. It is non-destructive method of soil salinity measurement and saves time, energy and manpower. This is particularly helpful for rapid assessment the soil salinity in large areas like subsurface drainage projects. Use of electromagnetic induction in measurement of apparent conductivity of soil was first practiced in late 1970's and early1980's in efforts to measure soil salinity (Corwin and Rhoades, 1982; Williams and Baker, 1982). The EM38 device contains appropriate circuitry to minimize instrument response to the magnetic susceptibility of the soil and to maximize response to electrical conductivity. It has an inter-coil spacing of 1 metre, operates at a frequency of 13.2 kHz, is powered by a 9 V battery, and reads out directly in terms of EC_a (Rhoades *et al.*, 1999). It is handy instrument and can be easily carried by a person. The calibration of the instrument is necessary before recording the EC_a observations and calibration in both horizontal (Fig. 2) and vertical position need to be done. The subsequent reading was taken at different location by placing the instrument on the ground surface in both vertical (Fig. 3) and horizontal positions.

Fig. 2 Calibration of EM - 38

Fig. 3 Recording EM_v observations

In present study, a grid survey was conducted to take reading with EM38 and locations of the grid points are shown in blue dots as shown in Fig. 4. Total 91 reading were taken using EM-38 and soil samples were taken from 9 locations (indicated by red circles) using soil auger. Soil

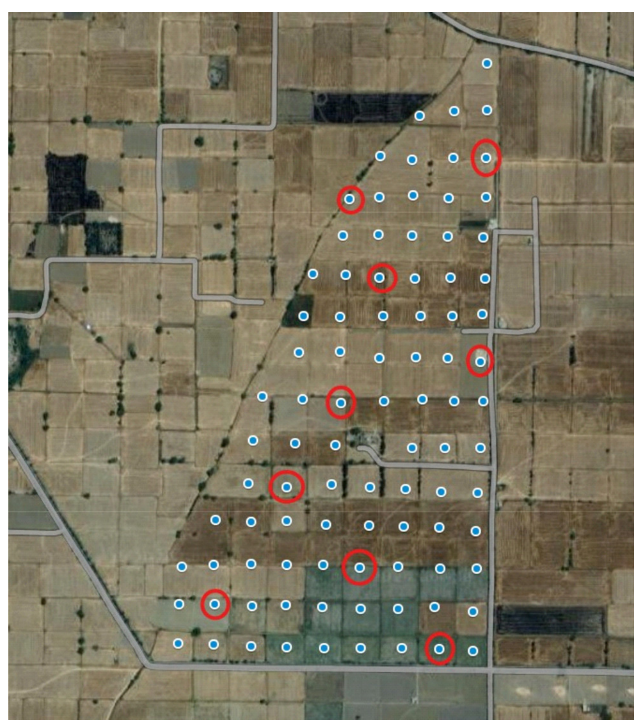

Fig. 4 EM38 observation points

samples were collected for different depths (0-15, 15-30, 30-60 & 60-90 cm) and sampling points are decided in such a way that the entire range of EC_a values got covered. The samples were air dried, grinded and subsequently passed through 2 mm sieve before starting chemical analysis. Then samples were subsequently analyzed in the laboratory for EC_e using methodology given by Richards (1954).

Relation between EC_a and EC_e

EM 38 gives value of EC_a of the soil and in order to estimate EC_e value, a multiple linear regression equation was developed. The EM38 readings in horizontal (EC_{ah}) and vertical (EC_{av}) positions were used as dependent variable in this case.

The model for multiple linear regression equation used in the study is as follows

$$EC_e = a + b \times EC_{av} + c \times EC_{ah}$$

Where,

EC_e: Electrical Conductivity of Saturation Extract

EC_{av}: Apparent EC value of EM-38 meter in Vertical position

EC_{ah}: Apparent EC value of EM-38 meter in horizontal position

a, b & c are the parameters of the equation

The equations for predicting soil salinity for 4 soil layers viz. 0-30, 30-60, 60-90 and 0-90 cm were developed. Using this equation EC_e values for 91 points were determined.

Spatial variability mapping

The surfer 9.0 tool was used for mapping spatial variation in soil salinity. The ordinary krigging technique was used and predicted EC_e data of 91 locations was used to generate map for an area of 36 ha. Map of average soil salinity of 4 soil layers i.e. 0-30, 30-60, 60-90 and 0-90 cm were prepared. The values predicted by krigging method were compared to measured values using scatter plot and prediction accuracy was evaluated using 1:1 line. The closeness of scatter plot to 1:1 line denotes the prediction accuracy.

Result and Discussion

Descriptive statistics of EM survey and EC_e values

The descriptive statistics of EM survey for all 91 locations as well as 9 calibration points is given in table 1. It was observed that majority of the variation in EC_a values was covered by calibration points. Skewness values was around 0.5 for both EC_{av} and EC_{ah} for survey as well as calibration and this shows slightly skewed data distribution. Mean and standard deviation of EC_{av} values was greater than EC_{ah} values for survey as well as calibration data. This shows higher value of EC_e in top layers and indicates inverted soil salinity profile in the area. Narjary (2017) also got similar results in Mokhra Kheri subsurface drainage area. The kurtosis values were more for calibration data set than survey data set. The descriptive statistics of soil EC_e value is shown in Table 1. The EC_e values were highest for top 15 cm layer varying

Table 1. Descriptive statistics for EC_{av} and EC_{ah} values for survey and calibration data of EM38, and EC_e values

Parameters	n	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
EC_a (Survey)							
EC_{av}	91	4.04	0.97	2.20	6.70	0.25	-0.28
EC_{ah}	91	3.68	0.88	1.90	6.70	0.58	0.58
EC_a (Calibration)							
EC_{av}	9	4.20	1.45	2.60	6.70	0.62	-1.01
EC_{ah}	9	3.89	1.00	2.70	5.60	0.38	-0.94
Soil Properties							
EC_e (0-15 cm)	9	5.66	2.17	3.55	9.19	0.88	-0.52
EC_e (15-30 cm)	9	3.65	2.00	1.70	6.74	0.47	-1.84
EC_e (30-60 cm)	9	3.17	1.82	1.28	6.08	0.66	-1.34
EC_e (60-90 cm)	9	2.77	2.00	0.71	6.71	1.08	0.33

EC_e (Electrical conductivity of saturation extract), EC_{av} apparent electric conductivity in vertical position, EC_{ah} apparent electric conductivity in horizontal position

Table 2. Multiple regression equations between EC_a and EC_e for different soil layers

Depth(cm)	Equation $EC_e = a + b \times EC_{av} + c \times EC_{ah}$	R^2
0 - 30	$EC_e = 1.436 + 1.163 \times EC_{av} - 0.452 \times EC_{ah}$	0.68
30 - 60	$EC_e = 0.552 + 1.472 \times EC_{av} - 0.564 \times EC_{ah}$	0.89
60 - 90	$EC_e = - 1.857 + 1.49 \times EC_{av} - 0.346 \times EC_{ah}$	0.94
0 - 90	$EC_e = 0.526 + 1.073 \times EC_{av} - 0.215 \times EC_{ah}$	0.7

EC_e (Electrical conductivity of saturation extract), EC_{av} apparent electric conductivity in vertical position, EC_{ah} apparent electric conductivity in horizontal position

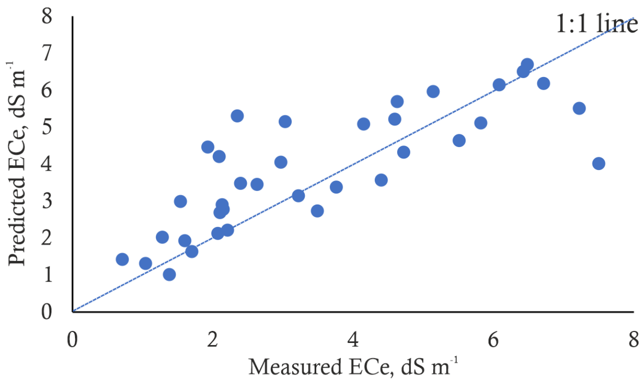

Fig. 5 Plot of measured and predicted values of ECe

from 3.55 to 9.19 dS m^{-1} indicating higher soil salinity in surface soil at all the locations.

Relation between EC_a and EC_e

As EM 38 gives value of apparent electrical conductivity (EC_a) of the soil and to estimate EC_e value from it a multiple linear regression (MLR) method was used. The EM 38 values in vertical (EC_{av}) and horizontal (EC_{ah}) positions were used as dependent variable in this case. The equations developed for different soil depths and their coefficient of determination is given in Table 2.

The R^2 was lower for top layer (0.68) whereas it was very good (around 0.94) for subsurface layers. As far as prediction of average soil salinity of entire top 90 cm soil layer is considered, the results showed good R^2 value of 0.7,Waghaye *et al*. (2018) also observed good R^2 value (0.7 to 0.9) for predicting ECe using EC_{av} and EC_{ah}, and MLR technique. The plot of measured and predicted values of EC_e is given in fig. 5 and majority of points are populated around 1:1 line showing good prediction.

The depth wise variation in measured EC_e values is shown in Fig. 6. For almost all location (except location 3), soil salinity was highest for surface layer (0-30 cm) and lower for subsurface layers (30-60 and 60-90 cm layers). The predicted EC_e values (Fig. 7) also showed similar trend.

Spatial variability mapping of EC using surfer

The equations given in Table 2 were used for estimating EC_e values of respective depths and spatial variability maps of EC_e were generated for different soil layers (Fig. 8 to Fig. 11) In these maps, the areas shown in dark brown colour are

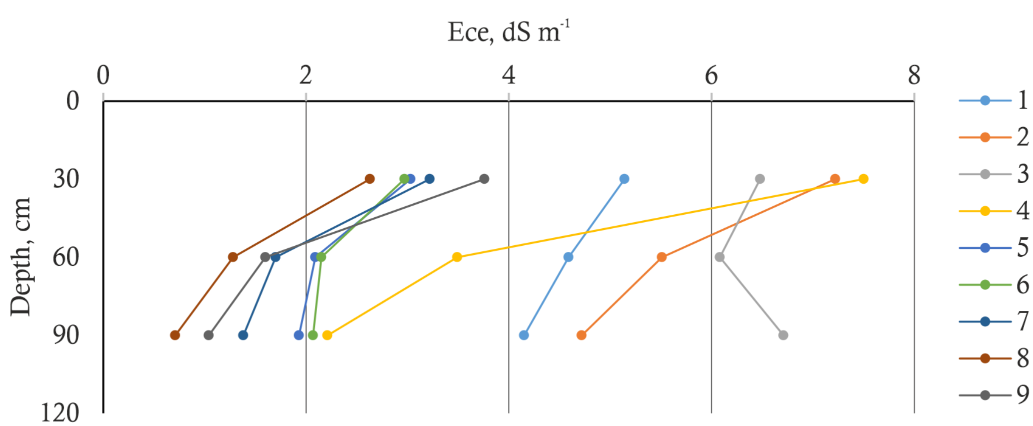

Fig. 6 Depth wise variation in soil ECe of observed data

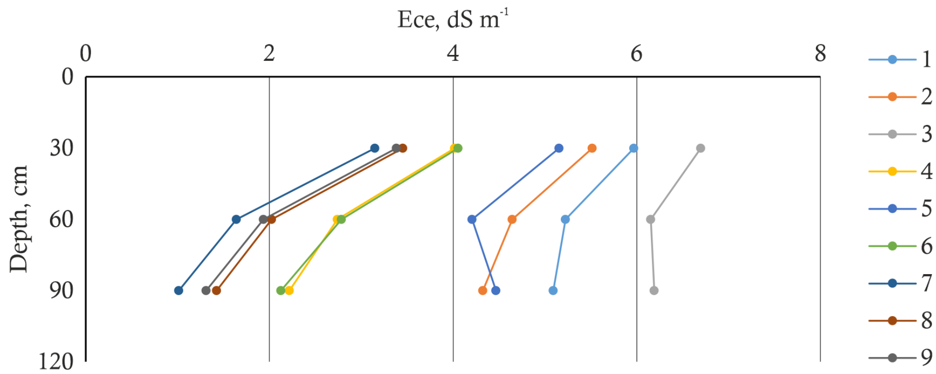

Fig. 7 Depth wise variation in soil ECe of predicted data

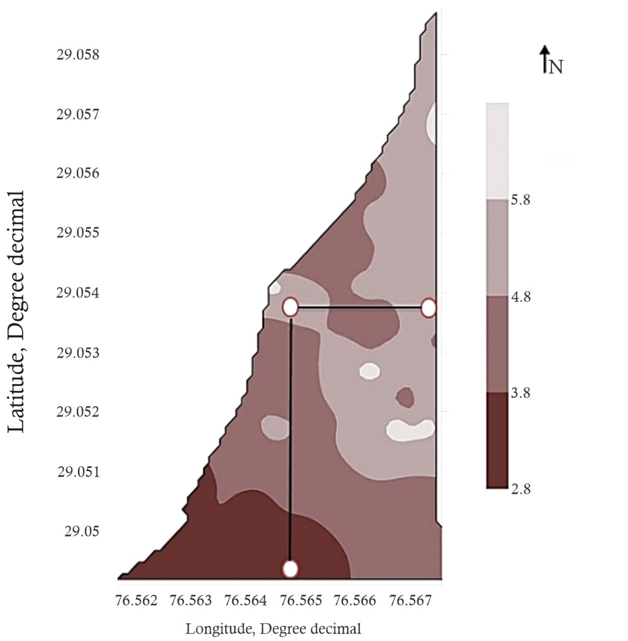

Fig. 8 Spatial variability of estimated ECe (dS m^{-1}) for 0-30 cm depth

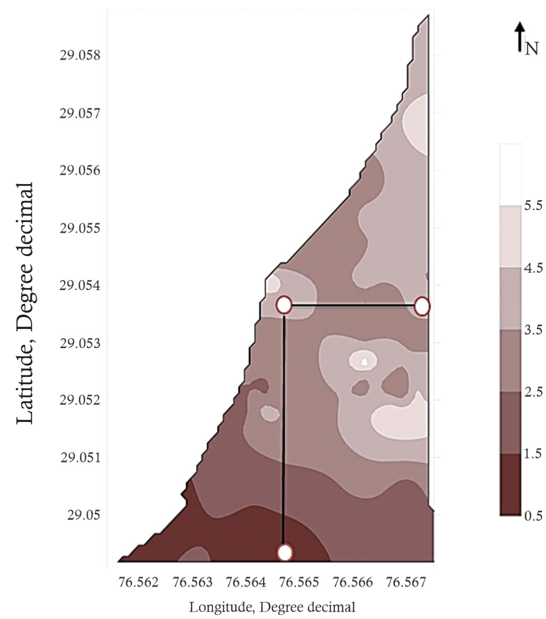

Fig. 10. Spatial variability of estimated ECe (dS m^{-1}) for 60-90 cm depth

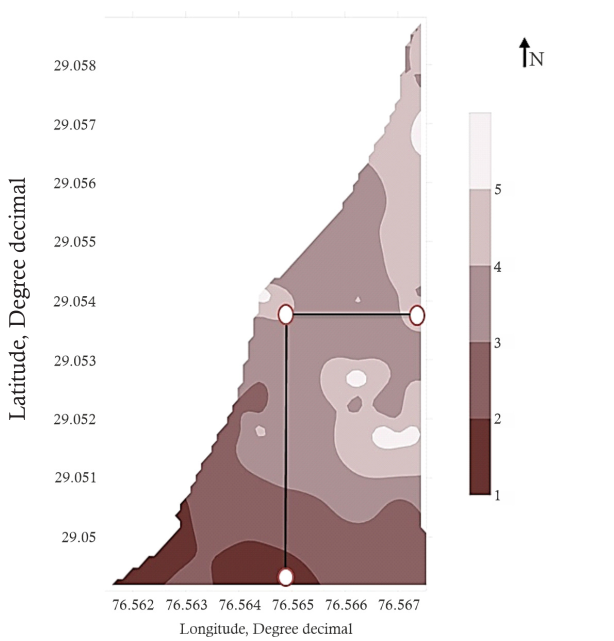

Fig. 9 Spatial variability of estimated ECe (dS m^{-1}) for 30-60 cm depth

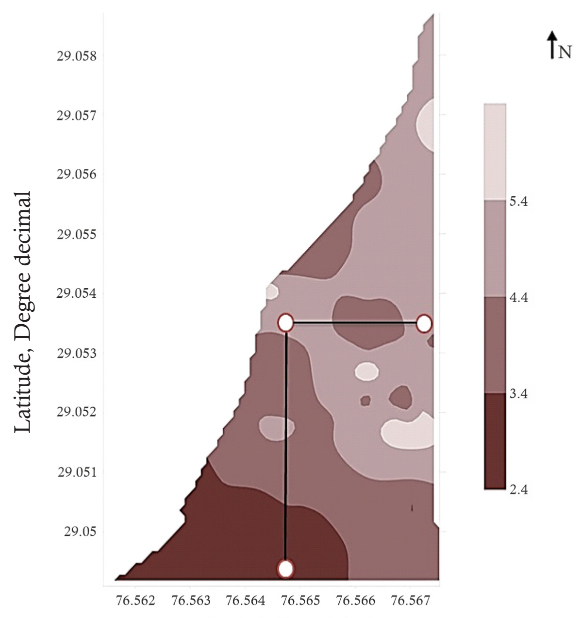

Fig. 11. Spatial variability of estimated ECe (dS m^{-1}) for 0-90 cm depth

having non-saline soils and increase in whitish tone of brown colour represents relative increase in soil salinity. For all soil depths the upper end of the study area showed presence of non-saline soil and salinity was increasing as we moved towards outlet point of the block.

Conclusions

For the large scale salinity management projects like subsurface drainage (SSD), the faster assessment and mapping of soil salinity is very much essential. The use of EM38 coupled with multiple regression technique have given good results with R^2 values varying from 0.68 to 0.94. The subsequent mapping of soil electrical conductivity carried out using krigging methods also showed good accuracy as predicted values were closely matching with observed values. Therefore, approach of soil salinity assessment using EM 38 and surfer tool can be an effective in assessment of initial conditions at SSD sites. Furthermore, monitoring of the SSD sites to ensure their efficient working can also be effectively undertaken using this approach. The generated spatial variability maps can help to understand salt movement through visualization of soil salinity in different sections of the block.

References

Chinchmalatpure AR, Vibhute SD and Kaledhonkar MJ (2020) Performance evaluation of subsurface drainage system under waterlogged saline vertisols for sugarcane crop in Ukai Kakrapar Canal command, Gujarat. *Journal of Agricultural Engineering* **57(3)**: 248-258.

Corwin DL and Rhoades JD (1982) An improved technique for determining soil electrical conductivity depth relations form above-ground electromagnetic measurements *Soil Science Society of America Journal* **46**: 517-520

Gheyi HR, Lacerda CF and Freire MBGS (2022) Management and reclamation of salt-affected soils: General assessment and experiences in the Brazilian semiarid region. *Revista Ciência Agronômica* **17(53)**:179-17.

Heil K and Schmidhalter U (2017) The application of EM38: Determination of soil parameters, selection of soil sampling points and use in agriculture and archaeology. *Sensors* **17(11)**: 2540

Kad SV, Raju R, Vibhute SD, Chinchmalatpure A, Singh RK and Bundela DS (2022) Subsurface drainage to overcome waterlogging and soil salinity in irrigated vertisols of Maharashtra: A lesson from farmer's perspective. *Indian Journal of Extension Education* **58(2)**:8-15.

Kamra SK, Kumar S, Kumar N and Dagar JC (2019) Engineering and biological approaches for drainage of irrigated lands. *Research developments in saline agriculture* pp 537-577.

Khongnawang T, Zare E, Srihabun P, Khunthong I and Triantafilis J (2021) Digital soil mapping of soil salinity using EM38 and quasi 3d modelling software (EM4Soil). *Soil Use and Management* **38(1)**: 277-291.

Kumar S, Narjary B, Kumar V, Anand V, Prajapat K and Bundela DS (2020) Subsurface drainage improves physico-chemical conditions of rhizosphere for sustainable crop production in waterlogged saline soil-a case study. *Journal of Soil Salinity and Water Quality* **12(2)**: 213-224.

Maji AK (2007) Assessment of degraded and wastelands of India. *Journal of Indian Society of Soil Science* **55**: 427–435.

Narjary B, Jangra P, Abhishek, R, Kumar N, Raju R, Thimappa K and Kamra SK (2017) Quantitative assessment of soil salinity using electromagnetic induction technique and geostatistical approach. *Journal of Soil Salinity and Water Quality* **9(2)**:156-166.

Paz MC, Farzamian M, Paz AM, Castanheira NL, Gonçalves MC and Monteiro SF (2020) Assessing soil salinity dynamics using time-lapse electromagnetic conductivity imaging. *Soil* **6(2)**: 499-511.

Petsetidi PA and Kargas G (2023) Assessment and Mapping of Soil Salinity Using the EM38 and EM38MK2 Sensors: A Focus on the Modeling Approaches. *Land* 12, no. **10**:19-32.

Raju R, Vibhute SD, Bundela DS and Kumar A (2022) Socio-economic impact and constraints in adoption of technology for reclamation of waterlogged saline soils in Maharashtra, India. *Indian Journal of Soil Conservation* **50(3)**: 240-8.

Ramzan S, Wani M and Bhat M (2017) Assessment of Spatial Variability of Soil Fertility Parameters Using Geospatial Techniques in Temperate Himalayas. *International Journal of Geosciences* **8**:1251-1263.

Rhoades JD, Chanduvi F and Lesch SM (1999) Soil salinity assessment: Methods and interpretation of electrical conductivity measurements. Food & Agriculture Org..

Richards L A (1954) Diagnosis and Improvement of Saline and Alkali Soils. U. S. Department of Agriculture Handbook Washington D. C. USA 60: 160.

Sharma DK and Singh A (2015) Salinity research in India-achievements, challenges and future prospects. *Water and Energy International* **58(6)**: 35-45.

Vibhute SD, Sarangi A and Singh DK (2016) Development of crop water demand based water delivery schedule for a canal command. *Journal of Agricultural Engineering* **53(2)**:12-23.

Vineeth TV, Vibhute SD, Ravikiran KT, Prasad I, Chinchmalatpure A and Sharma PC (2023) Biosaline agriculture and efficient management strategies for sustainable agriculture on salt affected Vertisols. In: *Plant Stress Mitigators: Types, techniques and functions*, (Eds) Mansour Ghorbanpour and Mohammad Adnan Shahid, Academic press, Elsevier, UK pp 268-288.

Waghaye AM, Saxena CK, Kumar S, Pathan A and Abhishek R (2018) Multiple linear modelling of electrical conductivity at a subsurface drainage site in Haryana using EM technique. *International Journal of Chemical Studies* **6(2)**:1953-60.

Williams BG and Baker DC (1982) An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. *Australian Journal of Soil Research* **20**:107-118.

Received: October 17, 2024; Accepted: October 29, 2024

Journal of Soil Salinity and Water Quality 16(2), 257-269, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156191

Clay Mineralogy and Solution Chemistry of Waterlogged Saline Soil Undergone Subsurface Drainage: Study from North-Western India

Raj Mukhopadhyay*[1], Diksha Saroha[1,2], Ranjan Paul[3], Bhaskar Narjary[1], Devendra Singh Bundela[1], Satyendra Kumar[1] and Arijit Barman[1,4]

[1]ICAR-Central Soil Salinity Research Institute, Karnal-132001, Haryana
[2]Chaudhary Charan Singh Haryana Agricultural University, Hisar-125004, Haryana
[3]Division of Soil Resource Studies, ICAR-National Bureau of Soil Survey and Land Use Planning, Nagpur-440033, Maharashtra
[4]ICAR-National Bureau of Soil Survey and Land Use Planning, Regional Centre, Jorhat-785004, Assam, India
*Corresponding author's Email: rajssaciari@gmail.com

Abstract

Subsurface drainage (SSD) is an effective technique to reclaim waterlogged saline soils and improving agricultural production with added economic returns. In 2019, Sampla (Rohtak, Haryana, India) SSD site was revisited to study the identification and characterization of clay minerals and their transformation in relation to soil solution chemistry under prevailing conditions. The soil was clay loam to clay in texture with high EC_e (3.48-4.67 dS m^{-1}) and pH_s (8.03-8.06). The 30-60cm soil-depth showed the highest cation exchange capacity (16.25 meq/100g) and exchangeable sodium percentage (8.04%) followed by the surface soils (14.17 meq/100g and 7.65% respectively). The exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) varied between 7.92-9.19 and 3.04-4.20 meq/100g, respectively, the highest being in 30-60cm soil-depth. The soluble cations followed the order Na^+ (17.73–24.79 $meqL^{-1}$) > $Ca^{2+}+Mg^{2+}$ (7.77–11.02 $meqL^{-1}$) > K^+ (5.93–7.61 $meqL^{-1}$) up to 90cm soil-depth. The soil structural stability ratios, namely, SAR, PAR, MCAR and CROSS, were found maximum (12.37, 3.80, 10.02 and 22.06 respectively) in 30-60cm soil-depth highlighting greater dispersion, poor soil structure and aggregate stability in the sub-surface. The clay minerals including hydroxy interlayered vermiculite, chlorite and mica were dominant at 0-60cm, followed by kaolin, quartz, rutile and K Feldspar at deeper soil layer (60-90cm). The soil chemical analysis showed the redevelopment of salinity with the dominance of Na^+ ions throughout the profile due to stoppage of SSD operation for a long time. The relative similarities in soil clay mineralogical composition within the profile suggested the inheritance of minerals from parent material, having no significant in-situ transformation under the prevailing conditions.

Key words: Clay mineralogy, Soil properties, Subsurface drainage, Waterlogged saline soils

Introduction

Soil salinity is a critical challenge for food security under current global climate change scenarios. Food and Agricultural Organization (FAO) (Madison USA. FAO, 2021) reported the maximum distribution (66.67%) of salt affected soils (SASs) under the arid and semi-arid climatic regions of the world. The extent and magnitude of salt-affected soils under cultivated (~20%) and irrigated agricultural (~33%) lands are expected to increase by 2050 (Sharma *et al.*, 2015). Around 3.77 million hectares (Mha) sodic and 2.96 Mha saline soils are reported to cause an annual loss of 16.84 million tons of food-grain production in India (Mukhopadhyay *et al.*, 2021; Mandal *et al.*, 2018). In addition to the arid and semi-arid regions, waterlogged saline soils are distributed in the coastal belt of India also (Kamra *et al.*, 2019). The arid and semi-arid ecological zones with high air temperature, evaporation losses from surface soil, saline water irrigation in the irrigated canal command areas have resulted in the development of waterlogged saline soils (Verma *et al.*, 2014). The oxygen deficit cause major yield reductions of crops in these soils (Saqib *et al.*, 2004). Poor aeration affects the seed germination, root growth, mobility, uptake and transport of nutrients, thus causing a reduction in net CO_2 assimilation and dry matter production. The prolonged waterlogged condition in soils contributes to the production of greenhouse gases (GHGs), namely, methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), which not only reduce the soil organic carbon (SOC) content but also accelerate the climate change (Mukhopadhyay *et al.*, 2023).

The SASs have excess soluble solutes, including bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), chloride (Cl^-) and sulphate (SO_4^{2-}) salts of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+). The dominance of adsorbed Na^+ ions on the exchange sites, high soil pH and leaching of excess soluble salts affect the pore size distribution of soils due to swelling/shrinkage of clay minerals and their dispersion under anoxic conditions (Rengasamy and Marchuk, 2011). After drying, such soils face the problems of crusting and hardening, which causes poor crop establishment and yield reduction. The increasing concentrations of carbonate and bicarbonate ions result in soil alkalinity (Sposito, 2016). The high-pH soils affect the availability of essential nutrients and might cause deficiencies or toxicities to crop plants (Tavakkoli *et al.*, 2022). In addition, higher soil pH increases the concentration of soluble fraction of organic carbon (dissolved organic carbon, DOC) which is prone to leaching loss and finally leading to the degradation of soil quality. Calcium (Ca^{2+}) ions help in SOC sequestration by cation bridging between organic compounds or calcium absorption on organic matter (Tavakkoli *et al.*, 2022). The soils treated with high EC (6 dS m^{-1}) and SAR (0, 5, 15 and 30) solutions prepared with NaCl and $CaCl_2$ caused wider cracks in soil aggregates, thus reducing their tensile strength and stability (Barzegar *et al.*, 1995). They also found that solutions having SAR greater than 20 caused complete structural loss, making restoring such soils challenging.

The waterlogged saline soils have poor structure, leading to lower infiltration and waterlogging (Valzano *et al.*, 2001). Thus, continuous waterlogging for many years causes compaction, oxygen deficiency and nutrient immobilization in the soils. Subsurface drainage (SSD) technologies effectively upgraded the soil quality through carbon sequestration and soil salinity reduction, supplemented the crop productivity, and restored the quality of waterlogged saline soils (Ritzema *et al.*, 2008). The initiation of SSD was based on the objective to improve the soil's physical properties by improving shallow groundwater table. However, it was also observed to be effective in the reclamation of saline-alkali waterlogged soils in arid regions (Wang *et al.*, 2017). Mukhopadhyay *et al.* (2023) studied the impact of long-term (10, 7 and 3 years) SSD on soil quality indicators of waterlogged saline soils of Haryana, India. The SSD technique improved the soil quality parameters in the topsoil layer (0-30 cm). For example, they showed a significant decrease in the electrical conductivity of soil saturation extract (EC_e), increased soil organic carbon (SOC) content and enzymatic activities. It also significantly enhanced the productivity and yields of rice and wheat after reclamation. Thus, the severely degraded waterlogged saline soils could be brought back to production with the help of SSD (Rao and Leeds-Harrison *et al.*, 1991). The desalination efficiency of surface soils through SSD was observed at an average of 80% after three years of installation (Bahçeci *et al.*, 2018). However, the technique is very time-consuming and costly; thus, its long-term maintenance is a daunting task for the scientific and farming community.

Clay minerals affect the fertility and productivity of sustainable agroecosystems (Kome *et al.*, 2019). The distribution of different clay minerals helps us to understand the soil genesis and characteristics of soil parent material. In SASs, clay minerals like potassium-rich muscovite and other minerals usually dominated the arid and semi-arid soils of Uttar Pradesh, Haryana and Punjab (Singh and Sawhney, 2006). Other minerals such as chlorite, vermiculite, calcite, feldspar (K), sepiolite and anatase were also present in the SASs of Southwest Punjab. However, the transformation of clay minerals in SASs is hardly seen and reported. X-ray diffraction analysis have provided evidence for mixed-layer minerals such as illite-interlayered smectite, chlorite-interlayered smectite and chlorite-interlayered vermiculite under salt-affected solonetzic and chernozemic soils of Western Siberia (Chizhikova and Khitrov, 2016). Such intermediate stages of mineral transformations were observed under geochemical changes namely, solodization, solonization, and weathering. The leaching of excess Na^+ ions from the exchange sites cause soil acidification which favors the formation of smectites from illite (Galán and Ferrel, 2006). The exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) also affect swelling, shrinkage and dispersion of alumino-silicate minerals thus affecting the porosity and structure of soils (Marchuk and Rengasamy, 2011).

Although the changes in soil physicochemical properties and ionic composition of soil solution in SSD reclaimed waterlogged saline soils have already been studied (Mukhopadhyay *et al.*, 2023), however, the type and distribution of clay minerals, their changes or transformation with altering soil condition from anoxic to oxic due to SSD operation have never been reported for reclaimed waterlogged saline soil in arid and semi-arid regions of Punjab, Haryana and Uttar Pradesh (India). Therefore, the present investigation focused on understanding the nature of clay minerals present in reclaimed waterlogged saline soil, their transformation occurred (if any) during reclamation through SSD in relation to prevailing soil chemical properties and concentration of soluble anions and cations.

Material and Methods

Description of the experimental site

The SSD was installed at Sampla (latitude: 28.45-28.85 °N, longitude: 76.46-76.90 °E) in Rohtak district of Indian state Haryana (Fig. 1) by Central Soil Salinity Research Institute (CSSRI), Karnal, in 1986 over an area of 10 ha. The experimental site had < 3.0 m depth of groundwater table with > 2.0 dS m^{-1} salinity level (up to 25 m depth) and thus, considered suitable for the installation of SSD as per the criteria suggested by Bos (2001) and Kamra *et al.* (2019). The site comes under the

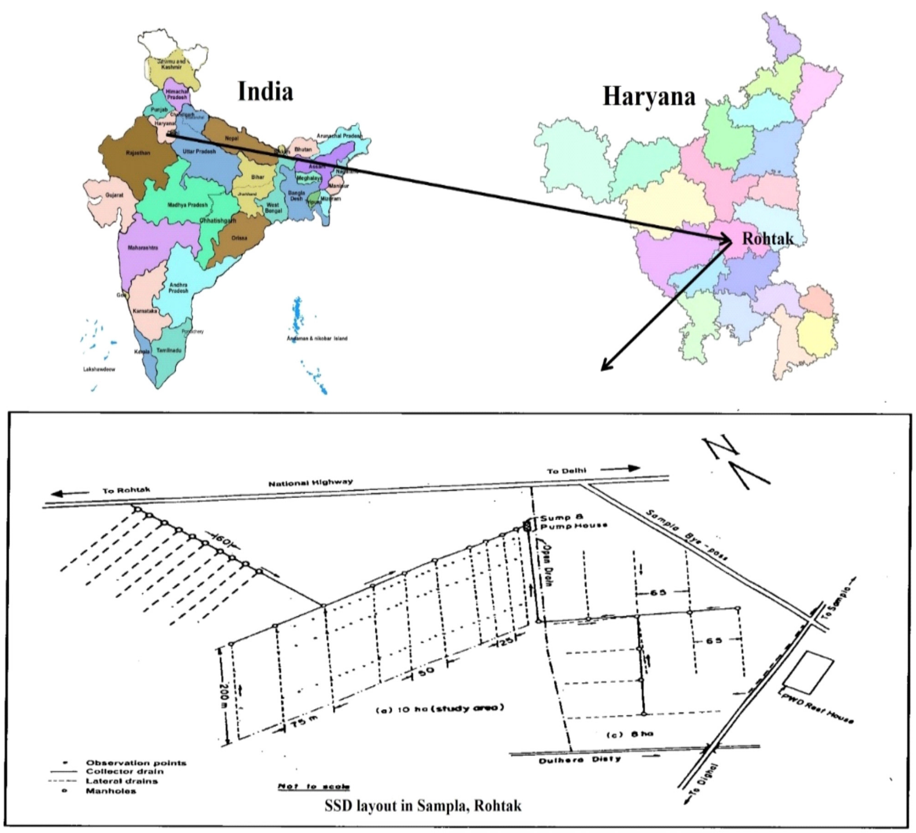

Fig. 1 Subsurface drainage (SSD) layout in Sampla (Rohtak), Haryana

hot semi-arid region with coarse loamy textured alluviums (agro-ecological region-4) of the Great Plains of India. The northern and southern topographical differences in the Great Plains converge to form depression near district Rohtak (Haryana) (Mishra, 2020). This low-lying basin area at 208 m of elevation above the mean sea level has shallow groundwater table with high salinity and poor quality of irrigation water from wells which directly contribute to soil salinity. The dry and hot summers (average annual rainfall of 650 mm) with high evapotranspiration (average annual evapotranspiration of 1650 mm) regulate the capillary rise of soil solution which accumulates excess salts on the topsoil. The groundwater table at Sampla site fluctuates between the soil surface to 1.8 m depth around the year including summer and monsoon seasons. Before the installation of SSD, the texture of the upper 1.8 m soil layer is sandy loam with 70 - 75% sand content and 1.0 m day^{-1} of hydraulic conductivity. The layer below 1.8 m depth was found loamy sand with higher hydraulic conductivity up to 7.5 m day^{-1} (Boonstra *et al.*, 2002). An impervious soil layer was found with very low hydraulic conductivity at 3.0-4.0 m soil depth (Boonstra *et al.*, 2002). The dominant clay minerals of the region include quartz, chlorites, feldspar, kaolinite, mica and vermiculites (NBSS & LUP, 2016). As shown in Fig. 1, the drains were installed at 25 m, 50 m and 75 m spacing at 1.75 m soil depth (Boonstra *et al.*, 2002). Before the installation of SSD, the average electrical conductivity of soil saturation paste extract (EC_e) of 0-30 cm (42.8 dS m^{-1}), 30-60 cm (25.7 dS m^{-1}) and 60-90 cm (23.2 dS m^{-1}) soil depths were observed extremely high (Verma *et al.*, 2014). The SSD was monitored till 1999 successfully for 14 years following pearl millet-wheat crop rotation and then handed over to village *Panchayat* for future maintenance.

Soil sampling and laboratory analysis

The soil samples were collected in 2019 from different depths (0 - 30, 30 - 60 and 60 - 90 cm) in triplicates and ground to < 2 mm size after air drying. The sampling was not carried out to further depths due to shallow groundwater table (<1.0 m). The soil texture was determined using hydrometer method given by Bouyoucos (1962) and the textural classes were identified using the United Nation Department of Agriculture (USDA) system (Hillel, 2004). The processed soil samples were analyzed for pH of saturation paste (pH_s) and EC_e using glass electrode pH meter and conductivity meter respectively (U.S. Salinity Laboratory Staff, 1954; Jackson, 1973). Cation exchange capacity (CEC) and exchangeable divalent cations (Ca^{2+} and Mg^{2+}) were determined by centrifuge method using neutral 1 *N* NH_4OAc (Jackson, 1973). The calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions concentration in the soil solution were determined using the complexometric EDTA-titration method. The concentration of sodium (Na^+) and potassium (K^+) ions in the soil solution was estimated with the help of a flame photometer. The chloride (Cl^-) and sulphate (SO_4^{2-}) ions were measured using Mohr titration and turbidity method respectively. The carbonates (CO_3^{2-}) and bicarbonates (HCO_3^-) were estimated using phenolphthalein and methyl red endpoint methods respectively (U.S. Salinity Laboratory Staff, 1954; Jackson, 1973). The sodium adsorption ratio (SAR), potassium adsorption ratio (PAR), monovalent cation adsorption ratio (MCAR) and cation ratio of structural stability (CROSS) were also calculated using the following equations (Marchuk and Rengasamy, 2010). Here, the soluble cations were estimated in 1:5 soil water extracts and the concentrations of the corresponding cations were expressed in meq L^{-1} units.

$$SAR = Na/[(Ca+Mg)/2]^{1/2}$$

$$PAR = K/[(Ca+Mg)/2]^{1/2}$$

$$MCAR = (Na + K)/[(Ca+Mg)/2]^{1/2}$$

$$CROSS = (Na+0.56K)/[(Ca+0.6Mg)/2]^{1/2}$$

Water quality analysis

The water quality of wells at Sampla site was tested at 25 m and 50 m depths by observing their electrical conductivity (EC) and pH (Table 1). The samples from the swamp sites at 25 m, 50 m and 75 m drain spacing were also examined for EC_e and pH_s (U.S. Salinity Laboratory Staff, 1954; Jackson, 1973).

Table 1. The EC and pH of the groundwater and swamp sites of waterlogged saline soils of India

Water Sample	ECe (dS m^{-1})	pH
Well sample (25 m)	5.21	7.42
Well sample (50 m)	4.52	8.71
Swamp 2 sample (50 m)	3.22	8.28
Swamp 2 sample (75 m)	2.46	8.24
Swamp 3 sample (25 m)	4.04	7.39
Swamp 3 sample (75 m)	2.26	8.94

Clay separation and X-ray diffraction analysis

The soil samples of 0 - 60 cm and 60 - 90 cm depths were collected from different points at Sampla site and representative composite samples were prepared in triplicate. Since, there was no such significant variation in soil texture across 0-30 and 30-60 cm soil depth, we considered 0-60 and 60-90 cm soil depth for clay mineralogical analysis. The samples were dried in shade, crushed and sieved (2 mm sieve) for X-ray diffraction (XRD) to generate well-defined and distinct peaks for the identification and characterization of minerals present in the soil clay fraction. The soil samples (< 2 mm) were sequentially treated with sodium acetate (1 *N*, pH 5), hydrogen peroxide (30%) and sodium citrate-bicarbonate buffer (0.3 *M* Na citrate + 0.125 *M* Na bicarbonate) followed by subsequent addition of sodium dithionate, to free the soil from the cementing agents, viz., soluble salts, organic matter and (hydr)oxides. The dispersed soil separates were collected through centrifugation (5 minutes) of the suspension at 500 rpm and the supernatant aliquot was discarded. The suspension of collected samples were prepared and sieved through 300 mesh to segregate the coarse (2-0.6 mm) and fine (0.6-0.02 mm) sand fractions. The clay fraction was extracted from the leftover suspension which was initially dispersed in a tall-form glass bottle followed by the siphoning out of clay particles obeying the Stokes' law (Mehra and Jackson, 1960). The XRD spectra were generated for the clay samples placed on the glass slide (either K or Ca-saturated with KCl and $CaCl_2$ solution) in a favorable orientation with Ni-filtered Cu-K radiation diffractometer (Philips Model PW 1710) at a scanning speed of 2°2θ min^{-1}. The identification of the clay minerals was carried out by using Jackson (1979) method. Before performing XRD, the clay samples were treated as (i) Ca saturation and air dried at 25°C; (ii) CaEG: Ca saturation and solvation with ethylene glycol; (iii) K25: K saturation at room temperature (25°C); (iv) K110: thermal treatment of K saturated clay samples at 110°C; (v) K300: thermal exposure of K saturated clay samples at 300°C; (vi) K550: thermal treatment of K saturated clay samples at 550°C.

Results and Discussion

Soil physico-chemical properties and water quality

The electrical conductivity (EC) and pH are the two major indicators used for the characterization of salinity. The EC and pH of the wells and swamp sites varied between 2.26 - 5.21 dS m^{-1} and 7.39 - 8.94 respectively (Table 1). The particle size distribution of the waterlogged saline soil under SSD varied slightly at different soil depths (Table 2). The soils at 0-30 and 60-90 cm were clay loam (28-40% clay), while the 30-60 cm soil depth were found clayey (> 40% clay). After SSD reclamation, the surface soils (0-15 cm) reached an average EC_e of 3.03 dS m^{-1} (1999) from 53.7 dS m^{-1} (1984) (Boonstra *et al*., 2002). The EC_e again increased to 4.67 dS m^{-1} at 0-30 cm soil depth (Table 2) due to the stoppage of SSD operation. At 0-30 cm soil depths, the average EC_e exceeded 4 dS m^{-1} which comes under the category of saline soils indicating excessive soluble salt concentration with respect to plant growth and development. The EC_e decreased to 3.48 dS m^{-1} and 3.63 dS m^{-1} in 30-60 cm and 60-90 cm soil depth in comparison to surface (0-30 cm) soils (4.67 dS m^{-1}). Water is the major carrier of salts in soils. Under the influence of high air temperature and evaporation, a large amount of salt accumulates in the topsoils with the upward movement of water (Heng *et al*., 2018). A high level of soluble electrolytes in the rhizosphere soil not only affects the soil quality but also affects the crop productivity (Kamra, 2015). The pH_s of the soil were found in the alkaline range between 8.03 to 8.06 up to 90 cm soil depth throughout the soil profile (Table 2). The overall soil pH_s of the profile was slightly alkaline, apparently due to the dominance of HCO_3^- ions in the soil solution. The CEC varied

Table 2. The depth-wise variation in soil chemical properties of waterlogged saline soils of India

Depth (cm)	pH_s	EC_e ($dS\ m^{-1}$)	Particle size distribution Sand (%)	Silt (%)	Clay (%)	Textural class	ESP (%)	CEC (meq (p+)/ 100 g	Exchangeable Ca^{2+}	Exchangeable Mg^{2+}
									(meq/ 100 g)	
0-30	8.05 ± 0.03	4.67 ± 0.03	32.4	35.88	31.72	Clay loam	7.65 ± 0.18	14.17 ± 1.34	7.92 ± 2.04	3.82 ± 0.52
30-60	8.03 ± 0.02	3.48 ± 0.16	26.4	32.88	40.72	Clay	8.04 ± 0.24	16.25 ± 1.73	9.19 ± 1.66	4.20 ± 0.67
60-90	8.06 ± 0.02	3.63 ± 0.61	36.4	28.88	34.72	Clay Loam	7.78 ± 0.11	14.93 ± 0.92	8.31 ± 1.38	3.04 ± 0.81

where, pH_s: pH of saturation paste; EC_e: electrical conductivity of saturation extract; ESP: exchangeable sodium percentage; CEC: cation exchange capacity; Ca^{2+}: calcium, Mg^{2+}: magnesium.

from 14.17-16.25 meq (p^+)/100 g within the soil profile (Table 2), highest (16.25 meq (p^+)/100 g) being in the 30-60 cm soil depth. Exchangeable sodium percentage (ESP) is one of the considerable criteria for the determination of salt-affected soils (U.S. Salinity Laboratory Staff, 1954). The ESP values (<15%) indicated that the soils are non-sodic. The highest ESP (8.04%) was observed in 30-60 cm soil depth followed by 7.65 and 7.78% at 0-30 cm and 60-90 cm, respectively (Table 2). The exchangeable Ca^{2+} was observed highest (9.19 meq/ 100 g soil) in 30-60 cm and lowest (7.92 meq/ 100 g soil) in surface soils (0-30 cm) (Table 2). Exchangeable Mg^{2+} followed the similar trend as that of exchangeable Ca^{2+} and varied from 3.04 to 4.20 meq/ 100 g soil throughout the profile (Table 2). The dynamic soil processes like weathering, leaching, biological nutrient cycling, fertilization, irrigation etc. led to the vertical distribution of exchangeable cations (James *et al.*, 2016). The soils treated with simulated solutions of divalent ions (Ca^{2+} and Mg^{2+}) showed improved soil structure and greater infiltrability values as compared to monovalent ions (Bai *et al.*, 2020). The interspecific attraction between the clay particles reduced with increasing adsorption of Na^+ ions on their negatively charged exchange sites leading to dispersion of clay minerals over drying causing structural collapse thus inhibiting the air and water movements (Bai *et al.*, 2020).

Solution cation and anion concentration

The unsaturated root zones of arid to semi-arid regions with shallow groundwater table cause primary salinization of the surface soils which causes detrimental effects on the soil physico-chemical characteristics (Heng *et al.*, 2018; Sahab *et al.*, 2021). The concentration of divalent cations (Ca^{2+} + Mg^{2+}) were highest (11.02 meq L^{-1}) in the 0-30 cm soil depth and decreased down the profile (Table 3). The Ca^{2+} + Mg^{2+} concentration ranged between 7.77 - 11.02 meq L^{-1} throughout the soil profile (0-90 cm). The monovalent cations (Na^+ and K^+) were found dominant (24.79 and 7.61 meq L^{-1} respectively) in the 30-60 cm, followed by 0-30 cm (21.32 and 7.07 meq L^{-1} respectively) and 60-90 cm (17.73 and 5.93 meq L^{-1} respectively) soil depths (Table 3). The Na^+ concentration was

Table 3. Depth-wise composition of soil saturation paste extract and structural stability ratios of the of waterlogged saline soils of India

Depth (cm)	$Ca^{2+} + Mg^{2+}$	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}	SAR	PAR	MCAR	CROSS
	(meq L^{-1})									
0-30	11.02 ± 1.43	21.32 ± 2.60	7.07 ± 0.39	1.38 ± 0.27	42.88 ± 3.25	113.46 ± 23.60	9.16 ± 1.59	3.02 ± 0.04	6.98 ± 0.98	16.22 ± 1.99
30-60	8.17 ± 1.43	24.79 ± 2.37	7.61 ± 0.88	1.58 ± 0.31	12.75 ± 1.74	153.72 ± 7.12	12.37 ± 1.23	3.80 ± 0.45	10.02 ± 1.06	22.06 ± 1.74
60-90	7.77 ± 1.32	17.73 ± 1.05	5.93 ± 0.27	1.58 ± 0.31	35.80 ± 2.49	215.77 ± 10.50	9.14 ± 1.29	3.05 ± 0.32	7.79 ± 1.34	16.70 ± 2.13

where, Ca^{2+}: calcium, Mg^{2+}: magnesium; Na^+: sodium; K^+: potassium; HCO_3^-: bicarbonate; Cl^-: chloride; SO_4^{2-}: sulphate; SAR: sodium adsorption ratio; PAR: potassium adsorption ratio; MCAR: monovalent cation adsorption ratio; CROSS: cation ratio of structural stability.

found dominant among all the soluble cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) throughout the soil profile.

Among the soluble anions, the Sampla site was dominated by Cl^- and SO_4^{2-} ions as compared to HCO_3^- ions (Table 3). The concentration of HCO_3^- ion was found highest (1.58 meq L^{-1}) in 30-60 and 60-90 cm soil depths and was observed least in surface soil (1.38 meq L^{-1}) layers. The concentration of Cl^- ions was highest (42.88 meq L^{-1}) in 0-30 cm and decreased to 12.75 meq L^{-1} in 30-60 cm soil depth. However, the concentration of SO_4^{2-} ions was recorded lowest (113.46 meq L^{-1}) in 0-30 cm and the highest (215.77 meq L^{-1}) in 60-90 cm soil depth showing an increasing trend with increasing depth (Table 3). The hygroscopic nature of the Na^+, K^+, Mg^{2+} and Ca^{2+} ions led to the formation of a diffuse double layer (DDL) whose thickness increased with a decrease in cationic radius and valency of the ions (Barman *et al.*, 2021) suggesting Na^+ ions forming thicker DDL than Ca^{2+} ions. The bigger hydration radii caused greater dispersion suggesting that the high Na^+ concentration level in the soil profile leads to the breakdown of soil aggregates and resulted into increased salinity over the days when SSD became non-operational in the Sampla site. These dispersed soils usually have poor infiltration rates which result in waterlogging (Valzano *et al.*, 2001). Moreover, the excessive salt concentration in soils generates high external osmotic potential that inhibits the water absorption by plant roots and thus, declines the plant growth and development (Sahab *et al.*, 2021).

Soil structural stability ratios

Various cationic ratios were formulated for salt affected soils to understand structural stability of soils with changing concentrations of the base cations (Marchuk and Rengasamy, 2010). Sodium adsorption ratio (SAR) ranged between 9.14 and 12.37 while potassium adsorption ratio (PAR) varied between 3.02 and 3.80 throughout the soil profile (0-90 cm) (Table 3). Due to greater hydration radius or thicker diffuse double layer of Na^+ and K^+ ions in comparison to Ca^{2+} and Mg^{2+} ions, the lower SAR and PAR values show the structural stability of soils (Barman *et al.*, 2021). The higher SAR and PAR values negatively influence the stability of soil aggregates. The structural stability of soils depends upon the type and content of clay minerals, exchangeable cations, water-stable aggregates, organic carbon, concentration of soil solution and wetting and drying cycles, etc (Barzegar *et al.*, 1995). The high SAR ratios indicate lower tensile strength of soils which become vulnerable to compaction due to poor soil aggregation, development of waterlogging and salinity. The monovalent cation adsorption ratio (MCAR) ranged between 6.98 and 10.02 and the cation ratio of structural stability (CROSS) was observed between 16.22 and 22.06 (Table 3). Within the soil profile, PAR, MCAR and CROSS were observed minimum in 0-30 cm and maximum in 30-60 cm soil depths. The MCAR and CROSS include the dispersion effects of Na^+ and K^+ ions in addition to the flocculating power of Ca^{2+} and Mg^{2+} ions (Marchuk *et al.*, 2013b). The increase in MCAR and CROSS decreases the structural stability of soils (Marchuk *et al.*, 2013a). Keeping the Na^+, Ca^{2+} and Mg^{2+} ions concentrations and SAR constant, the increasing concentration of K^+ increased the MCAR, CROSS and the zeta potential of soil clays (Marchuk *et al.*, 2013b). The excessive K^+ ions alone could result in soil vulnerability to crack formation with increasing values of CROSS. The anisotropic nature of the soils decreases with increasing values of CROSS, that is, the variation in the soil physico-chemical, biological and mineralogical properties become almost constant in all directions which ultimately affects the soil quality (Yan *et al.*, 2024).

Soil clay mineralogy

The clay mineralogy was studied down the soil profile to determine the identity and nature of different minerals in the clay fraction and their transformation within the soil profile (0-60 cm and 60-90 cm) of the SSD reclaimed Sampla site. The X-ray diffractogram of clays at 0-60 cm depth (Fig. 2) showed the dominance of mica (at ~1.00 nm) followed by kaolin (identified by diffraction peak at ~0.71 nm), hydroxy interlayered vermiculite (HIV) (at ~1.44 nm in CaEG treated sample), K-feldspar (at ~0.32 nm), chlorite (at ~1.42 nm in K550 treated sample), quartz (at ~0.42 nm) and rutile (at ~0.325 and 0.326 nm). The diffractogram of 60-90 cm soil depth (Fig. 3) showed similar type of minerals as present in the clay fraction of 0-60 cm depth, with a bit of variation for chlorite (at ~1.45 nm in 0-60 cm and at ~1.42 nm in 60-90 cm) and rutile (at ~0.325 nm in 0- 60 cm and at ~0.326 nm in 60 - 90 cm). The characteristic peak at ~1.0 nm region and its persistence during glycolation, K-treatment and heating at 550°C indicated the presence of mica in the samples. The presence of HIV was confirmed from the very small peak at ~1.4 nm upon ethylene glycol solvation which did not collapse readily at ~1.0 nm peak on exposure to 110 °C but showed slight tailings on acute angle side of 1.0 nm peak after thermally treating the K-saturated clays at 550 °C. The peak at ~1.45 nm on heating the K-saturated samples at 550 °C was the characteristic peak of true chlorite (Pal *et al.*, 2012). The presence of a 0.7 nm peak in all the clay samples confirmed the presence of kaolinite. The disappearance of this peak during the K-saturation at 550°C also confirmed the presence of kaolinite. However, the nature of the 0.7 nm peak and its behavior to the K-saturated and heated samples indicated the presence of kaolinite interstratification with other 2:1 mineral. Therefore, this kaolinite is called kaolin (Bhattacharyya *et al.*, 1993; Chandran *et al.*, 2005). Sehgal (1974) postulated that in the alluvial soils of Punjab, biotite was altered to chlorite, followed by mica, vermiculite and chloritized vermiculite stages. In contrast, Jassal *et al.* (2004) investigated typical salt-affected soils of Punjab for their mineral assemblages and found that the X-ray diffractograms of the clay fraction of the soils showed the presence of mica, chlorite, smectite and kaolinite with occasionally a very small amount of vermiculite. Similarly, the clay minerology was studied for the natric endopedon of saline-sodic soils adjoining saline water lake and the sodic/solod soils adjoining brackish water lake (Andrade *et al.*, 2020). The findings suggested that the minerals transform into mixed layered minerals with respect to the variation in the soil chemistry. The mixed-layered illite-smectite (I-S), kaolinite-smectite (K-S) and kaolinite-illite (K-I) minerals were observed in the saline-sodic soils with the dominance of illite (73-76%) > kaolinite (14-16%) > smectite (10-11%). However, the relative proportion of illites (52-68% and 36-41%) reduced with concurrent increase in the kaolinite (19-35% and 21-31%) and smectites (7-21% and 31-37%) in the interstratified I-S, K-I and K-S mixed-layered minerals of the sodic and solod soils, respectively. These soils were also found with illite-interstratified vermiculites. Therefore, the progressive changes in the mineral assemblage were likely due to transformations under the changing geochemical conditions of the brackish lakes (Andrade *et al*., 2020). However, in our study, the X-ray diffractograms did not show any variation within the mineral characteristics in both the soil depths after Ca-saturation, Ca-EG treatment and K-saturation at different temperatures (25 °C, 110 °C, 300 °C and 550 °C) (Fig. 2 and 3). The sharpness of the X-ray diffraction peaks indicates the strong crystalline nature of the clay minerals (Vishnu *et al*., 2022). Therefore, it proved the presence of mica (at ~1.00 nm) as strongly crystalline mineral in 0-60 cm than in 60-90 cm soil depth.

The soils at the experimental site was formed from Quaternary Himalayan deposits carried by the Ganges (Pal *et al*., 2000). These soils typically contain mica, vermiculite, smectite, kaolinite, chlorite and mixed-layer minerals (Pal *et al*., 2012). Biotite mica has weathered into trioctahedral vermiculite through a 1.0-1.4 nm mixed-layer intermediate phase during an earlier warm and humid period (6500–4000 years BP) (Kapoor *et al*., 1981; Pal and Deshpande, 1987). With the end of the humid climate, vermiculite has been preserved up to the present (Pal *et al*., 2009). The presence of mica-vermiculite is linked to soil formation under alkaline conditions (Kapoor *et al*., 1981), while kaolinite and chlorite are associated with acidic soil conditions (Mohindra and Parkash, 1990). This could also be stated as the leaching prone acidic regions advance mineral weathering and lead to the formation of kaolinite and chlorites. The transformation of 2:1 type mineral into kaolinite through a 1.0-1.4 nm interstratified phase is most favorable in acidic

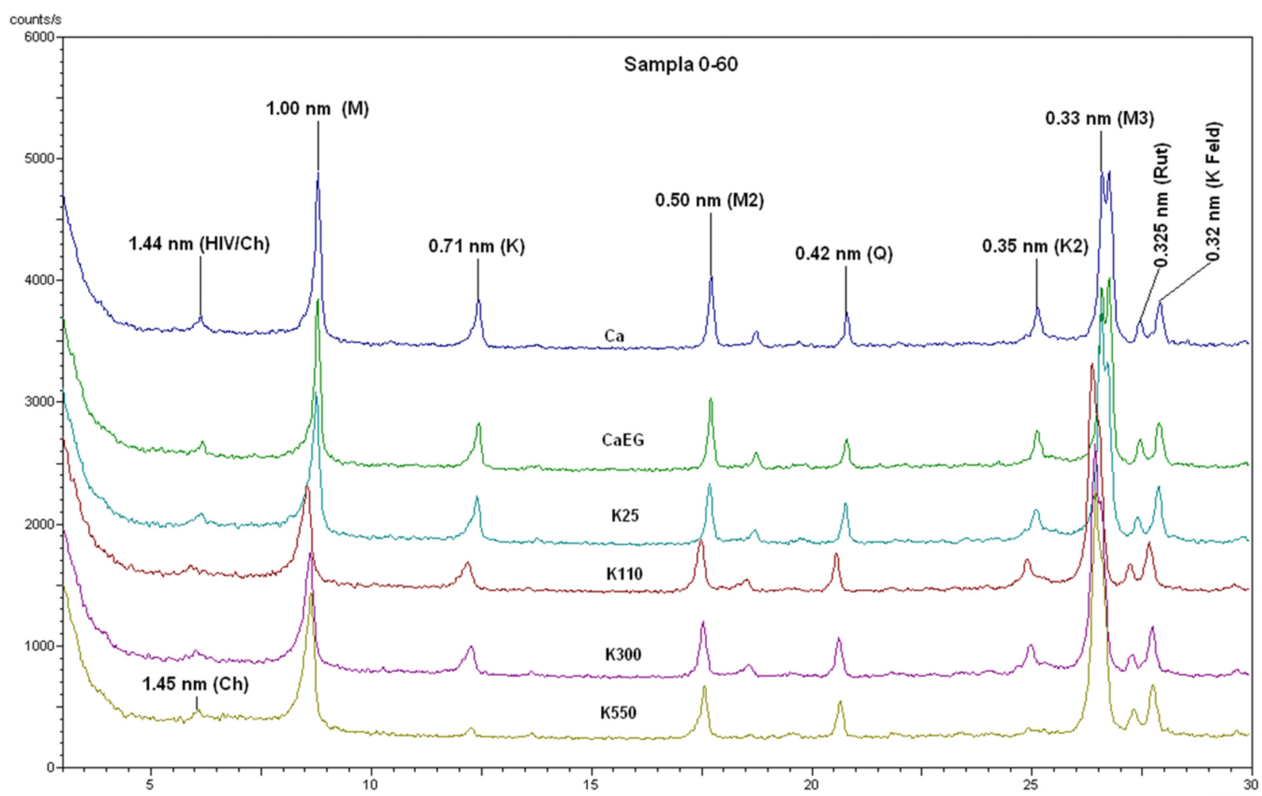

Fig. 2 X-ray diffractogram of total clay Ca (Ca-saturated); CaEG (calcium saturated and ethylene glycol-solvated; K25, K110, K300 and K550 (K-saturated soils samples at room temperature and heated to 110°, 300° and 550°) of the 0-60 cm soil depth soils of Sampla SSD during revisit. Here, HIV = Hydroxy Interlayered Vermiculite; Ch = Chlorite; M = Mica; Amp = Amphibole; K = Kaolin; M2 = 2nd order Mica; Q Quartz; K2 = 2nd order Kaolin; M3 = 3rd order Mica; Rut = Rutile; K Feld = K Feldspar.

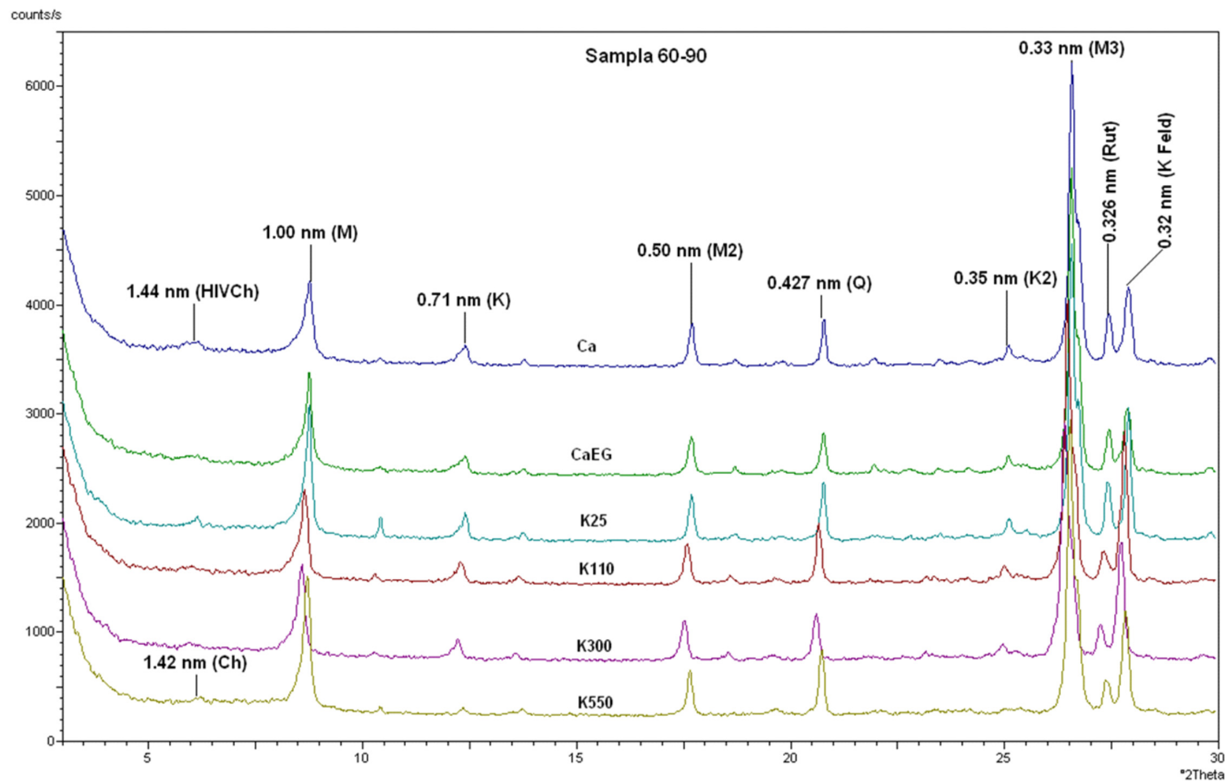

Fig. 3 X-ray diffractogram of total clay Ca (Ca-saturated); CaEG (calcium saturated and ethylene glycol-solvated; K25, K110, K300 and K550 (K-saturated soils samples at room temperature and heated to 110°, 300° and 550°) of the 60 - 90 cm soil depth soils of Sampla SSD during revisit. Here, HIV = Hydroxy Interlayered Vermiculite; Ch = Chlorite; M = Mica; Amp = Amphibole; K = Kaolin; M2 = 2nd order Mica; Q Quartz; K2 = 2nd order Kaolin; M3 = 3rd order Mica; Rut = Rutile; K Feld = K Feldspar.

soils, a condition typically brought about by a tropical humid climate (Bhattacharyya *et al.*, 1993). Thus, presence of kaolinite might be a remnant from a past humid climate (Pal and Durge, 1989; Srivastava *et al.*, 1998) or an inheritance from the parent alluvium. Therefore, the presence of Ca^{2+}, Mg^{2+}, and K^{+} in the soil solution and exchange sites does not confirm the dominance of any specific minerals. The degree of dispersion of soils after wetting due to sodium (Na^{+}) saturation over the clay colloids was found to be governed by the type of clay minerals (Greene *et al.*, 2002). They found that the illite/ smectite interstratified minerals were more dispersed with increasing exchangeable Na^{+} as compared to pure illites or kaolinites. That is, the higher the charges of the clay minerals, greater is the adsorption of Na^{+} ions. Thus, the dominance of Na^{+} ions decrease the soil aggregation under waterlogged saline soils. This finding is also in agreement with the increased stability ratios (SAR, PAR, MCAR and CROSS) in this study. The clay minerals are subjected to interact through inner sphere and outer sphere complexation with the exchangeable cations (Sposito *et al.*, 1999). The outer sphere complexes (electrostatic attraction) were observed vulnerable to hydration reactions as compared with the inner sphere complexes (covalent bonding). Such hydration reactions result into swelling and dispersion of clay minerals (Marchuk and Rengasamy, 2011). They also found that ionicity of clay-cation complexes determine the stability of soil structures. The ionicity of clay-monovalent cation complexes were observed greater than that of clay-divalent cation complexes. Moreover, the hydration energy was found proportional with the ionicity of the complexes, thus, indicating the poor structure of soils dominated with monovalent cations. Thus, the relatively dominant Na^{+} ions in the soil solution and on exchange sites were contributing to the redevelopment of waterlogging at the reclaimed SSD site.

Conclusions

The SSD reclaimed Sampla site had clay loam to clay texture, alkaline pH, and high soil EC_e, suggesting that salinity was rebuilding due to the stoppage of SSD operation in Sampla since 2000. The relative abundance of exchangeable bases (Ca^{2+} and Mg^{2+}) was higher in subsurface (30-60 cm) as compared to surface soils (0-30 cm). Throughout the profile, the distribution of soluble ions followed the order $Na^+ > Ca^{2+} + Mg^{2+} > K^+$ and $SO_4^{2-} > Cl^- > HCO_3^-$ for cations and anions respectively. The soil structural stability ratios such as SAR, PAR, MCAR, and CROSS were higher in the 30-60 cm soil depth than in surface soils. The ESP was also observed maximum in the subsurface soils (30-60 cm), although soils are non-sodic. In addition, the vertical distribution and increasing abundance of soluble salts redeveloped the soil salinity. The X-ray diffraction didn't show any differences among clay minerals throughout the profile. The dominant clay minerals were mica, kaolin, HIV, K-feldspar, chlorite and quartz. Their sharp diffraction peaks showed that mica, quartz and K-feldspar were strongly crystalline. The relative similarities in the mineralogy of this SSD reclaimed site suggested that all the clay minerals were inherited from the parent material, having no significant *in-situ* transformation under prevailing conditions. The soil ESP value and nature of various phyllosilicate clay minerals in different depths doesn't explain the presence of waterlogging. Poorly drained conditions arise from a shallow groundwater table near the soil surface, causing waterlogging.

Acknowledgements

The authors acknowledge Director, ICAR-Central Soil Salinity Research Institute for providing the necessary facilities to complete the field and laboratory analysis. The authors are grateful to Director, ICAR-National Bureau of Soil Survey and Land Use Planning, Nagpur for allowing analysis of clays in the XRD instrument available at the Division of Soil Resource Studies. This project was funded by Indian Council of Agricultural Research, New Delhi, India.

References

Andrade GRP, Furquim SAC, do Nascimento TTV, Brito AC, Camargo GR and de Souza GC (2020) Transformation of clay minerals in salt-affected soils, Pantanal wetland, Brazil. *Geoderma* **371**: 114380.

Bahçeci Ý, Nacar AS, Topalhasan L, Tari AF and Ritzema HP (2018) A new drainpipe envelope concept for subsurface drainage systems in irrigated agriculture. *Irrigation and Drainage* **67**: 40-50.

Bai Y, Qin Y and Lu X (2020) Fractal dimension of particle-size distribution and their relationships with alkalinity properties of soils in the western Songnen Plain, China. *Scientific Reports* **10**: 20603. https://doi.org/10.1038/s41598-020-77676-w.

Barman A, Sheoran P, Yadav RK, Abhishek R, Sharma R, Prajapat K, Singh RK and Kumar S (2021) Soil spatial variability characterization: Delineating index-based management zones in salt-affected agroecosystem of India. *Journal of Environmental Management* **296**: 113243.

Barzegar AR, Rengasamy P and Oades JM (1995) Effects of clay type and rate of wetting on the mellowing of compacted soils. *Geoderma* **68(1-2)**: 39-49.

Bhattacharyya T, Pal DK and Deshpande SB (1993) Genesis and transformation of minerals in the formation of red (Alfisols) and black (Inceptisols and Vertisols) soils on Deccan basalt in the Western Ghats, India. *Journal of Soil Science* **44(1)**: 159-171.

Boonstra J, Ritzema HP, Wolters W, Oosterbaan RJ and van Lieshout AM (2002) Research on the control of waterlogging and salinization in irrigated agricultural lands: recommendations on waterlogging and salinity control based on pilot area drainage research. CSSRI/Alterra-ILRI.

Bos MG (2001) Selecting the drainage method for agricultural land. *Irrigation and Drainage Systems* **15**: 269–279.

Bouyoucos GJ (1962) Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal* **54**: 464–465.

Chandran P, Ray SK, Bhattacharyya T, Srivastava P, Krishnan P and Pal DK (2005) Lateritic soils of Kerala, India: their mineralogy, genesis, and taxonomy. *Australian Journal of Soil Research* **43(7)**: 839-852.

Chizhikova NP and Khitrov NB (2016) Diversity of clay minerals in soils of solonetzic complexes in the southeast of Western Siberia. *Eurasian Soil Science* **49**: 1419–1431.

Madison USA. FAO (2021) GSASmap GLOBAL MAP soils of salt-affected soils, pp. 1–20.

Galán E and Ferrel RE (2006) *Genesis of Clay Minerals.* In: Bergaya F and Lagaly G (eds). *Handbook of Clay Science. Part A: Fundamentals.* Elsevier, Amsterdam, 2nd Ed., p. 83-126.

Greene RS, Eggleton RA and Rengasamy P (2002) Relationships between clay mineralogy and the hardsetting properties of soils in the Carnarvon horticultural district of Western Australia. *Applied Clay Science* **20(4-5)**: 211-223.

Heng T, Liao R, Wang Z, Wu W, Li W and Zhang J (2018) Effects of combined drip irrigation and sub-surface pipe drainage on water and salt transport of saline-alkali soil in Xinjiang, China. *Journal of Arid Land* **10**: 932-945.

Hillel D (2004) *Introduction to Environmental Soil Physics*. Elsevier Academic Press, p. 44.

Jackson ML (1973) *Soil Chemical Analysis*. Prentice Hall of India Private Ltd., New Delhi, pp. 56–70.

Jackson ML (1979) *Soil Chemical Analysis - Advanced Course*. Published by the author, Wisconsin, USA.

James J, Littke K, Bonassi T and Harrison R (2016) Exchangeable cations in deep forest soils: Separating climate and chemical controls on spatial and vertical distribution and cycling. *Geoderma* **279**:109-121.

Jassal HS, Singh J, Sawhney JS and Sharma BD (2004) Geochemical environment and clay mineral formation of some salt affected soils of Punjab. *International conference on sustainable management of sodic lands held at Lucknow*. pp. 156-158.

Kamra SK (2015) An overview of subsurface drainage for management of waterlogged saline soils of India. *Water and Energy International* **58(6)**: 46-53.

Kamra SK, Kumar S, Kumar N and Dagar JC (2019) Engineering and biological approaches for drainage of irrigated lands. *Research Developments in Saline Agriculture*: 537-577.

Kapoor BS, Singh HB, Goswami SC, Abrol IP, Bhargava GP and Pal DK (1981) Weathering of micaceous minerals in some salt-affected soils. *Journal of the Indian Society of Soil Science* **29(4)**:486-92.

Kome GK, Enang RK, Tabi FO and Yerima BPK (2019) Influence of clay minerals on some soil fertility attributes: A Review. *Open Journal of Soil Science* **9**: 155-188.

Mandal S, Raju R, Kumar A, Kumar P and Sharma PC (2018) Current status of research, technology response and policy needs of salt-affected soils in India–a review. *Journal of the Indian Society of Coastal Agricultural Research* **36**: 40-53.

Marchuk AG and Rengasamy P (2010) Cation ratio of soil structural stability (CROSS). In *Proceedings 19th World Congress of Soil Science 2010* (Vol. 1, pp. 5981-5983). CSIRO Publishing.

Marchuk A and Rengasamy P (2011) Clay behaviour in suspension is related to the ionicity of clay-cation bonds. *Applied Clay Science* **53**:754–759.

Marchuk A, Rengasamy P, McNeill A and Kumar A (2013a) Nature of the clay–cation bond affects soil structure as verified by X-ray computed tomography. *Soil Research* **50(8)**: 638-644.

Marchuk A, Rengasamy P and McNeill A (2013b) Influence of organic matter, clay mineralogy, and pH on the effects of CROSS on soil structure is related to the zeta potential of the dispersed clay. *Soil Research* **51(1)**: 34-40.

Mehra OP and Jackson ML (1960) In: *Iron Oxide Removal from Soils and Clays by Dithionite-Citrate Systems Buffered with Sodium Bicarbonate.* Pergaman Press, London, pp. 317–327.

Mishra BB (2020) *The Soils of India*. Springer.

Mohindra R and Parkash B (1990) Clay mineralogy of the Gandak megafan and adjoining areas, Middle Gangetic Plains, India/Minéralogie des argiles du" mégafan" de Gandak et des régions avoisinantes, Moyennes Plaines du Gange, Inde. Sciences Géologiques, bulletins et mémoires **43(2)**: 203-12.

Mukhopadhyay R, Sarkar B, Jat HS, Sharma PC and Bolan N (2021) Soil salinity under climate change: challenges for sustainable agriculture and food security. *Journal of Environmental Management* **280(6)**: 111736.

Mukhopadhyay R, Fagodiya RK, Narjary B, Barman A, Prajapat K, Kumar S, Bundela DS and Sharma PC (2023) Restoring soil quality and carbon sequestration potential of waterlogged saline land using subsurface drainage technology to achieve land degradation neutrality in India. *Science of The Total Environment* **885**: 163959.

NBSS & LUP (2016*) India: Agro-ecological Region*. Revised edition. Publication no. 170.

Pal DK and Deshpande SB (1987) Parent material, mineralogy and genesis of two benchmark soils of Kashmir valley. *Journal of the Indian Society of Soil Science* **35(4)**:690-8.

Pal DK and Durge SL (1989). Release and adsorption of potassium in some benchmark alluvial soils of India in relation to their mineralogy. *Pedologie* (Ghent) **39**:235-48.

Pal DK, Bhattacharyya T, Deshpande SB, Sharma VAK and Velayutham M (2000) Significance of minerals in soil environments of India. NBSS Review Series 1, ISBN: 81-85460-57-4.

Pal DK, Bhattacharyya T, Srivastava P, Chandran P and Ray SK (2009) Soils of the Indo-Gangetic Plains: their historical perspective and management. *Current Science* **10**:1193-202.

Pal DK, Bhattacharyya T, Sinha R, Srivastava P, Dasgupta AS, Chandran P, Ray SK and Nimje A (2012) Clay minerals record from Late Quaternary drill cores of the Ganga Plains and their implications for provenance and climate change in the Himalayan foreland. *Palaeogeography, Palaeoclimatology, Palaeoecology* **356**:27-37.

Rao KVGK and Leeds-Harrison PB (1991) Desalinization with subsurface drainage. *Agricultural Water Management* **19**: 303-311.

Rengasamy P and Marchuk A (2011) Cation ratio of soil structural stability (CROSS). *Soil Research* **49(3)**: 280-285.

Ritzema H, Satyanarayana T, Raman S and Boonstra J (2008) Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. *Agricultural Water Management* **95**: 179-189.

Sahab S, Suhani I, Srivastava V, Chauhan PS, Singh RP and Prasad V (2021) Potential risk assessment of soil salinity to agroecosystem sustainability: Current status and management strategies. *Science of the Total Environment* **764**: 144164.

Saqib M, Akhtar J and Qureshi RH (2004) Pot study on wheat growth in saline and waterlogged compacted soil. *Soil and Tillage Research* **77 (2)**: 169–177.

Sehgal JL (1974) Nature and geographic distribution of clay minerals in soils of different moisture regimes in Punjab, Haryana and Himachal Pradesh. Proc. *Indian National Science Academy* **40**: 151-159.

Sharma DK, Singh R, Singh A and Bhardwaj AK (2015) CSSRI Annual Report 2014-15.

Singh J and Sawhney JS (2006) Clay mineralogy of the salt-affected soils of south-west Punjab. *Journal of the Indian Society of Soil Science* **54(4)**: 461-464.

Sposito G (2016) *Soil salinity.* In: The chemistry of soils (3rd ed., pp. 273). Oxford University Press, Incorporated.

Sposito G, Skipper NT, Sutton R, Park S, Soper AK and Greathouse JA (1999) Surface geochemistry of the clay minerals. *Proceedings of the National Academy of Sciences*, USA **96**: 3358–3364.

Srivastava P, Parkash B and Pal DK (1998) Clay minerals in soils as evidence of Holocene climatic change, central Indo-Gangetic Plains, north-central India. *Quaternary Research* **50(3)**: 230-239.

Tavakkoli E, Uddin S, Rengasamy P and McDonald GK (2022) Field applications of gypsum reduce pH and improve soil C in highly alkaline soils in southern Australia's dryland cropping region. *Soil Use and Management* **38(1)**: 466-477.

US Salinity Laboratory Staff (1954) *Diagnosis and improvement of saline and alkali soils*. Agricultural Handbook 60. U.S. Department of Agriculture, Washington, DC.

Valzano FP, Greene RSB, Murphy BW, Rengasamy P and Jarwal SD (2001) Effects of gypsum and stubble retention on the chemical and physical properties of a sodic grey Vertosol in western Victoria. *Soil Research* **39(6)**: 1333-1347.

Verma AK, Gupta SK and Isaac RK (2014) Application of soil–water–atmosphere–plant model to assess performance of subsurface drainage system under semi arid monsoon climate. *Irrigation and Drainage* **63(1)**: 93-101.

Vishnu PS, Sandeep S and Anil-Kumar KS (2022) Soil Taxonomy and Mineralogy of Varying Geological Parent Material in Moist Deciduous Forests in Southern Western Ghats, Kerala. *Clay Research* **41(2)**: 102-112.

Wang ZH, Heng T, Li WH, Zhang JZ, Yang BL and Jiang YS (2017) Effects of drainage pipe drainage on soil salinity leaching under drip irrigation. *Transactions of the Chinese Society for Agricultural Machinery* **48**: 253–261.

Yan S, Zhang T, Zhang B, Feng H and Siddique KH (2024) Calibration of saline water quality assessment standard based on EC and CROSS considering soil water-salt transport and crack formation. *Journal of Hydrology*: 130975.

Received: September 8, 2024; Accepted: October 28, 2024

Journal of Soil Salinity and Water Quality 16(2), 270-279, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.157080

A Geographic Information System (GIS) based Soil Erosion Model for Estimation of Sediment Yield for Kshipra River Basin, Madhya Pradesh India

Pramod Kumar Meena[1], Deepak Khare[2], Mohan Lal[3]*, Dheeraj Kumar[3], Jitendra Kumar[4], Surendra Kumar Chandniha[5] and Rishi Pathak[6]

[1]*Department of Agricultural Engineering, Ministry of Agriculture and Farmer Welfare, Betul, Madhya Pradesh*
[2]*Department of Water Resources Development and Management, IIT Roorkee, Uttarakhand*
[3]*Department of Irrigation and Drainage Engineering, G.B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand*
[4]*Scientist, ICAR-Central Soil Salinity Research Institute, Karnal, Haryana*
[5]*Department of Soil and water Engineering, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh*
[6]*National Institute of Hydrology, Roorkee, Uttarakhand*
**Corresponding author's E-mail: mohan841987@gmail.com*

Abstract

The present study was carried out to simulate the sediment yield from Kshipra River basin, which is a southern tributary of Yamuna River basin-the second largest river basin of India. A Geographic Information System (GIS) based soil erosion model was used to estimate the sediment yield of river basin. Four different grid sizes such as 15×15 m, 30×30 m, 60×60 m and 90× 90 m were used in sediment estimation, among which 15×15 m grid size found to estimate good results. The annual rate of soil erosion estimated for 16 years (1995 to 2010) was found to vary between 10.02 to 20.31 t $ha^{-1}yr^{-1}$ along with an average of 15.31 t $ha^{-1}yr^{-1}$. The study reported about 78% area of Kshipra River basin is slightly or moderately affected by soil erosion having annual sediment production rate of less than 10 tha^{-1}. A governing equation has been derived for estimation of rainfall erosivity and sediment yield for river basin. The findings of study will be most useful for predicting sediment yields where only rainfall and flow data are available at site.

Key words: Geographic Information System (GIS), Sediment yield, USLE, and Erosivity

Introduction

The sediment load at the outlet of a catchment is caused by the physical processes of detachment, transportation, and deposition of the soil layer by various erosion factors. The magnitude and concentration of sediments are mainly affected by the amount and intensity of precipitation, physical properties of the soil (texture and detachability), topography (slope steepness and complexity), and land use (Melesse *et al.*, 2011). Estimating sediment yield from rivers, particularly where suspended load dominates, is crucial for developing soil conservation and pollution control strategies, as well as for the design and management of dams, reservoirs, canals, and other hydraulic structures (Singh *et al.*, 2013; Ayteek and Kisi *et al.*, 2008; Caroni *et al.*, 1984). Globally, soil erosion is recognized as a severe issue stemming from agricultural intensification, land degradation, and potentially global climate change (Yang *et al.*, 2003). Sediment deposition not only diminishes reservoir capacity but also leads to river bed and bank accumulation, causing flood plain expansion during high water events. Approximately 53% of India's total geographical area is adversely affected by soil erosion and various forms of land degradation (Reddy, 1999). The interplay of numerous, often interconnected physiographic and climatic factors renders the rainfall-runoff-sediment yield process highly complex to comprehend and exceptionally challenging to model (Zhang and Govindaraju, 2003).

Researchers have developed various empirical models to evaluate soil loss (Misra *et al.*, 1984; Jose and Das 1982). The Morgan-Morgan and Finney (MMF) model, which was based on more physical principles (Meyer and Wischmeier, 1969), offers an alternative to the widely-used universal soil loss equation (USLE) (Wischmeier and Smith, 1978). USLE has been extensively utilized in its lumped form for small watersheds (Williams and Berndt, 1972, 197; Dickinson and Collins, 1998) and larger catchment areas (Jain *et al.*, 2001; Baba and Yusof, 2001; Devatha, *et. al.*, 2015). Additional research utilizing satellite data (Onyando *et al.*, 2005; Wu *et al.*, 2005; Dabral *et al.*, 2008) has involved dividing watersheds into cells, regular grids, or units to model soil loss in specific areas. For instance, Pandey *et al.* (2007) employed 200 m × 200 m grid cells to estimate average annual sediment yield and identify critical erosion-prone areas in the Karso Watershed of Hazaribagh, Jarkhand State, India. In another study, Pandey *et al.* (2009) applied both the MMF model and USLE, incorporating remote sensing and GIS techniques, to assess soil loss in a Himalayan watershed. However, their research lacked verification of the simulated results due to the absence of observed data.

Geographic information systems (GIS) may contain the necessary data for USLE calculations, enabling GIS-based methods to determine factor values for predicting erosion in grid cells using the USLE (Kinnell, 2010). However, many attempts to combine GIS with USLE for modelling spatial variations in soil loss have often neglected to address issues related to assumptions made when scaling up USLE applications from plots to larger areas. Researchers worldwide have investigated sediment generation dynamics from plot to watershed scale using both observed and satellite data (Liu *et al.*, 2000; Jain *et al.*, 2001; Fistikoglu *et al.*, 2002; Angima *et al.*, 2003; Wu *et al.*, 2005; Kinnell, 2010; Fu *et al.*, 2011; Parveen and Kumar 2012; Fu *et al.*, 2015; Mondel *et al.*, 2016). However, sediment data availability is limited and scarce in developing countries such as India. No soil erosion estimates have been conducted for the Yamuna catchment of the Kshipra River in Madhya Pradesh. Considering this challenge and the limited availability of sediment data in the Indian context, this study aims to estimate the magnitude and spatial distribution of soil loss using GIS-based USLE methods.

Study area

The study catchment Kshipra is located in western part of Madhya Pradesh. It falls in the semi-arid sub-tropical climatic region of India (Fig.1). Geographically, the Kshipra watershed is located between 75°25′04″ to 76°13′19″ longitude and 22°27′29″ to 23°56′40″ N latitude. It covers a geographical area of 5617 km^2 having elevation ranges from 444 m at the outlet and 819 m at the ridge line in upper reaches.

The slope of the watershed varies from 0 to 15%. Approximately 51% of the area is occupied by agricultural practice, followed by fallow land, barren land, and open forests. The built-up area can be found only at around Indore, Ujjian and Dewas cities. Soils of the watershed are classified as Clay (38.28%), Loam (31.72%), Sandy loam (0.07%) and Silt clay (29.85%) respectively (NBSSLUP, Nagpur). The annual rainfall ranges between 581.94 and 1299.13 mm, and most (about 80%) of the rainfall is concentrated in the months July, August, and September (or monsoon season). Daily mean temperature ranges from a maximum of 45.5 °C (May) to minimum of 6 °C (January). The water of the Kshipra River is being used for drinking, industrial and irrigation purposes.

Hydrological data collection

In the study catchment, rainfall is measured at four major stations: Mahidpur, Alot, Indore and Dewas. However, the runoff and sediment were only observed at Mahidpur gauging station. The rainfall data used in the present study was collected from state data centre, Bhopal, Madhya Pradesh. The daily rainfall data for the period of 16 years (January 1995 to December 2010) measured at four different stations has been used for analysis. The Thiessen polygon method was used to estimate the mean rainfall over the study basin. The observed mean annual rainfall (PA) (based on 16-year data record) in the Kshipra basin was found to be about 915 mm with more than 85% of the rainfall occurs during the monsoon months

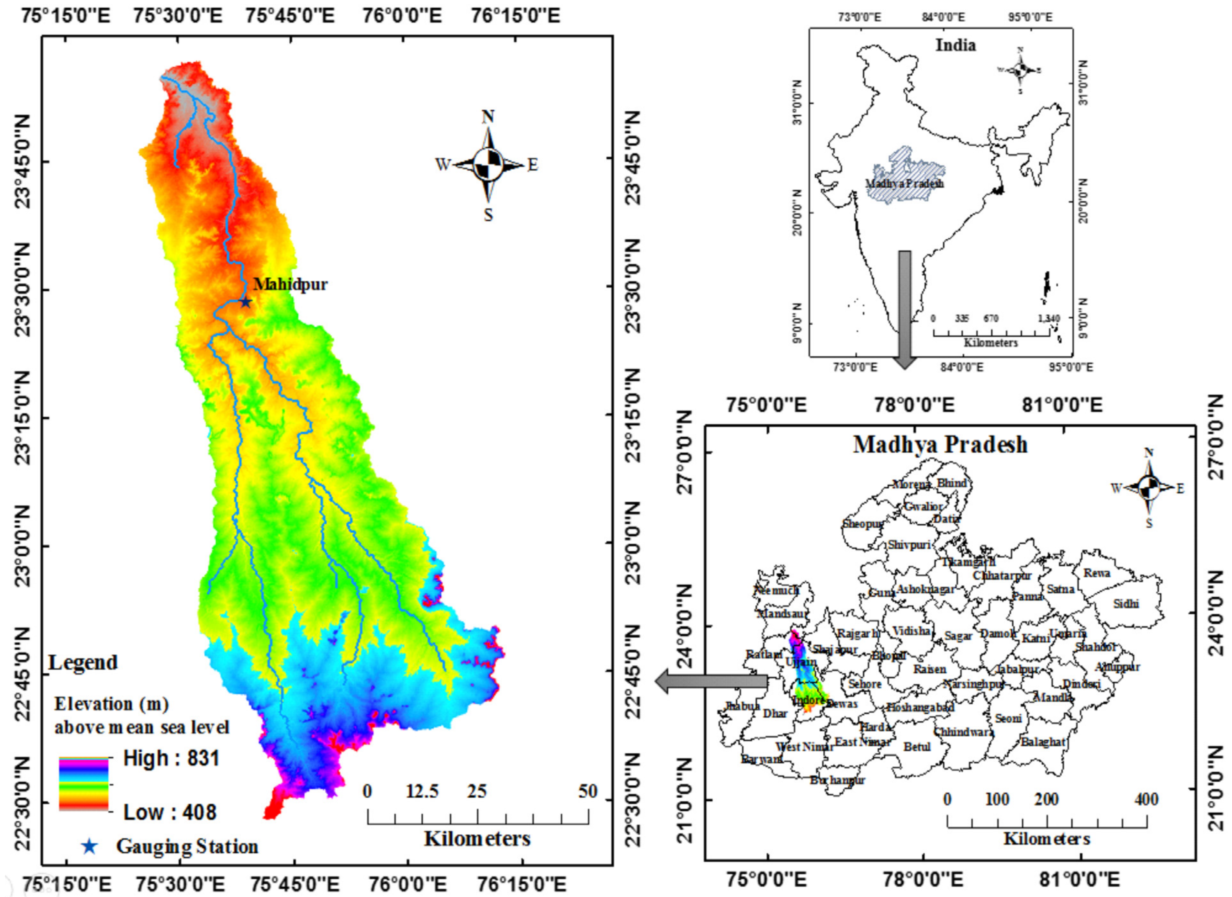

Fig. 1 Location map of Kshipra river basin

(June–September). The runoff and sediment data used in present study was collected from department of the Central Water Commission Circle, Jaipur, India. The sampling of sediment was done manually at Mahidpur gauging station on daily basis. Discharge flowing through the stream at the Mahidpur gauging station was measured by notching the staff gauge reading and rating curve. The volume of runoff (m^3) times the sediment concentration (mg/l) adjusted for units gave the sediment production from a rainfall event. The sediment production values of all rainfall events in a year were summed up to get the annual value in tonnes. The annual sediment production in tonnes divided by the watershed area gave the annual sediment yield in tonnes per hectare.

Universal soil loss equation (USLE)

The Universal Soil Loss Equation (USLE) has been found to produce realistic estimates of surface water erosion (Wischmeier and Smith, 1978; Onyando *et al.*, 2005; Pandey *et al.*, 2007). Although USLE is a lumped empirical model, this equation has been the part of several spatially distributed process-based models. In the present study, USLE has been used for evaluation of gross soil erosion from each cell is expressed as:

$$A_i = R_i K_i LS_i C_i P_i \quad \ldots(1)$$

where A_i = Gross soil erosion in cell i (MT ha^{-1} year^{-1}); R_i = Rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}); K_i = Soil erodibility factor in the cell i (MT ha h ha^{-1} MJ^{-1} mm^{-1}); LS_i = Slope steepness and length factor for cell i (dimensionless); C_i = Cover management factor (dimensionless) and Pi = Supporting practice factor for cell i (dimensionless).

Rainfall erosivity (R)

The erosivity factor of rainfall (R) is a function of the falling rainfall intensity. It is the product of kinetic energy of the raindrop and the 30 min maximum rainfall intensity (EI_{30}). In India, Babu *et al*. (2004) estimated EI_{30} values using data from the storms greater than 12.5 mm observed at 123 rain gauging stations located at different climatic zones of India. They proposed a linear regression relationship between average annual rainfall and erosivity factor (R) for computing the EI30 values for different zones in India. Since rainfall intensity for the present study watershed could not be estimated in the absence of a recording type rain-gauge; and therefore, monthly values were used in annual calculations using the following relationship as proposed by Babu *et al*. (2004):

$$R = x\,Rn + y \qquad \ldots(2)$$

Where, R is the average annual erosivity Index; Rn is the average annual rainfall whose value ranges from 340 mm to 3500 mm; x and y are the empirical coefficients having values 0.38 and 81.5, respectively.

In present study, the estimation ability of Babu *et al*. (2004) (Eq. 2) approach was also analysed by optimizing (by least square fitting) the parameters x and y; and hence a new equation, similar to, Babu *et al*. (2004) has been proposed in present study.

Soil erodibility factor (K)

Wischmeier and Mannering (1969) created a complex multiple regression equation incorporating various factors such as sand, silt, and clay ratios, organic matter content, soil moisture, bulk density, slope, pH levels, structure, soil layer thickness, and land use/cover. Although statistically accurate and technically valid, this equation proved too intricate for practical use by technicians. Consequently, Wischmeier *et al*. (1971) simplified the process for determining soil erodibility by developing an equation based on five soil parameters, which are utilized in the current study. Among these parameters, sand, silt, and clay percentages, along with organic matter content, were calculated from soil analysis data. Soil permeability and structure code were assessed using Tables 1 and 2. The Soil erodibility map of Kshipra Basin is presented in Fig. 2.

The K-factor was calculated using the following relationship (Wischmeier *et al*. 1971):

Table 1. Permeability code for different types of soil

Code	Description	Rate, mm/h
1	Rapid	>130
2	Moderate to rapid	60-130
3	Moderate	20-60
4	Slow to moderate	5-20
5	Slow	1-5
6	Very slow	<1

Table 2. Structure code for different types of soil.

Code	Structure	Size, mm
1	Very fine granular	<1
2	fine granular	1-2
3	Medium or coarse granular	2-10
4	Blocky, platy or massive	>10

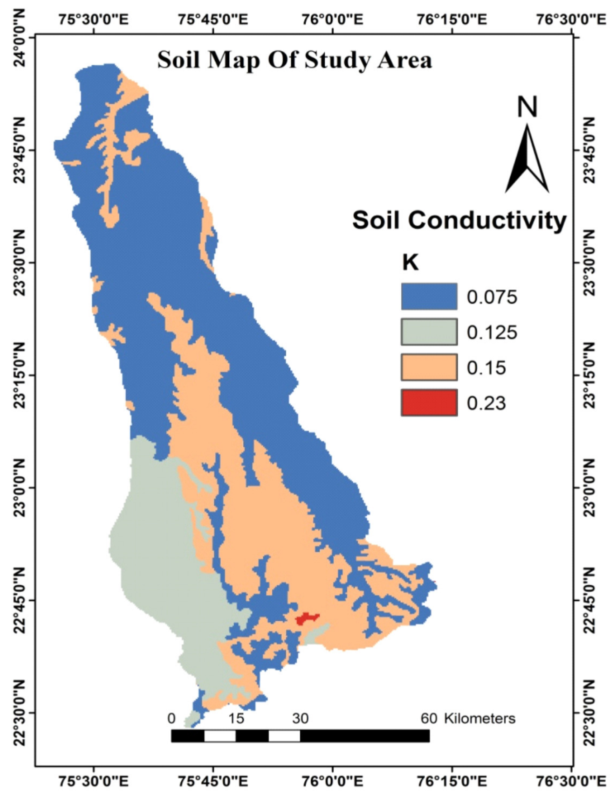

Fig. 2 Soil erodibility map of Kshipra Basin

$$100\,K = 2.1\,M\,1.14\,(10\,\text{-}4)\,(12 - a) + 3.25\,(b - 2) + 2.5\,(c\text{-}3) \qquad \ldots(3)$$

Where, K = soil erodibility factor, t ha h ha-1 MJ-1mm-1, M = particle size parameter (% silt + 0.7 × % sand) × (100 - % clay), a = organic matter content (percent), b = soil structure code and c = soil permeability class.

Slope length and gradient factor (LS)

The effect of topography on erosion was accounted by the LS factor in USLE, which combines the effects of a hill slope-length factor (L) and a hills slope-gradient factor (S). Generally, as hill slope length and/or hill slope gradient increase, soil loss increases due to the progressive accumulation of runoff in the down slope direction.

Hill slope-Length Factor (L): Based on long term observations, Wischmeier and Smith (1978) derived an expression relating the soil loss with slope length. The expression used in present study is as follows;

$$L = (\lambda / 22.13)^m \quad \ldots(4)$$

where, λ = slope length measured from the water divide of the slope (m)

m = exponent dependent upon slope gradient and may also be influenced by soil properties, type of vegetation etc (generally taken as 0.4) (Baba and Yusof, 2001)

Hill slope-gradient factor (S): The hill slope-gradient factor (S) reflects the effect of hill slope-profile gradient on soil loss. For a unit plot, with a 9% gradient as described earlier, the S value is equal to 1. The S values vary from 0 to 1 depending on whether the gradient is greater than or less than that of the unit plot.

The slope gradient factor (S) is the ratio of soil loss from a plot of known values of the factor S. In this study, slope gradient factor (S) is calculated by using following equation (McCool *et al.*, 1987),

$$S = 10.8 \sin\theta + 0.03 \text{ for slopes } > 4 \text{ m, and } s < 9\% \quad \ldots(5)$$

where, θ = field slope in degrees= $\tan^{-1}$(field slope/ 100).

Slope length and gradient factor (LS) map has been prepared in ARC GIS 9.3 environment by multiplying L and S factor using Eqs.4 and 5. In present study, to know the effect of grid size on soil erosion, four different grid cell sizes of 15 m × 15 m, 30 m × 30 m, 60 m × 60 m, and 90 m × 90 m were used for estimating the LS. The LS map for the grid sizes of 30 m × 30 m is given in Fig. 3.

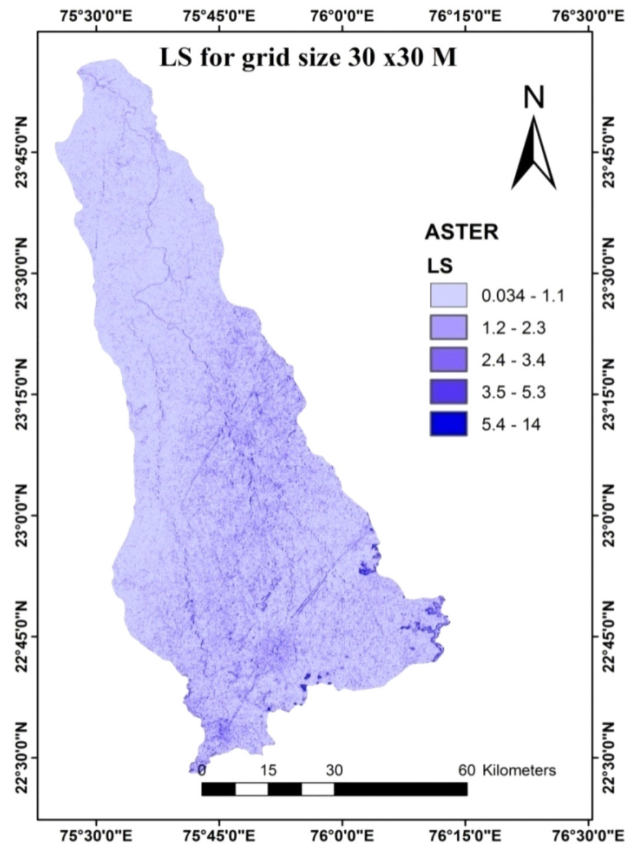

Fig. 3 Spatial distribution of topographic factor (LS) for grid cell size 30 m × 30 m

Cover-management factor (C)

The cover-management factor (C) represents the effects of vegetation, management, and erosion-control practices on soil loss. The study area has been classified into six land use classes: Water body, Dense Forest, Agriculture land, Wasteland, Built-up land and Open Forest. The spatial distribution map of cover-management factor (C) is presented in Fig. 4, where its value found to vary from 0.001 to 0.7. The assigned values of C factors for various land use are given in Table 3.

Table 3. Crop cover management factor (C) for different types of land use.

SI No.	Class	C value
1	Built-up Area	0.05
2	Water body	0.009
3	Dense forest	0.01
4	Barren land	0.7
5	Agriculture	0.42
6	Fallow land	0.7

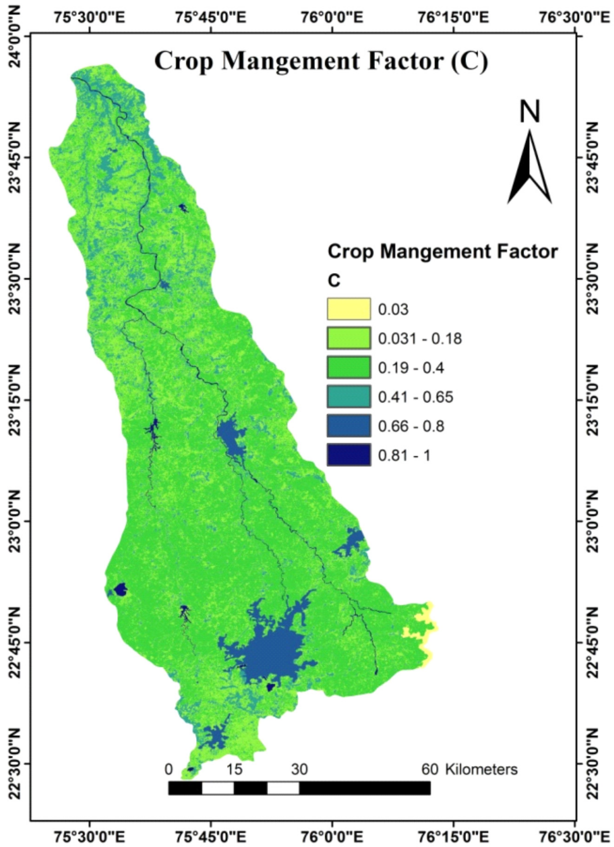

Fig. 4 Spatial distribution of crop management factor (C)

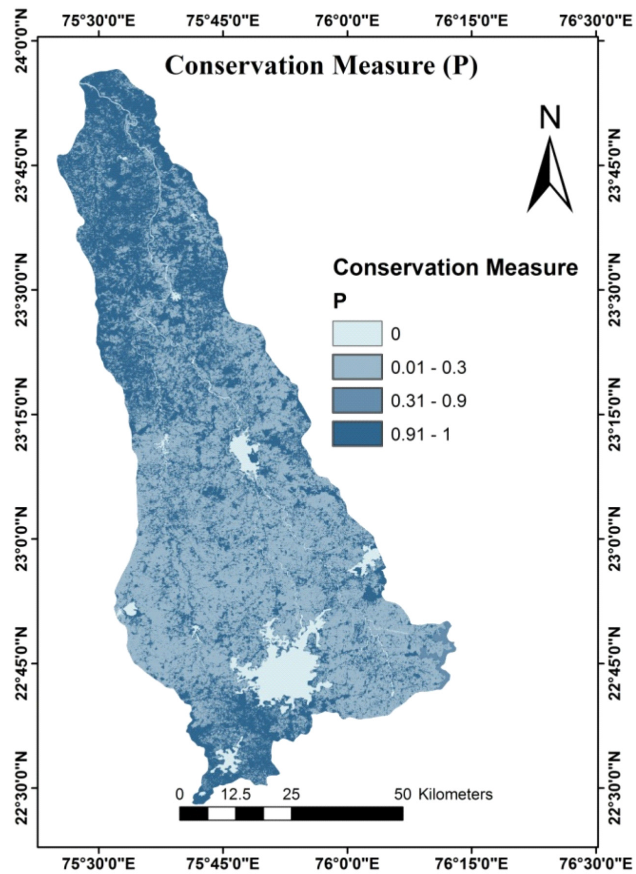

Fig. 5 Spatial distribution of conservation measure (P)

Support-practice factor (P)

The P value in USLE is the ratio of soil loss with a specific support practice to the corresponding soil loss with straight-row up slope and down slope tillage. P factor map has been prepared in ARC GIS environment as shown in Fig. 5. The support management factor for various practices is given in Table 4.

Performance indicator

In present study, the performance of the model was evaluated based on root mean square error (RMSE), root mean square error ratio (RMSR), Nash –Sutcliffe Efficiency (NSE) as mentioned below: -

$$NSE = 1 - \frac{\sum(So - Sp)^2}{\sum(So - Som)^2} \quad \ldots(6)$$

$$RMSE = \sqrt{\frac{\sum(Sp - So)^2}{n}} \quad \ldots.(7)$$

$$RMSR = RMSE/S.D. \quad \ldots(8)$$

Where So, Sp, Som and Spm are observed sediment, estimated sediment, mean observed

Table 4. Support practice factor (P) for different conservation practices

S. No.	Practices	Slope (%)	P factor
1	strip cropping	3 to 8	0.25
	strip cropping	1 to 2 & 9 to 12	0.3
	strip cropping	17 to 20	0.4
	no practices	remaining slope	1
2	Contouring	3 to 8	0.5
	Contouring	9 to 12	0.6
	Contouring	17 to 20	0.8
	no practices	remaining slope	1
3	Terracing & Contouring/ trenches	3 to 8	0.1
	Terracing & Contouring/ trenches	9 to 12	0.12
	Terracing & Contouring/ trenches	17 to 25	0.16
	no practices	remaining slope	1
4	Contour Strip cropping	1 to 2	0.3
	Contour Strip cropping	3 to 7	0.25
	Contour Strip cropping	8 to 12	0.3
	Contour Strip cropping	13 to 18	0.4
	Contour Strip cropping	19 to 24	0.45
	no practices	remaining slope	1

sediment and mean sediment and n is the number of samples.

Results and Discussion

Effect of DEM grid size on sediment yield

The ASTER–DEM was used to generate slope map and drainage map of the study watershed. The study area was divided into 15×15 m, 30×30 m, 60×60 m, 90× 90 m grid cells. Table 5 shows the average annual soil loss estimation distributions of the four different DEMs cells (*i.e.* 15 m × 15 m; 30 m × 30 m; 60 m × 60; 90 m × 90 m). As seen, the Sediment Yield estimated by various DEMs cells varies significantly. The estimated sediment yield for 15 m ×15 m grid size was found to vary from 9.62 to 17.28 tha^{-1}year^{-1}. Similarly, the range of estimated sediment yield for 30, 60 and 90 m were 9.65 to 13.38, 7.4 to 10, and 4.91 to 6.81 t/ha/year, respectively. In general, a reciprocal pattern has been obtained between grid size and SY estimation. As the grid size increases, the efficiency of SY estimation decreases. In present study, 15 m × 15 m grid found to performed good as compared to other grid sizes. Table 6 shows the comparison between

Table 5. Estimated annual sediment yield (t/ha/year) using USLE model in different grid cell.

SI. No.	Year	Rainfall (mm)	Observed Sediment yield (t/ha/year)	Rainfall Erosivity Index	15 m ×15 m	30 m×30 m	60 m×60 m	90 m×90 m
					Estimated Sediment yield (t/ha/year)			
1	1995	1031	14.32	473.28	13.91	10.77	8.11	5.48
2	1996	1332	20.31	587.99	17.28	13.38	10	6.81
3	1997	1299	20.22	575.17	16.91	11.13	8.32	5.67
4	1998	1239	19.56	514.34	15.12	10.64	7.95	5.41
5	1999	864	15.74	410.03	12.06	9.87	7.38	5.02
6	2000	700	14.04	339.29	9.97	12.9	9.64	6.56
7	2001	1016	16.25	362.55	10.66	11.72	8.76	5.97
8	2002	581	12.91	302.64	9.04	9.65	7.22	4.91
9	2003	739	14.04	467.63	13.75	10.64	7.94	5.42
10	2004	927	16.45	434.14	12.76	10.5	7.83	5.35
11	2005	645	12.01	326.62	9.6	10.36	7.72	5.28
12	2006	1077	16.51	491.07	14.44	10.23	7.62	5.21
13	2007	1141	16.62	515.45	15.16	10.09	7.51	5.14
14	2008	524	10.02	280.98	8.26	9.95	7.4	5.07
15	2009	678	12.9	347.84	10.23	9.81	7.29	5
16	2010	854	13.07	406.15	12.13	9.68	7.19	4.93

Table 6. Comparison of estimated sediment (15 m × 15 m grid) with observed sediment yield.

Year	Annual Rainfall (mm)	Rainfall Erosivity (R)	Observed Sediment Yield (t/ha/year)	Estimated Sediment Yield (t/ha/year)	Error (%)
1995	1031	473	14.32	13.91	2.83
1996	1333	599	20.31	17.62	13.26
1997	1299	575	20.22	16.91	16.35
1998	1239	514	19.56	15.12	22.69
1999	865	410	15.74	12.06	23.41
2000	701	339	14.04	9.97	28.98
2001	1016	363	16.25	10.66	34.4
2002	582	303	12.91	9.04	30
2003	739	468	14.04	13.75	2.09
2004	928	434	16.45	12.76	22.43
2005	645	327	12.01	9.6	20.06
2006	1078	491	16.51	14.44	12.54
2007	1142	515	16.62	15.16	8.79
2008	525	281	10.02	8.26	17.62
2009	678	348	12.9	10.23	20.74
2010	854	406	13.07	12.13	7.21

Table 7. Statistic of sediment estimation using original Ram Babu and modified equation for 15m ×15m grid size

	Ram babu erosivity equation R=0.38*P +81.5 (Eq. 2)	By using proposed erosivity equation R=0.3579*P +182.559 (Eq. 8)	
	15 m × 15 m	Calibration	Validation
CC	0.866	0.912	0.961
NSE	-0.146	0.829	0.855
RMSR	1.132	0.414	0.421
R^2	0.751	0.833	0.923

observed sediment yield and estimated sediment yield using 15 m × 15 m grid. The percentage deviation was found to vary from 2.83 to 34.4 %.

In the present study, the Babu *et al*. (2004) (Eq. 2) equation is used for calculating the R values for all the studied grids. The results of sediment yield estimation using original Eq. 2 for 15 m ×15 m grid size is shown in Table 7. As seen, the use of original Eq. 2 in sediment estimation using the 15 m × 15 m grid size resulted into poor value of NSE as -0.146. The value of RMSR was also found as 1.132 (Table 7). The results shows that the performance of Babu *et al*. (2004) equation in not satisfactory in the study region for use in calculation of Erosivity. Therefore, an alternative attempt should be made to modify the equation. To improve the estimation ability of Babu *et al*. (2004) equation, a new equation was proposed by optimizing the parameters of Eq. (2) employing least square fitting technique.

R=0.3579*Rn +182.559

Where Rn= average annual rainfall (mm)

For the development and validation of the above equation, 60% data was used in training while remaining dataset was used in testing of equation. As seen from Table 7, good NSE value as 0.829 was obtained during testing of model. The values of NSE, however, improved to 0.855 in validation phase. The coefficient of correlation (CC) between estimated and observed sediment yield during training was found as 0.912, whereas during validation it was 0.961. The RMSR of estimated and observed sediment yield was 0.414 and 0.421 during training and validation, respectively. The results from this table show that the proposed equation performed significantly well during training as well as validation.

Table 8 shows the comparison of observed sediment yield with sediment yield estimated by purposed Eq. 8. The percent deviation of the simulated sediment loss from the observed values was found to vary from 1.16 to 13.24 %. According to Bingner *et al*. (1989), Universal soil loss equation model simulation within twenty percentage limits is considered as the acceptable levels of accuracy. Thus, the results from purposed equation show that USLE (using Eq. 8 for erosivity calculation) can be successfully employed for estimation of sediment loss from Kshipra River watershed.

Generation of erosion potential maps:

Land use, soil, slope steepness, and management practices are the main factors governing soil erosion potential at a particular location. Gross soil erosion (GSE) of the Kshipra catchment was assessed using ArcGIS Raster Calculator. Then, the evaluated values of LS, K, C, and P from the maps were multiplied by the values of R to estimate the total soil loss in tons per annum for the whole catchment. Multiplication of the annual R factor into the KLSCP factor map resulted in maps of gross erosion for the corresponding years. Finally, the average annual soil erosion was estimated on a cellular basis, as shown in Fig. 6. The cell/grid based spatial distribution and magnitude of potential soil erosion on various priority scales as per the guidelines suggested by Singh *et al*. (1992) for Indian conditions can be derived and results are given in Table 9. As seen, about 78% area of Kshipra River basin is slightly or moderately affected by soil erosion having annual sediment production rate of less than 10 t/ha.

Conclusions

The losses due to soil erosion is one of the most

Table 8. Comparison of simulated sediment yield with the observed sediment yield using proposed erosivity equation.

Year	Annual Rainfall (mm)	Rainfall Erosivity (R)	Observed Sediment Yield (t/ha/year)	Estimated Sediment Yield (t/ha/year)	Error (%)
1995	1031	552	14.32	16.22	-13.24
1996	1333	660	20.31	19.38	4.55
1997	1299	647	20.22	19.04	5.83
1998	1239	626	19.56	18.41	5.90
1999	865	492	15.74	14.47	8.11
2000	701	433	14.04	12.74	9.28
2001	1016	546	16.25	16.06	1.16
2002	582	391	12.91	11.67	9.61
2003	739	447	14.04	13.14	6.40
2004	928	515	16.45	15.13	8.04
2005	645	413	12.01	12.16	-1.18
2006	1078	568	16.51	16.71	-1.21
2007	1142	591	16.62	17.38	-4.62
2008	525	370	10.02	10.89	-8.61
2009	678	425	12.90	12.51	3.07
2010	854	488	13.07	14.59	-11.56

Table 9. Classification of area under different classes of soil erosion in Kshipra basin

Sediment yield (t/ha/year)	Percent area	Soil erosion area
<5	45.39	Slight
5 to 10	32.92	Moderate
11 to 20	14.12	High
21 to 40	4.55	very high
40 to 80	3.17	severe
> 80	0.30	very severe

critical environmental hazards of recent times. It has adverse effects on reservoir sedimentation and nutrient losses of agricultural land. A new equation similar to Ram Babu has been proposed which found to perform significantly better than the previous one. The average soil erosion for Kshipra River Basin was found to be 15.31 t ha^{-1} yr^{-1} . It is proposed to treat the area by technical intervention of bioengineering measures and efficient utilization of natural resources in future perspective. According to the shape of the watershed, results indicate that only a few areas are generating higher soil erosion problems, so a distributed approach of watershed treatment will give better results both from a proper management- and an economic point of view. The result of the study clearly demonstrates that the Kshipra River Basin is more prone to soil erosion but requires regular monitoring from the planners and decision makers for making it better in terms of land and water conservation. Using the GIS and Remote sensing data can be employed to derive scenarios of sediment yield for the basin for efficient natural resource management. This study suggests to develop a guideline for erosion control and treatment activity for sustainable way to manage sediment yield at the basin scale.

References

Angima SD, Stott DE, O'neill MK, Ong CK and Weesies GA (2003) Soil erosion prediction using RUSLE for central Kenyan highland conditions. *Agriculture Ecosystems & Environment* **97(1)**: 295-308.

Ayteek A and Kisi O (2008) A genetic programming approach to suspended sediment modeling, *Journal of Hydrology* **351**:288–298.

Baba SMJ and Yusof KW (2001) Modeling soil erosion in tropical environments using remote sensing and geographical information systems. *Hydrological Sciences Journal* **46(1)**: 191-198.

Babu R, Dhyani BL and Kumar N (2004) Assessment of erodibility status and refined iso-erodent map of India. *Indian Journal of Soil Conservation* **32(3)**:171–177

Caroni E, Singh VP and Ubertini L (1984) Rainfall-runoff-sediment yield relation by stochastic modeling, *Hydrological Sciences Journal* **29(2)**:203–218.

Dabral PP, N Baithuri and PandeyA (2008) Soil erosion assessment in a hilly catchment of north eastern India using USLE, GIS and remote sensing. *Water Resources Management* **22**: 1783-1798.

Devatha CP, Deshpande V and Renukaprasad MS (2015) Estimation of Soil loss Using USLE Model for Kulhan Watershed, Chattisgarh-A Case Study. *Aquatic Procedia* **4**:1429-1436.

Dickinson A and Collins R (1998) Predicting erosion and sediment yield at the catchment scale. Soil erosion at multiple scales. *CAB International*. 317-342.

Fistikoglu O and Harmancioglu NB (2002) Integration of GIS with USLE in assessment of soil erosion. *Water Resources Management* **16(6)**: 447-467.

Fu B, Liu Y, Lü Y, He C, Zeng Y and Wu B (2011) Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. *Ecological Complexity* **8(4)**: 284-293.

Fu S, Cao L, Liu B, Wu Z and Savabi M R (2015) Effects of DEM grid size on predicting soil loss from small watersheds in China. *Environmental Earth Sciences* **73(5)**:2141-2151.

Jain SK, Kumar S and Varghese J (2001) Estimation of soil loss for a Himalayan watershed using GIS technique. *Water Resources Management* **15**: 41-54.

Jose CS and Das DC (1982) Geomorphic prediction models for sediment production rate and intensive priorities of watershed in Mayurakshi catchment. *In: Proceedings of the international symposium on hydrological aspects of mountainous watershed held at school of hydrology*. University of Roorkee 15-23.

Kinnell PIA (2010) Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review. *Journal of Hydrology* **385(1)**: 384-397.

Liu B Y, Nearing MA, Shi PJ and Jia ZW (2000) Slope length effects on soil loss for steep slopes. *Soil Science Society of America Journal* **64(5)**:1759-1763.

Melesse AM, Ahmad S, McClain ME, Wang X and Lim YH (2011) Suspended sediment load prediction of river systems: An artificial neural network approach. *Agricultural Water Management* **98(5)**:855-866.

Meyer LD and WH Wischmeier (1969) Mathematical simulation of the process of soil erosion by water. Trans. ASABE **12**: 754-758.

Misra NT, Satyanarayana and Mukherjee RK (1984) Effect of topo elements on the sediment production rate from subwatersheds in upper Damodar valley. *Journal of Agricultural Engineering* **21(3)**: 65-70.

Mondal A, Khare D and Kundu S (2016) Uncertainty analysis of soil erosion modelling using different resolution of open-source DEMs. *Geocarto International* 1-16.

Onyando JO, Kisoyan P and Chemelil MC (2005) Estimation of potential soil erosion for river perkerra catchment in Kenya. *Water Resource Management* **19**: 133-143.

Pandey A, Chowdary VM and Mal BC (2007) Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. *Water Resource Management* **21:** 729- 746.

Pandey A, Mathur A, Mishra SK and Mal BC (2009) Soil Erosion Modeling of a Himalayan Watershed Using RS and GIS. *Environ. Earth Sciences* **59(2)**: 399-410

Parveen R and Kumar U (2012) Integrated approach of Universal Soil Loss Equation (USLE) and geographical information system (GIS) for soil loss risk assessment in Upper South Koel Basin, Jharkhand.

Reddy MS (1999) Theme paper on "Water: vision 2050. *Indian Water Resources Society*. Roorkee, pp. 51–53.

Singh A, Imtiyaz M, Isaac RK and Denis DM (2013) Comparison of artificial neural network models for sediment yield prediction at single gauging station of watershed in eastern India. *Journal of Hydrologic Engineering* **18(1)**: 115-120.

Williams JR and Berndt HD (1972) Sediment yield computed with universal equation. *Journal of Hydraulics Engineering* ASCE **98**: 2087-2098.

Wischmeier WH and Mannering JV (1969) Relation of soil properties to its erodibility. *Proceedings of American Soil Science Society* **33**: 131-137.

Wischmeier WH and Smith DD (1978) Predicting rainfall erosion losses, Agricultural Handbook No. 537, US Dept of Agriculture, Science and Education Administration.

Wu S, Li J and Huang G (2005) An evaluation of grid size uncertainty in empirical soil loss modeling with digital elevation models. *Environmental Modeling & Assessment* ***10(1)***: 33-42.

Yang D, Kanae S, Oki T, Koikel T and Musiake T (2003) Global potential soil erosion with reference to land use and climate change. *Hydrological Processes* **17(14)**:2913–2928.

Zhang B and Govindaraju RS (2003) Geomorphology-based artificial neural networks (GANNs) for estimation of direction runoff over watersheds, *Journal of Hydrology* **273**:18–34.

Received: September 24, 2024; Accepted: October 28, 2024

Journal of Soil Salinity and Water Quality 16(2), 280-288, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156658

Predominant Cropping Systems Affect Soil Organic Carbon Content in the Soil Profile of North–West India

Pradeep Kumar, Parul Sundha*, Nirmalendu Basak*, Priyanka Chandra, Sandeep Bedwal and Arvind Kumar Rai

ICAR–Central Soil Salinity Research Institute, Karnal-132 001, Haryana
**Corresponding author's E-mail: parul.sundha@icar.gov.in; nirmalendu.basak@icar.gov.in*

Abstract

The soil organic carbon (SOC) content depends on the physiography, climatic conditions, soil type, and cropping patterns of a particular region. The improvement in soil health contributes to better productivity of the soil. The present study focused on the estimation of the organic carbon content in soil profile of predominant cropping system in Karnal and Kaithal districts of Haryana. Soil samples were collected at four different depths *viz.*, 0–0.15, 0.15–0.30, 0.30–0.45 and 0.45–0.60 m from the different predominant cropping systems for the estimation of pH, electrical conductivity, and fractions of organic carbon and calcium carbonate content ($CaCO_3$). The organic carbon was greater at the surface and decreased along the depth in all the cropping systems in Karnal district. The total organic carbon (TOC) in soil for Karnal district was higher (11 g kg^{-1}) in the vegetable–vegetable system. In Kaithal district the Walkley Black organic C content was greater in the surface soil (0–0.15 m depth), then a decrease at the sub–surface (0.15–0.30 m), followed by 0.30–0.45 and 0.45–0.60 m depth. The rice–barseem/rice–wheat and sugarcane–sugarcane maintained a higher amount of TOC (8.03–9.19 g kg^{-1}) in surface soil. Irrespective of the cropping system and region, total OC and its oxidizable fraction showed a negative correlation with $CaCO_3$. The alkaline to moderately alkali soils presented higher values of pH with poor performance of crops resulting in lower root biomass return to soils and low C content. This study will provide valuable insights for formulating better management practices in soils inclined towards degradation to achieve goals of sustainable land use in predominant cropping-systems in Haryana.

***Key words*:** Agricultural productivity, Cropping system, Environmental sustainability, Soil organic carbon, Soil health

Introduction

The soil organic carbon (SOC) content in the form of different pools is regulated by parent materials, physiography, climatic conditions, soil type, and cropping patterns. This SOC storage in different carbon pools of soil remains in equilibrium. The improvement in soil health contributes to better productivity of the soil (Poffenbarger *et al.*, 2018; van Es and Karlen, 2019). The fertility and productivity of agricultural lands are much dependent on the SOC sequestered in the soil. Different land–use management practices exhibit divergent stocks of carbon whether organic or inorganic (Basak *et al.*, 2021a; Derrien *et al.*, 2023). The higher content of soil organic matter (SOM) results in higher available nitrogen, and enhances microbial abundance and activity; thereby increasing the availability of nutrients to the plants for crop growth and yield (Bossolani *et al.*, 2023). SOC in soil promotes soil aggregation and improves soil aeration and water infiltration to aid optimum plant growth and crop productivity through enhanced soil fertility. Globally, an estimated ~680 Pg of SOC stock is reported in the upper soils (0–30 cm depth) affects the soil flora and fauna, nutrients management, water balance, and gas exchange (FAO, 2017, www.fao.org). Sequestration of any form of carbon to soil enriches the carbon reservoir ensures better food production and contributes to lowering global warming. However, this phenomenon depends on climatic conditions, environmental conditions and human interventions. The eighty percent of the total geographical area of Haryana state is under cultivation. Around eighty four percent of the cultivated area is irrigated with a cropping intensity of 181 percent. This results in the production of 13 million tonnes of food grain in the state (https://atarijodhpur.res.in/agro-climatic-zones-haryana.php). The dominating cropping patterns followed are rice–wheat, rice–barseem, sorghum–wheat, cotton–wheat and pearl–millet–wheat etc. However, about 62 percent area of the state is affected by poor–quality water. Haryana has an appreciable area under degraded soil, particularly saline and sodic (Mandal, 2024), often low in nutritional content and organic carbon (CSSRI, 2015; Datta *et al.*, 2015, 2017). The central part of the state covering four districts, namely, Karnal, Kurukshetra, Panipat, and Sonepat, account for 52% of the total geographical area under salt–affected soil. There are twin problems of declining fresh underground water in some parts as well as rising water tables of saline water or poorly drained areas, waterlogging or secondary salinization altogether decline the soil health and stunted crop productivity (Mandal, 2016). The dynamics of SOC pools for different cropping systems may predict the SOC stock, nutrient supply capacity, and to some extent the soil biological health. Based on physiography, argo–ecology and cropping pattern, Haryana state is divided into three zones and the study area will include study areas under Zone–I. The soils of Northern India contribute a major share of the national food productivity and improving the soil quality for better gains is of utmost importance (Shukla *et al.*, 2015). Several studies have been done on the variations in labile and non–labile pools of SOC across the globe. Limited literature is available on SOC storage in different layers of agricultural or forest lands lying under arid and semi–arid regions in India (Basak *et al.*, 2021b; Datta *et al.*, 2017; Meena *et al.*, 2019). However, the classification of areas with varying carbon pools is important to assess the extent of the threat to soil health and sustainable crop productivity (Datta *et al.*, 2015).

The evaluation of SOC content for six different predominant cropping systems in agro–ecological zone–I with varying depths to identify the systems with enriched SOC was done. It is hypothesized that the different cropping systems carry distinct signatures on SOC contents. Therefore, the present study was aimed at evaluating SOC content in soils under two districts Karnal and Kaithal of Haryana state with diversified cropping systems along depth to identify the system.

Materials and Methods

The soil samples were collected from six predominant cropping systems rice–wheat, rice–barseem, sorghum–wheat, sugarcane–sugarcane, vegetable–vegetable and pasture land, continuing from more than 20 years and more in the different areas of state Haryana. This study refers to cropping systems practised in Karnal and Kaithal regions of Haryana categorised in zone–I (Fig. 1).

Soil sampling

The collection of soil samples was done for four depths *viz.*, 0–0.15, 0.15–0.3, 0.3–0.45 and 0.45–0.60 m with an auger during summer months (April and May) when there was no crop in the field. For individual sites, samples were taken in triplicate from random places and pooled together depth–wise to prepare a composite sample. After sample collection, they were dried in shade in the laboratory. Thereafter, the samples were processed, ground and sieved through a nylon sieve of 2.0 mm diameter and kept safely for further analysis. The latitude and longitudes of the respective sampling points was recorded with the help of the Global positioning system (GPS).

Dominant cropping systems in the study area

The choice of cropping system depends on factors like landform, topography, soil type, climate, irrigation availability, available resources, labour and economic conditions. Conservation of the soil and water resources to enhance the productivity of the soil depends upon the cropping patterns followed, the practise of management and judicious use of inputs. The two districts of Haryana were studied for the diversity of cropping systems in the area *viz.*, Karnal and Kaithal. The dominant cropping system in Karnal was rice–wheat followed by pasture land, vegetables and rice–berseem, sugarcane, sorghum–berseem, and scattered eucalyptus plantations and some pockets of sorghum–wheat cropping system at few places.

At present, rice–based cropping system is predominated in the studied districts. Rice is one preferred crop of *kharif* season (July to October) followed by wheat or barseem in *rabi* (November to April). Other cropping systems are sugarcane–

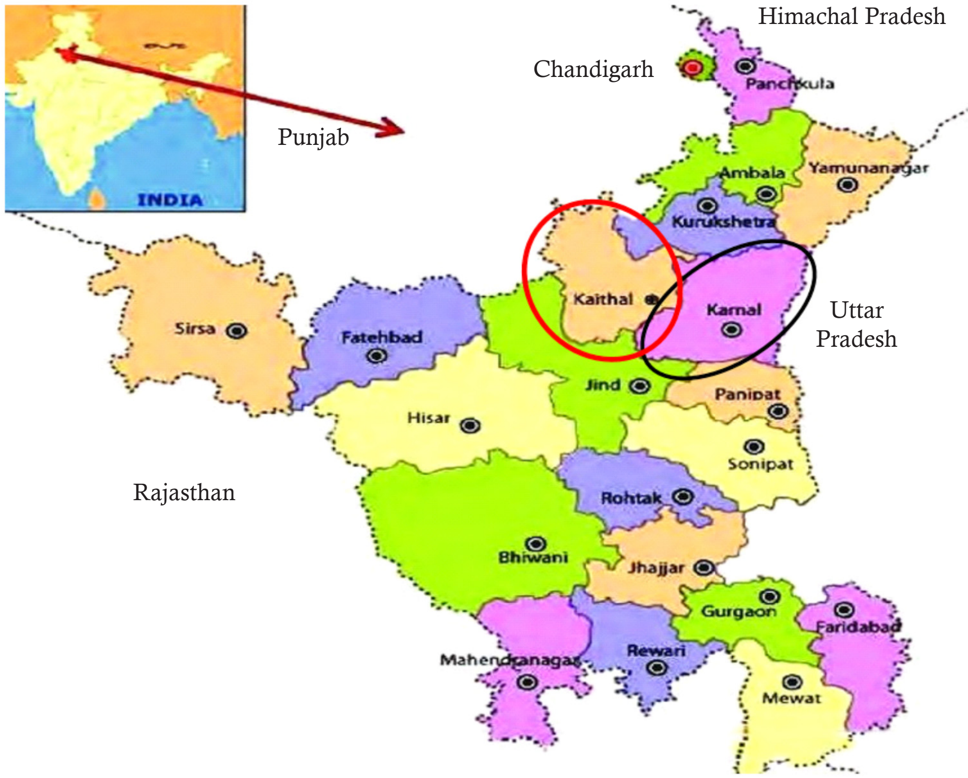

Fig. 1 Location map of the sampling sites

sugarcane, sorghum–barseem or wheat, vegetable–vegetable, and very few tree plantations like eucalyptus and few pasture lands. The soil reaction of Haryana varied from normal to saline, sodic and saline–sodic and groundwater use for irrigation purposes has residual sodium carbonate (RSC) is variable and as high as 12 meq L^{-1} at certain places (Mandal, 2022). The arid to semi–arid climatic conditions and irrigation through canal and tube wells with high RSC are often considered the primary factors for soil degradation (Mandal et al. 2019). It has been studied that about 32–84% of groundwater in the Indo–Gangetic plains of northwest India is categorised as either saline or alkali (Mandal, 2022).

Soil sample analysis

The soil pH was determined by the glass electrode method in the ratio of one part of the soil to two parts of solution using deionised water (pH_w), as described by Page et al. 1982. The EC of soil used was measured in a 1:2 soil-water suspension with the help of a conductivity meter (Page *et al.*, 1982). Calcium carbonate equivalent was measured by neutralization with HCl (Allison and Moodie, 1965). Walkley and Black wet oxidation method (Walkley and Black, 1934) was used to determine the oxidizable organic carbon content. Total organic carbon was estimated by the instrument TOC analyser (Perkin Elmer).

Statistical analysis

Windows based SPSS programme (SPSS Inc., Chicago, IL, USA) was used to perform nonparametric test to capture the statistical significance of two districts and cropping systems on response variables. The Kruskal–Wallis test was used to perform the analysis of variance of districts (Karnal and Kaithal) and cropping systems, respectively. All pair–wise comparisons were made using P values adjusted by the Benferroni correction for multiple tests. A value of $P < 0.05$ was considered statistically significant for distinguishing the responses in the compared groups using means and their range. Correlation matrix was also worked out among the SOC content and other soil attributes by Windows–based SPSS version 10.0 of statistical analysis.

Results and Discussion

Status of soil pH, EC and organic carbon (OC) in the study area

The soil samples collected from four different depths 0–0.15 m, 0.15-0.30 m, 0.30-0.45 m and 0.45-0.60 m under different cropping systems were analyzed for soil $pH_{1:2}$, electrical conductivity ($EC_{1:2}$) and organic carbon. For the soils of Karnal, it was observed that the pH of the pasture land (8.97) was the highest among all the cropping systems and was in the alkaline reaction followed by rice–wheat (8.6) > sugarcane–sugarcane (8.4) > rice–barseem (8.3) ($P < 0.05$). The lowest average pH was in the vegetable–vegetable system (8.29). The pH showed an increasing trend with an increase in depth.

For the soils of Kaithal, the highest pH was in sugarcane–sugarcane (9.0) followed by rice–wheat (8.9) > rice barseem (8.7) > sorghum–wheat (8.6) ($P < 0.05$). The pH showed an increasing trend up to 0.30 m depth and there was a decline at 0.30–0.45 m and again an increase in the pH was observed at 0.60 m depth (Fig. 2; Table 1). The soils of Kaithal were sodic and the irrigation water had high residual sodium carbonate at different places. The pH of soils is also higher in this region and soils suffer sodicity–induced land degradation (Basak *et al.*, 2021a; Minhas *et al.*, 2019).

The electrical conductivity (EC) was observed low in the soils of Karnal than Kaithal (Fig. 3). The surface EC values were higher in sugarcane–sugarcane (1.21 dS m^{-1}) and vegetable–vegetable (1.64 dS m^{-1}) cropping systems in the surface soil (0–15 cm). The overall value of EC was highest in vegetable–vegetable (0.80 dS m^{-1}) followed by pasture land (0.76 dS m^{-1}) > rice–wheat (0.62 dS m^{-1}) > sugarcane–sugarcane (0.59 dS m^{-1}) > rice-barseem (0.52 dS m^{-1}). Similarly, in Kaithal region, there was an increase in the EC of the soil with increasing depth of the soil. The overall range of EC varied from 0.60–0.78 dS m^{-1} for different cropping systems. The overall value of EC was highest in sugarcane–sugarcane (0.90 dS m^{-1}) followed by rice–wheat (0.84 dS m^{-1}) > rice–barseem (0.69 dS m^{-1}) > sorghum–wheat (0.53 dS m^{-1}). In almost all the sampling sites, the EC values were lower.

The oxidizable organic carbon (OC) showed variation in different cropping systems in the Karnal (Fig. 4). The value of organic carbon was higher at the surface and decreased with increasing depth in all the cropping systems except sugarcane–sugarcane cropping system where there was an increase at 0.45–0.60 m (2.74 g kg^{-1}) than 0.30–0.45 m (1.97 g kg^{-1}). The overall value of OC was highest in vegetable-vegetable (4.24 g kg^{-1}) followed by rice-barseem (4.15 g kg^{-1}) > sugarcane-sugarcane (4.0 g kg^{-1}) > rice-wheat (3.1 g kg^{-1}) > pasture land (3.0 g kg^{-1}) ($P < 0.05$). The OC values in the Kaithal region were higher in surface soil (0–0.15 m depth), then a decreased at the sub–surface (0.15–0.30 m), and further increased at

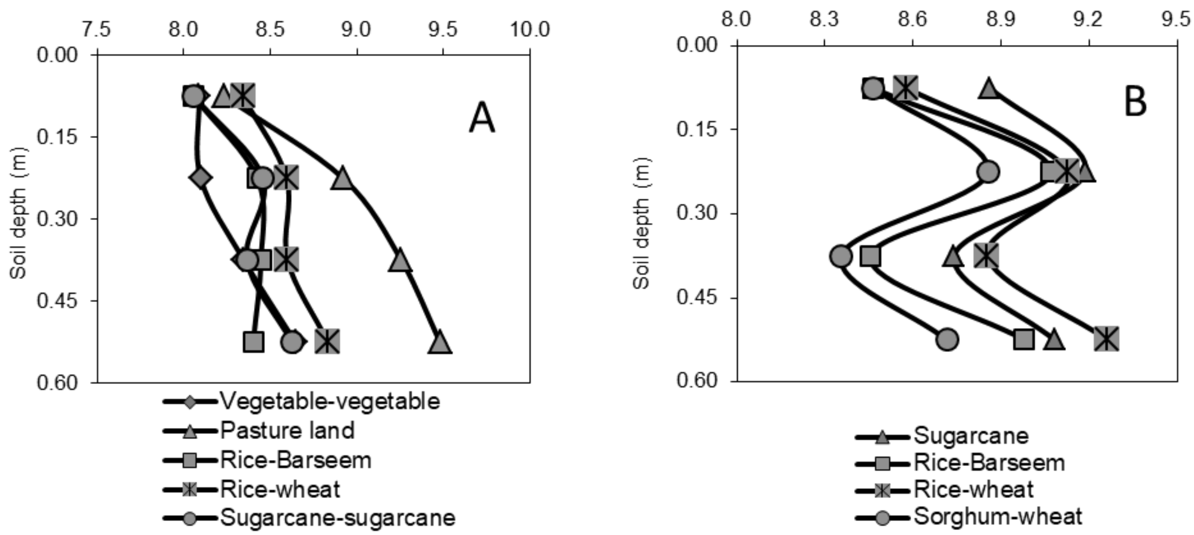

Fig. 2 Influence of cropping systems on depth-wise variations of pH in Karnal (A) and Kaithal (B) regions of Haryana

Table 1. Effects of cropping systems on soil physico-chemical properties and organic C fractions along different cropping systems along depths of two districts of Haryana

Cropping system	pH	OC (g kg^{-1})	$CaCO_3$ (%)	TOC (g kg^{-1})	pH	OC (g kg^{-1})	$CaCO_3$ (%)	TOC (g kg^{-1})	pH	OC (g kg^{-1})	$CaCO_3$ (%)	TOC (g kg^{-1})	pH	OC (g kg^{-1})	$CaCO_3$ (%)	TOC (g kg^{-1})
	0.0-0.15 m				0.15-0.30 m				0.30-0.45 m				0.45-0.60 m			
KPL	8.24^{ab}	3.74^{d}	1.08	8.33	8.92^{abc}	4.10^{abcd}	0.68	5.16^{bc}	9.26^{a}	2.20^{d}	2.32^{bcd}	$7.15^{\mathbf{abc}}$	9.48^{a}	2.17^{bc}	2.18^{ab}	6.63
KRB	8.06^{b}	6.43^{abc}	1.33	9.12	8.43^{abc}	5.71^{ac}	1.09	8.47^{ac}	8.45^{c}	2.63^{ab}	0.58^{cd}	$5.44^{\mathbf{ac}}$	8.40^{b}	1.83^{c}	0.37^{b}	5.33
KRW	8.34^{ab}	4.92^{abcd}	1.34	9.17	8.59^{c}	3.04^{abcd}	0.69	4.99^{bc}	8.60^{c}	2.76^{ab}	1.51^{d}	$5.19^{\mathbf{c}}$	8.83^{ab}	1.68^{c}	1.35^{ab}	5.34
KSS	8.06^{b}	6.72^{c}	0.28	6.76	8.46^{abc}	4.68^{a}	0.91	3.33^{c}	8.36^{c}	1.97^{ab}	0.47^{d}	$6.33^{\mathbf{abc}}$	8.62^{ab}	2.74^{abc}	0.48^{ab}	5.91
KVV	8.14^{ab}	6.76^{ac}	0.86	10.56	8.20^{c}	4.46^{abc}	0.71	3.33^{c}	8.43^{c}	2.60^{ab}	1.40^{bd}	$6.15^{\mathbf{bc}}$	8.68^{ab}	2.31^{abc}	1.33^{ab}	5.99
KIRB	8.46^{ab}	4.05^{abcd}	2.49	8.03	9.07^{abc}	2.93^{abcd}	3.20	5.73^{c}	8.46^{c}	3.68^{ab}	1.63^{bcd}	$5.63^{\mathbf{c}}$	8.98^{ab}	1.79^{c}	1.71^{ab}	5.45
KIRW	8.58^{ab}	4.87^{abcd}	1.23	9.19	9.13^{ab}	2.87^{abcd}	0.83	2.86^{c}	8.85^{abc}	3.84^{a}	3.95a	$6.50^{\mathbf{bc}}$	9.26^{ab}	1.68^{c}	4.47^{a}	5.68
KISW	8.46^{ab}	3.82^{abcd}	0.46	10.24	8.86^{abc}	2.78^{abcd}	0.32	3.88^{c}	8.36^{c}	4.04^{ab}	1.15d	5.53^{c}	8.72^{ab}	2.31^{abc}	0.60^{ab}	5.31
KISS	8.86^{a}	4.98^{abcd}	0.66	8.81	9.19^{a}	2.09^{d}	0.53	2.96^{c}	8.74^{c}	3.45^{ab}	0.85d	$4.69^{\mathbf{c}}$	9.08^{ab}	1.43^{c}	1.07^{ab}	4.91

KPL: Pasture land (Karnal); KRB: Rice-Barseem (Karnal); KRW: Rice-wheat (Karnal); KSS: Sugarcane- Sugarcane (Karnal); KVV: Vegetables-Vegetables (Karnal); KIRB: Rice-Barseem (Kaithal); KIRW Rice-wheat (Kaithal); KISW: Sorghum-Wheat (Kaithal); KISS: Sugarcane- Sugarcane (Kaithal)

[values with different letters (a–d) in columns are significantly different ($P < 0.05$) among cropping systems in two districts of Haryana]

0.30–0.45 m depth with a decline in the deeper layer (0.45–0.60 m). The overall range of OC varied from 1.80–4.43 g kg^{-1} for different cropping systems along the soil depth. The overall value of OC was highest in rice–wheat (3.31 g kg^{-1}) followed by sorghum–wheat (3.24 g kg^{-1}) > rice–barseem (3.11 g kg^{-1}) > sugarcane–sugarcane (2.99 g kg^{-1}) ($P < 0.05$). The organic carbon status in salt–affected soils is generally low to medium due to poor vegetative growth, arid to semi–arid climatic conditions and management practices followed (Bhardwaj *et al.*, 2019; Shirale *et al.*, 2018).

The results of total organic carbon (TOC) for Karnal district indicated higher values (11 g kg^{-1}) in the vegetable–vegetable system at the surface but showed a decline in the lower depths (Fig. 5; Table 1). However, the rice–barseem cropping system had higher TOC at the surface as well as sub–surface depth and declined for lower depths. For Kaithal district, rice–barseem/rice–wheat and sugarcane–sugarcane maintained a higher amount of TOC (8.03–9.19 g kg^{-1}) in surface soil than sorghum–wheat cropping system (7.24 g kg^{-1}) ($P < 0.05$). Rice–barseem or rice–wheat cropping system have rice a common crop that is transplanted in flooded conditions. There is anaerobic environment in the transplanted rice crop for almost three to four months resulting in retarded oxidation conditions and the formation of stable clay–humus and lignin–rich complexes formed during rice cultivation (Wissing *et al.*, 2013). As a result, there is buid–up of the organic carbon in the soil. The content of SOC under different cropping systems decreased along the depth, except rice–barseem system, with comparatively higher TOC at sub–surface. The Karnal region soils have a higher content of organic carbon compared to Kaithal region across different cropping systems because the presence of larger alkalinity stress in the soils and dependency on alkali water irrigation for a large number of areas of Kaithal makes SOC more mobile and susceptible to loss (Basak *et al.*, 2021b; Datta *et al.*, 2019).

Correlation study

Correlation matrix among different components showed a negative correlation with pH of the soil

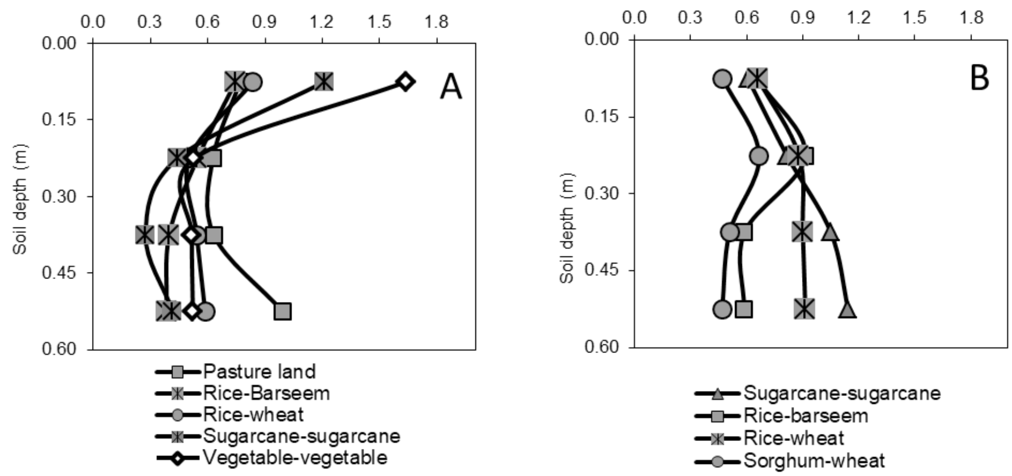

Fig. 3 Influence of cropping systems on depth-wise variations of electrical conductivity (dS m^{-1}) in soils in Karnal (A) and Kaithal (B) regions of Haryana

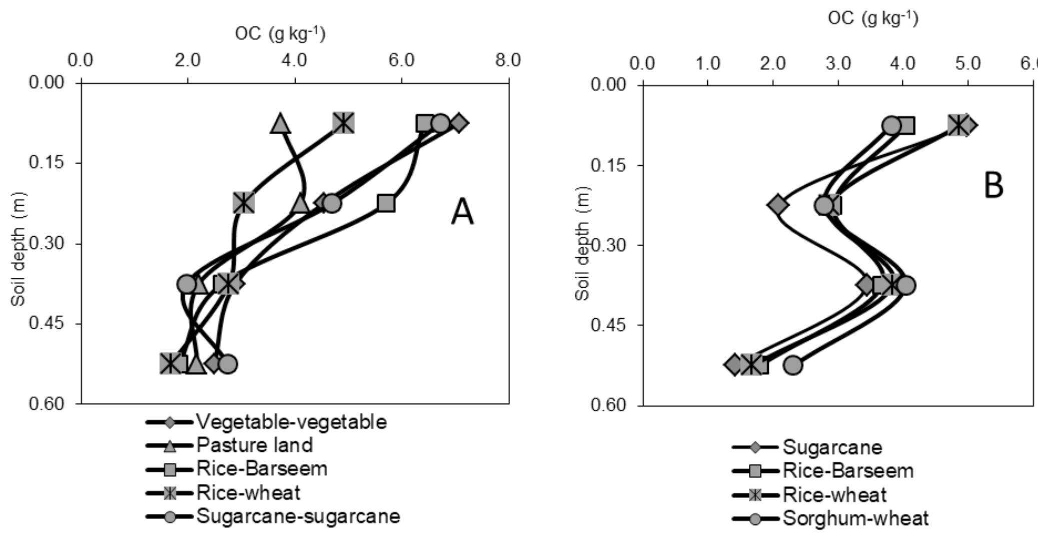

Fig. 4 Influence of cropping systems on organic C (g kg^{-1}) in Karnal (A) and Kaithal (B) region of Haryana

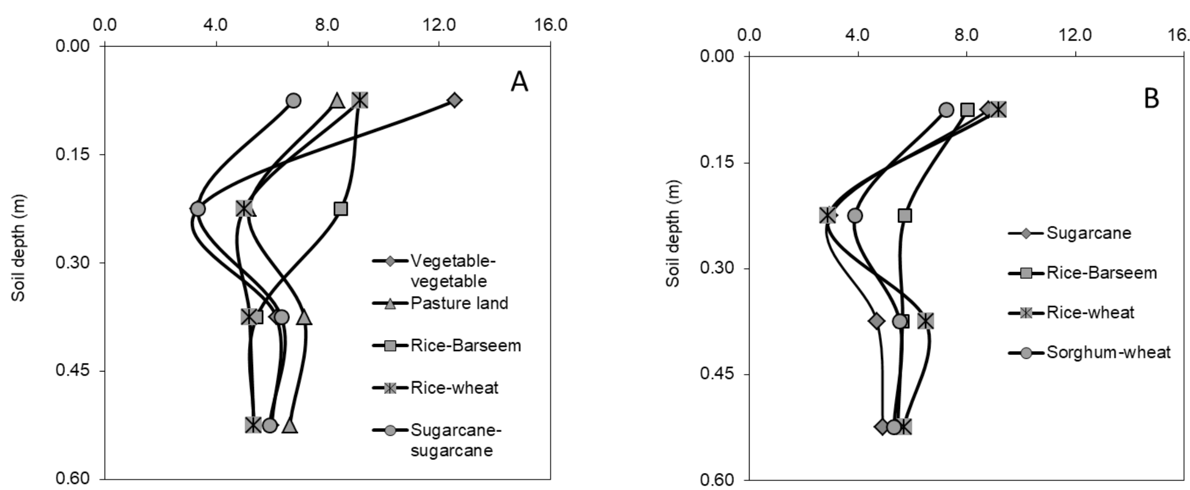

Fig. 5 Influence of cropping systems on total organic C (g kg^{-1}) in Karnal (A) and Kaithal (B) region of Haryana

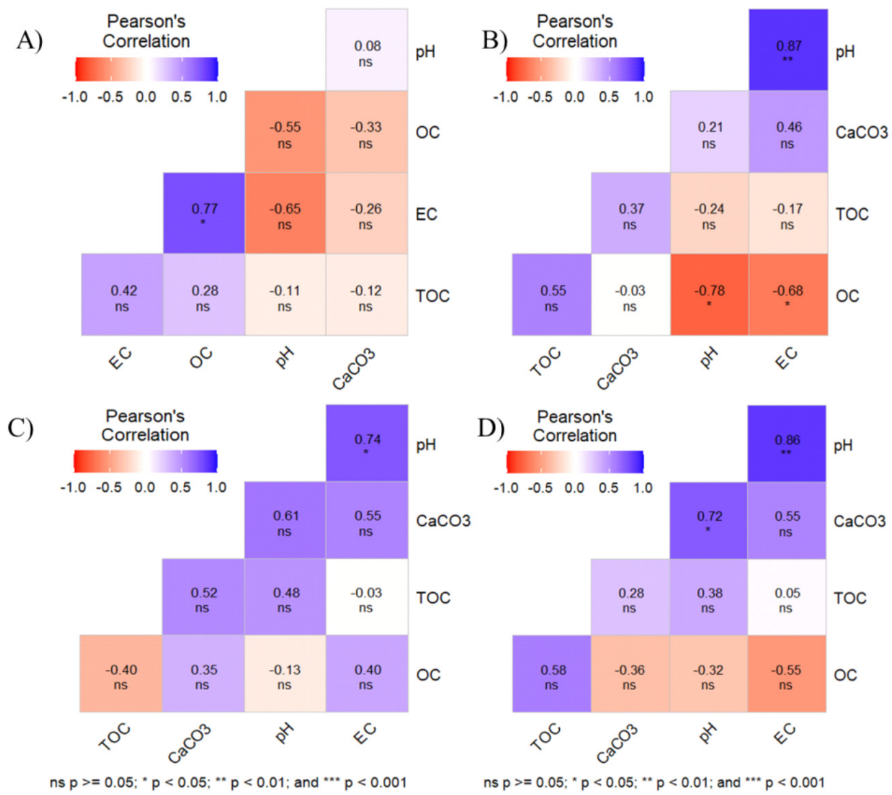

Fig. 6 Correlation matrix between pH; EC: electrical conductivity; $CaCO_3$: calcium carbonate (%); TOC: total organic carbon of different cropping systems at depth 0.0-0.15 m (A); 0.15-0.30 m (B); 0.30-0.45 m (C); 0.45-0.60 m (D) in two districts of Haryana; ns: P> 0.05; * *P*< 0.05 and ** *P*< 0.01

indicating the low content of organic carbon in the alkaline soils (Fig. 6). Irrespective of cropping system and region, total OC and its oxidizable fraction showed a negative correlation with $CaCO_3$. The calcium carbonate depositions were higher in soils with low carbon inputs. In general, soil pH presented a negative correlation with $CaCO_3$ but this relationship was statistically significant at lower depths (0.45-0.60 m). This is due to the higher $CaCO_3$ content in this layer. This was previously reported that increasing the soil pH (>8.5), Ca^{2+} starts precipitating and resides as $CaCO_3$ (Bajwa and Swarup, 2012). Except, the soil of the upper surface, EC of soil was positively correlated with soil pH. The soil reaction of the studied region is alkaline to moderately alkali in nature. Therefore, the presence of alkali hydrolysable carbonate and bicarbonate present higher values of pH with increasing electrolyte load (Basak *et al.*, 2022). This results in poor performance of crops in the high pH soils causing lower root biomass return to soils and low C content which is similar to earlier findings of Bhardwaj *et al.* (2019) and Basak *et al.* (2021b).

Conclusions

The two districts of state Haryana, Karnal and Kaithal were studied for their total organic carbon content. The soils of Kaithal district are inclined towards the alkalinity with higher pH which influences the content of total organic carbon in the area. On average, rice–based cropping (rice–barseem or rice–wheat) systems had higher soil organic carbon content and oxidizable fractions at surface and lower depths. The calcium carbonate depositions were higher in the agricultural lands with low carbon inputs and negatively correlated with carbon content. Soil degradation in the cultivated land is an emerging threat to agricultural productivity and environmental sustainability in India. This study will provide valuable insights for formulating better management practices for predominant cropping systems in Haryana.

Acknowledgements

The authors would like to acknowledge the Director, ICAR–Central Soil Salinity Research Institute (CSSRI), Karnal (Haryana) for providing technical and laboratory assistance. This research article was approved by the Prioritization, Monitoring and Evaluation Cell (PME), ICAR–CSSRI (Research Article No 24/2024).

Funding

Indian Council of Agricultural Research, New Delhi (India) and RKVY, RAFTAAR (Govt. of Haryana) funded project (NRMACSSRISOL 202100401025) "Assessment and use of soil health as a tool for doubling farmers income, sustainable production and resource conservation in salt-affected soils of Haryana (2021–2023).

References

Allison LE and Moodie CD (1965) Carbonate. In: Black CA (ed) *Methods of Soil Analysis. Part 2. Chemical and Microbiological properties*. American Society of Agronomy, Madison, 1379–1396

Bajwa MS and Swarup A (2012) Soil Salinity and Alkalinity. In: Goswami NN, Rattan RK, Dev G, Narayansamy G, Das DK, Sanyal SK, Pal DK and Rao DLN (eds) *Fundamentals of Soil Science*. New Delhi, 329–339.

Basak N, Mandal B, Datta A, Kundu MC, Rai AK, Basak P and Mitran T (2021a) Stock and stability of organic carbon in soils under major agro-ecological zones and cropping systems of sub-tropical India. *Agriculture, Ecosystems and Environment* **312**: 107317.

Basak N, Rai AK, Barman A, Mandal S, Sundha P, Bedwal S, Kumar S, Yadav RK, Sharma PC (2022) Salt Affected Soils: Global Perspectives, in: Shit PK, Adhikary PP, Bhunia GS, Sengupta D. (Eds.), Soil Health and Environmental Sustainability: Application of Geospatial Technology. Springer International Publishing, Cham, pp. 107–129. https://doi.org/10.1007/978-3-031-09270-1_6

Basak N, Sheoran P, Sharma R, Yadav R, Singh R, Kumar S, Thimmappa K and Sharma P (2021b) Gypsum and pressmud amelioration improve soil organic carbon storage and stability in sodic agroecosystems. *Land Degradation and Development* **32**: 4430–4444.

Bhardwaj AK, Mishra VK, Singh AK, Arora S, Srivastava S, Singh YP and Sharma DK (2019) Soil salinity and land use-land cover interactions with soil carbon in a salt-affected irrigation canal command of Indo-Gangetic plain. *Catena* **180**: 392–400.

Bossolani JW, Leite MFA, Momesso L, ten Berge H, Bloem J and Kuramae EE (2023) Nitrogen input on organic amendments alters the pattern of soil–microbe-plant co-dependence. *Science of The Total Environment* **890**: 164347.

CSSRI (2015) Vision 2050. ICAR-Central Soil Salinity Research Institute, Karnal, India. Pp.31. www.cssri.res.in.

Datta A, Basak N, Chaudhari SK and Sharma DK (2015) Soil properties and organic carbon distribution under different land uses in reclaimed sodic soils of North-West India. *Geoderma Regional* **4**: 134–146.

Datta A, Basak N, Chinchmalatpure AR, Banyal and Chaudhuri SK (2017) Land-use Influences Soil Properties of Sodic Land in Northwest India. *Journal of Soil Salinity and Water Quality* **9**: 178–186

Datta A, Setia R, Barman A, Guo Y, Basak N (2019) Carbon Dynamics in Salt-affected Soils. In: Dagar JC, Yadav RK and Sharma PC (eds) *Research Developments in Saline Agriculture*. Springer Singapore: Singapore, 369–389.

Derrien D, Barré P, Basile-Doelsch I, Cécillon L, Chabbi A, Crème A, Fontaine S, Henneron L, Janot N, Lashermes G, Quénéa K, Rees F and Dignac M-F (2023) Current controversies on mechanisms controlling soil carbon storage: implications for interactions with practitioners and policy-makers. A review. *Agronomy for Sustainable Development* **43**: 21.

Mandal A (2022) Necessity for quantified measurement of soil sodicity and selection of suitable gypsum amendment for proper reclamation of sodic soil. *Pedosphere* **33**: 231–235.

Mandal AK (2016) Mapping and characterization of salt-affected and waterlogged soils in the Gangetic plain of central Haryana (India) for reclamation and management. *Cogent Geoscience* **2**: 1213689.

Mandal AK (2024) Spatial assessment and chemical characterization of degraded (salt-affected) soils at post-reclamation stage of the Indo-Gangetic Plain in Haryana State. *Environmental Monitoring and Assessment* **196**: 213.

Meena A, Bidalia A, Hanief M, Dinakaran J and Rao KS (2019) Assessment of above- and belowground carbon pools in a semi-arid forest ecosystem of Delhi, India. *Ecological Processes* **8**: 8.

Minhas PS, Qadir M and Yadav RK (2019) Groundwater irrigation induced soil sodification and response options. *Agricultural Water Management* **215**: 74–85. DOI: https://doi.org/10.1016/j.agwat.2018.12.030

Page AL, Miller RH and Keeney DR (1982) *Methods of Soil Analysis*. Soil Science Society of America, Madison, Wisconsin, USA.

Poffenbarger HJ, Sawyer JE, Barker DW, Olk DC, Six J and Castellano MJ (2018) Legacy effects of long-term nitrogen fertilizer application on the fate of nitrogen fertilizer inputs in continuous maize. *Agriculture, Ecosystems and Environment* **265**: 544–555.

Shirale AO, Kharche VK, Wakode RR, Meena BP, Das H and Gore RP (2018) Influence of Gypsum and Organic Amendments on Soil Properties and Crop Productivity in Degraded Black Soils of Central India. *Communications in Soil Science and Plant Analysis* **49**: 2418–2428.

Shukla A, Srivastava P, Tiwari P, Prakash C, Patra A, Singh P and Pachauri S (2015) Mapping Current Micronutrients Deficiencies in Soils of Uttarakhand for Precise Micronutrient Management. *Indian Journal of Fertilizers* **11**: 52–63

van Es HM and Karlen DL (2019) Reanalysis Validates Soil Health Indicator Sensitivity and Correlation with Long-term Crop Yields. *Soil Science Society of America Journal* **83**: 721–732.

Walkley A and Black IA (1934) An Examination of the Degtjareff Method for Determining Soil Organic Matter, and a Proposed Modification of the Chromic Acid Titration Method. *Soil Science* **37**: 29–38.

Wissing L, Kölbl A, Häusler W, Schad P, Cao Z-H and Kögel-Knabner I (2013) Management-induced organic carbon accumulation in paddy soils: The role of organo-mineral associations. *Soil and Tillage Research* **126**: 60–71.

Received: September 17, 2024; Accepted: October 16, 2024

Journal of Soil Salinity and Water Quality 16(2), 289-306, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.158519

Tree Plantation Established with Saline Groundwater on Degraded Calcareous Soils of Dry Regions of North-Western India as an Option for Biomass Production and Soil Amelioration in the Scenario of Changed Climate

JC Dagar[1,2], RK Yadav[1], OS Tomar[1], PS Minhas[1,3], Gajender Yadav[1]* and SR Gupta[4]

[1]*ICAR-Central Soil Salinity Research Institute, Karnal–132001, Haryana*
[2]*Indian Council of Agricultural Research, Krishi Anusandhan Bhavan-II, Pusa, New Delhi-110012*
[3]*National Institute of Abiotic Stress Management, Malegaon, Baramati (Pune)-413115, Maharashtra*
[4]*Department of Botany, Kurukshetra University, Kurukshetra-136119, Haryana*
**Corresponding author's E-mail: gajender.icar@gmail.com*

Abstract

A long-term field study was conducted to assess the performance of 31 potential tree species of economic importance for their biomass production and rehabilitation of calcareous soils using saline groundwater in low rainfall areas. Tree saplings were planted in the sill of the furrows, which were established and irrigated with saline groundwater (EC 9.3 dS m^{-1}) available at site. Irrigations were provided regularly (4-6 times $year^{-1}$) for the initial 3 years, thereafter only once in a year for the next 5 years, and kept rainfed afterwards up to 20 years. Survival, growth, biomass production, and water-use-efficiency of the tree species and changes in underneath soil properties were monitored during the study period. The top performer species were *Tamarix articulata, Acacia nilotica, A. tortilis, Prosopis juliflora, Eucalyptus tereticornis, Azadirachta indica* were *Cassia siamea* in given order. . Supplemental irrigation/s produced higher water-use-efficiency of different trees during initial 4-8 years than that of the earlier reported rainfed conditions. *Tamarix articulata* recorded highest (42.79 Mg ha^{-1}) and *Guazuma ulmifolia* lowest (2.01 Mg ha^{-1}) water-use-efficiency for the total growth period. After 20 years, total aboveground biomass production ranged from 123 to 391 Mg ha^{-1}; being maximum for *Tamarix articulata.* With tree growth, soil organic carbon increased but $CaCO_3$ and exchangeable sodium percentage (ESP) decreased in surface 30 cm soil layer. Thus, planting of the successful tree species with available saline groundwater can improve soil properties and carbon assimilation in tree biomass, and lead to productive rehabilitation of highly degraded calcareous soils of arid regions.

Key words: Afforestation, Carbon sequestration, Furrow irrigation, Salt tolerant tree species, Soil amelioration, Water use efficiency

Introduction

Vast tracts of land in arid and semi-arid regions of the world including India remain unproductive because of scanty occurrence and uneven distribution of rainfall with long dry spells resulting in the water deficits and desertification (Armitage, 1984; Gupta *et al*., 1995; Dagar and Minhas, 2016; Dagar *et al*., 2020a, b). Drylands cover about 46.2% (±0.8%) of the total global land area (Koutroulis, 2019). These regions usually lack water availability for supplemental irrigation, except for the low yielding, often very deep and saline, groundwater aquifers. With a hypothesis that these land can be rehabilitated with tree cover by planting species native to arid environments, stress tolerant and with efficient use of limited saline groundwater resources by application of suitable planting techniques. In the past, efforts for utilization of saline groundwater have been aimed mainly at enhancing the production of annual crops and high value fruit trees (Minhas, 1996; Dagar *et al*., 2016b). Though, many tree species have the potential for producing timber, fuel wood, and fodder besides reclaiming the degraded lands afflicted with salinity (Minhas *et al*., 1998; Dagar, 2014; Dagar *et al*., 2016b, 2024). However, irrigated forestry with saline water has attracted little attention (Minhas *et al*., 1998; Tomar *et al*., 2003; Dagar *et al*., 2016b).

Further, there are limitations of availability of stress-tolerant tree species. Some workers, however, evaluated several tree species for salt-affected soils and identified successful species suitable for sodic soils (Dagar *et al*., 2001; Singh and Dagar, 2005; Singh *et al*., 2022), saline soils (Tomar *et al*., 1998) and saline vertisols (Minhas *et al*., 1998). In sodic and calcareous soils, the presence of hard calcite layer in soil profile acts as a barrier for root proliferation, hence this layer needs to be pierced with auger holes and in saline soils or with use of saline waters, management practices should control salinity in root zone within the tolerance limits of the tree species. Tomar *et al*. (1998) found that sub-surface plantation and furrow irrigation using saline water was a successful technique. These results helped to hypothesise the choice of technique and species for these studies. The reason of taking large number of species was based on the stress tolerance of the species, suitability to the dry regions and wider utility in terms of fuelwood, timber, forages and fruits. Always there will be limited number of successful species which must be economical important for the stakeholders.

Generally, the afforestation programs in dry regions result in poor tree growth mainly due to reluctance of foresters to use saline groundwater for irrigation. Traditional approach of sustaining the use of saline water includes more frequent irrigations so as to facilitate leaching of salts below the rooting zone (Ayers and Westcot, 1985; Yadav and Dagar, 2016). Nevertheless, such practices require application of additional quantities of saline water leading to increased salt load in soil. Such approach has been advocated for shallow rooted crops in arid environments as it helps in leaching the added salts below the root zone (Tomar *et al*., 2003). However, the extra salts added with higher frequency of irrigations during establishment of deep-rooted plantations are likely to persist and aggravate the problem within their expanding root zone and ultimately hinder the growth of trees. Therefore, for successful establishment of saplings, irrigation with saline water should aim to avoid excess salt build up, and create favourable niches of salt and moisture in the tree rhizosphere. Several studies have shown that irrigating only the limited area in furrows planted with tree saplings reduce root zone salt load due to lesser use of saline water for irrigation and assist in leaching of added salts with concentration of rainwater run-off into furrows (Tomar *et al*., 1994, 1998, 2003; Minhas *et al*., 1997a, b; Tomar and Minhas, 1998; Dagar *et al*., 2008, 2016b).

For sustaining viable wood producing enterprise (timber/fuel wood) and fodder supply under saline irrigation conditions, tree species need to be identified in terms of adaptation to local agro-climate, tolerance to salt and water stress and the potential to supply fodder during the lean periods. Though, scanty information on short-term salinity tolerance of some tree species is available from pot experiments (Tomar and Yadav, 1985; Yadav, 1991; Ahmad and Ismail, 1992; Dagar and Singh, 2000; Dagar *et al*., 2004) and field studies (Schofield, 1992; Marcar *et al*., 1993; Davidson and Galloway, 1993; Gupta *et al*., 1995; Tomar and Minhas, 1998; Tomar *et al*. 1998; Qureshi and Barrett-Lennard, 1998; Dagar *et al*., 2001, 2008, 2016b). Gupta *et al*., (1995) reported the variable adaptability of some tree species (Table 1). However, these studies were confined to few species and very limited information is available on long-term performance of tree species established with saline water irrigation given in furrows and their effect on carbon build up in calcareous soils in semi-arid climatic conditions (Tomar *et al*., 2003; Dagar and Minhas, 2016; Dagar *et al*., 2016b). Moreover, there are certain benefits of saline irrigation in increasing biomass as compared to rainfed plantations in dry areas provided the salinity in root zone is managed in a limit. In the scenario of changed climate production of trees (both forest and fruit trees) in isolation or in combination with crops is always a better option in dry regions for enhancing income particularly from degraded lands. Thus, the present long-term field study (during 1995 to 2015) was conducted to identify high biomass producing suitable tree species for rehabilitation of calcareous soils in dry areas underlain with saline groundwater.

Material and Methods

Site characteristics and climate

A long-term field experiment was conducted during 1995 to 2015 on highly calcareous soil at

Table 1. Recommended tree species for the afforestation on salt-affected soils

Salinity / ECe (dS m^{-1}) below 0.3 m	Tree species
20–30	*Acacia farnesiana, Prosopis juliflora, Parkinsonia aculeate, Tamarix aphylla*
14–20	*Acacia nilotica, A. pennatula, A. tortilis, Callistemon lanceolatus, Casuarina glauca, C. obese, C. equisetifolia, Eucalyptuscamaldulensis, Ferronia limonia, Leucaena leucoephala, Ziziphus jujube*
10–14	*Casuarina canninghamiana, Eucalyptus teriticornis, Terminalia arjuna*
5–10	*Albizia caribaea, Dalbergia sissoo, Gauzuma ulmifolia, Pongamia Pinnata,Samanea saman*
< 5	*Acacia auriculiformis, A. deamii, A. catechu, Syzygium cumini, Salixspp., Tamarindus indica*

Source: Gupta *et al*. (1995)

Hisar (29°10′ N and 75°44′ E with altitude of 220 m above mean sea level) Haryana in north-west India. The climate at the study site is semi-arid and monsoonal. The study period recorded average annual rainfall of 498 ± 165 mm, the most (70-80%) of which occurred during July-September. The average annual open pan evaporation during the period was 1888 ± 243 mm. The area represents semi-arid to arid dry-land conditions with low precipitation to open pan evaporation ratio (~0.26) and high inter-annual rainfall variability. The annual maximum and minimum daily temperature during the study period was 31.3 ± 0.8°C and 16.1 ± 0.8°C, respectively (Fig. 1).

Soil and water characterization

Before initiating the experiment (June 1995), soil samples were collected from 0-0.15, 0.16-0.30, 0.31-0.60, 0.61-0.90 and 0.91-1.20 m profile depths at a grid of 60 m × 70 m (from 12 profiles). Soil samples were air-dried, ground and passed through 2 mm sieve. Saturation extract of soil samples was obtained using a vacuum pump. Soil pH was recorded in soil saturation paste itself using digital pH meter and electrical conductivity (ECe) measured in saturation paste extract by digital conductivity meter as described by Richards (1954). Mechanical analysis of soil samples was done by the International Pipette method (Piper, 1967) while $CaCO_3$ was determined using the method described by Jackson (1967). The soils of the study site are highly calcareous. Initial physico-chemical properties of the soil are given in Table 2.

Soil samples were collected, during June at yearly interval, from 0-0.15, 0.16-0.30, 0.31-0.60, 0.61-0.90 and 0.91-1.20 m soil depths between two centre plants of the middle row of each species from all replications. These were analysed for soil salinity (ECe dS m^{-1}) and organic carbon. Organic carbon was determined using Walkley and Black (1934) method. Water samples were collected every month from the ~13 m deep tube well existing at the site and analysed for electrical conductivity (EC), Na^+, Ca^{2+}+ Mg^{2+}, Cl^-, CO_3^{2-} and HCO_3^-. Na^+ was determined using the flame photometer (Richards 1954) while Ca^{2+}+ Mg^{2+}, Cl^-, CO_3^{2-} and HCO_3^- as per the standard methods for respective ions as described in Jackson (1967). Sodium adsorption ratio (SAR) used for judging the suitability of water for irrigation, was calculated using the following equation:

$$SAR= Na^+/\sqrt{[(Ca^{2+} + Mg^{2+})/2}; (mmol\ l^{-1})^{1/2}]$$

Site preparation and transplanting of saplings

Experimental area was cleared of natural vegetation during June 1995. The natural vegetation comprised of a mixture of few bushy trees and shrubs found scattered, open for grazing. These included *Acacia nilotica* (Linn.) Delile, *Azadirachta indica* A. Juss., *Capparis decidua* Edgew., *C. sepiaria* Linn., *C. spinosa* Linn., *Prosopis cineraria* Druce, *P. juliflora* Druce, *Salvadora persica* Linn., *Clerodendrum phlomidis* Linn.f., *Maytenus emarginata* (Willd.) Ding Hou, *Mimosa hamata* Willd., *Ziziphus nummularia* (Burm.f.) Wight & Arn. And *Calotropis procera* (Ait.) *R. Br* etc. In addition to these, some herbaceous species, such as *Achyranthes aspera* Linn., *Asparagus racemosus*

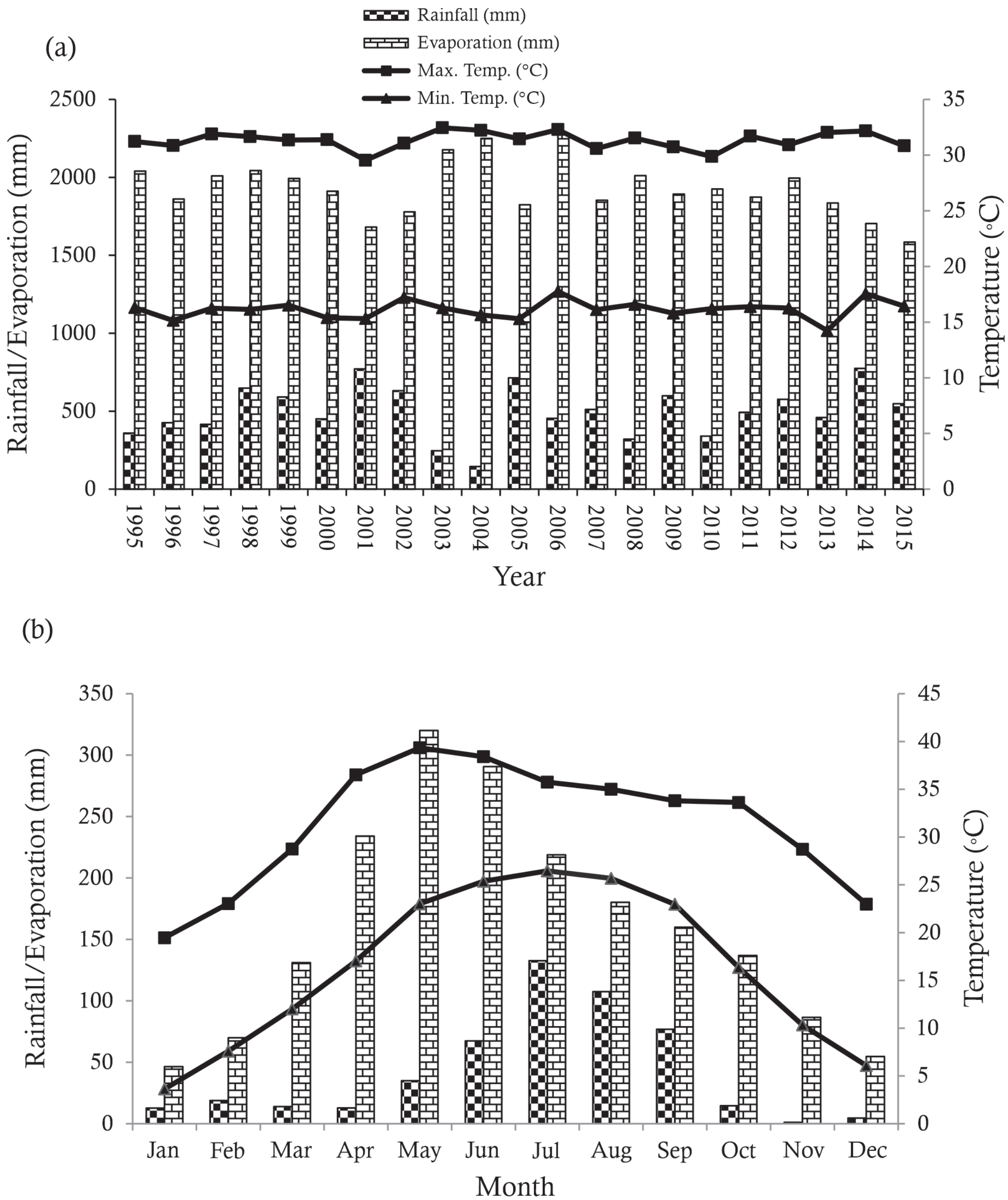

Fig. 1 Yearly (a) and monthly (b) rainfall, open pan evaporation and temperature data at study site during study period (1995-2015). The maximum and minimum temperatures are mean and rainfall and evaporation are cumulative annual (a) and monthly (b) data

Table 2. Initial (June 1995) physico-chemical properties of the soils of the experimental site at Hisar in north western India (Mean of 12 profiles with SD)

Soil depth (m)	Clay (%)	Silt (%)	Sand (%)	pHs	ECe (dS m^{-1})	ESP (%)	$CaCO_3$ (%)	Na^+ (me l^{-1})	K^+ (me l^{-1})	$Ca^{2+} + Mg^{2+}$ (me l^{-1})
0-0.15	18.6±1.2	19.6±0.8	61.8±2.1	8.3±0.2	1.6±0.1	9±0.3	6.2±3.4	5.6±0.4	0.27±0.3	5.6±0.8
0.15-0.3	18.4±1.4	20.5±0.7	61.1±1.4	8.2±0.3	1.7±0.1	11±0.2	7.2±4.3	8.9±0.6	0.17±0.3	3.8±0.3
0.3-0.6	18.0±1.2	22.2±1.1	59.8±1.8	8.1±0.2	2.0±0.1	12±0.5	8.4±4.7	21.7±1.7	0.12±0.2	7.9±1.2
0.6-0.9	17.6±1.3	21.5±0.6	60.9±0.7	7.9±0.2	2.6±0.2	10±0.4	8.0±5.1	21.3±2.1	0.13±0.1	12.0±1.7
0.9-1.2	18.2±1.1	21.4±1.0	60.4±1.6	8.0±0.1	2.9±0.1	10±0.6	7.8±4.9	15.7±1.2	0.22±0.4	11.8±1.0

Willd., *Chenopodium album* Linn., *C. murale* Linn., *Cenchrus ciliaris* Linn., *Cynodon dactylon* Pers., *Dactyloctenium sindicum* Boiss., *Sporobolus marginatus* Hochst. ex A. Rich., and *Tribulus terrestris* Linn.; were also present.

Whole experimental area of about 1.54 ha was properly ploughed, levelled and divided into three blocks, each as a replication. Furrows (0.15 m deep and 0.60 m wide) were made at 2.5 m interval using a tractor drawn furrow maker in each block. Auger holes (0.2 m dia and 1.2 m deep) were dug at 2.0 m interval in sill of the furrows. These auger holes were re-filled with a mixture of original soil + 8.0 kg farmyard manure, 30 g single superphosphate, 15 g $ZnSO_4$ and 15 g $FeSO_4$. Six months old uniform height (intra genus CV ± 8%) 32 saplings (4 rows of 8 plants each) of each of 31 forestry species (Table 3) were planted in randomly selected plots of 160 m^2 each in every block during 7 -11August 1995. The layout of the experiment is shown in Fig. 2.

Table 3. Tree species grown in long-term trial on calcareous soils in northwest India and their importance

Tree species	English/ trade name(s)	Vernacular /) local name(s	Important uses
Acacia auriculiformis A. Cunn.	Australian wattle	Australian kikkar	Fire wood, small timber
Acacia farnesiana (Linn.) Willd.	Cassie-flower	Gandhelo babul	Fire wood, fodder
Acacia nilotica (Linn.) Delile	Gum arabic	Desi kikkar, babul	Timber, fire wood, fodder, edible gum from branches
Acacia tortilis Hayne	Umbrella tree	Israeli kikkar	Timber, fire wood, fodder
Acacia tortilis Hayne (Hybrid)	Umbrella tree	Israeli kikkar	Timber, fire wood, fodder
Albizia lebbeck Benth.	East India walnut	Siris	Timber, fire wood, fodder
Azadirachta indica A. Juss.	Neem, margosa	Neem	Timber, fire wood, fodder, medicine, landscape
Bauhinia variegata Linn.	Mountain-ebony	Kachnar	Timber, fire wood, fodder
Callistemon lanceolatus DC.	Bottle brush	-	Timber, fire wood, landscape
Cassia fistula Linn.	Indian-laburnum	Amaltas	Timber, fire wood, ornamental. landscape
Cassia glauca Lamk.	-	-	Fire wood
Cassia javanica Linn.	-	-	Fire wood, timber
Cassia siamea Lamk.	Siamese senna	Kassod	Timber, fire wood
Casuarina equisetifolia Linn.	Beef wood	-	Timber, fire wood, landscape
Crescentia alata H.B.K.	Gaurd tree	-	Timber, fire wood
Dalbergia sissoo Roxb.	Sissoo	Shisham, taali	Timber, fire wood, fodder, landscape
Eucalyptus tereticornis Sm.	Red gum	Safeda	Timber, fire wood
Feronia limonia (Linn.) Swingle	Wood apple	Kaith	Timber, fire wood, fodder, fruit
Guazuma ulmifolia Lamk.	Bay cedar	-	Timber, fire wood
Melia azedarach Linn.	Bead tree, Persian lilac	Drek, Bakaan	Timber, fire wood, medicine
Moringa oleifera Lamk.	Drumstick	Sonjana, saunjana	Timber, fire wood, fodder, vegetable, all parts rich in nutrition
Pithecellobium dulce (Roxb.) Benth.	Madras-thorn	Jangle jalebi	Timber, fire wood, fodder
Pongamia pinnata Pierre	Pongam	Papri, karanj	Timber, fire wood, fodder, bio-fuel
Prosopis cineraria Druce	-	Khejri, Jand	Timber, fire wood, fodder, vegetable (pods)
Prosopis juliflora DC.	Mesquite	Vilayati kikkar/babul	Timber, fire wood, fodder (pods)
Samanea saman Merrill	Rain tree	-	Timber, fire wood, fodder, landscape
Syzygium cuminii (Linn.) Skeels	Black plum	Jamun	Timber, fire wood, fruit edible and medicinal
Tamarix articulata Vahl	-	Frash	Fire wood, agricultural implements
Tecomella undulata (Sm.)	Rohida	Rohida	Timber, fire wood
Terminalia arjuna (Roxb.)	Arjun	*Arjun*	Timber, fire wood, medicine
Ziziphus mauritiana Lamk.	Jujube	Ber	Fruit, timber, fire wood, fodder

2 m

Replication-I (2.5 m)	S1	S8	S9	S16	S17	S24⊠	S25	No tree
	S2	S7 ⊠	S10	S15	S18	S23	S26	S31
	S3	S6	S11	S14⊠	S19	S22	S27	S30
	S4	S5	S12	S13	S20	S21	S28	S29⊠
Replication -II	S1	S17	S26	S24	S12	S29	S6	S15
	S9⊠	S2	S11	S19	S20⊠	S5	S22	S23
	S16	S10	S18⊠	S8	S4	S21	S14⊠	S7
	S25	S27	S3	S28	S30	S13	No tree	S31
Replication -III	S10	S3⊠	S11	S16	S18	S13	S14	S2
	S19	S6	S7	S1	S4⊠	S23	S8	S15
	S22	S17	S21⊠	S25	S29	S5	S24⊠	S9
	S26	S30	S28	No tree	S12	S27	S31	S20
The tree removal schedule after 5 years (o), 8 years (Δ) and 20 years (x) of plantation								
	x	o	x	o	x	o	x	o
	Δ	o	Δ	o	Δ	o	Δ	o
	x	o	x	o	x	o	x	o
	Δ	o	Δ	o	Δ	o	Δ	o

Fig. 2 (A) Layout of all the 31 species randomly planted in 3 replications at the sill of furrows (B) with plant to plant 2m and row to row 2.5 m space (32 plants of each species in each plot ⊠ Depicts the position of soil profile and neutron probe measurement points (B) shows details of plantations in each plot of a single species (o) denotes alternate trees removed after 5 years of growth; (Δ) denotes trees removed after 8 years of growth; (x) denotes the left over trees after 8 years of growth and harvested after 20 years of growth

Water quality and irrigation schedules

The tube well water used for irrigation had an electrical conductivity (EC_{iw}) 9.3±0.7 dS m^{-1} and pH 7.9±0.3; while Ca^{2+}+Mg^{2+}, Na^{+}, Cl^{-}, HCO_3^{-} and SAR values were 23.6±1.7, 69.0±2.4, 46.2±1.8, 4.6±0.3 meq L^{-1} and 20.8±0.4 (mmol $L^{-1})^{1/2}$, respectively. Irrigation was applied only in the furrows ~7.0 cm depth to meet the water requirement of trees mainly during dry season from October to May each year. The irrigation was applied immediately after planting. Numbers of irrigations applied during 1st, 2nd and 3rd year of growth were 6, 5 and 4 per year, respectively. As the furrows were long, the irrigation was applied from one end to another while the next irrigation was initiated from opposite end of the furrow to balance the duration of irrigation. To protect the plants from frost during winter, a single irrigation was given yearly in December/January for the next 5 years.

Growth and performance of trees

Out of the total 31 species planted initially; only 18 tree species (*Tamarix articulata*, *Acacia nilotica*, *A. tortilis*, *Prosopis juliflora*, *Eucalyptus tereticornis*, *Azadirachta indica, Cassia siamea*, *Acacia tortilis* (hybrid), *Ziziphus mauritiana, Pithecellobium dulce, Melia azedarach, Cassia fistula, C. javanica, Callistemon lanceolatus, Acacia farnesiana, Feronia limonia, Guazuma ulmifolia* and *Prosopis cineraria*), which survived till 24 October 2015 were included for final comparisons. Initial observations were taken for all the trees. The height and girth of these were monitored annually during the month of October/November. Height was recorded with the help of a bamboo pole up to 8 years of growth and later on with altimeter; whereas girth was calculated from diameter at breast height (1.35 m above soil surface) measured with vernier calliper. Air-dried pruned biomass of each species was recorded after 2 years, after 5 years, alternate trees felled from every row and after 8 years of growth alternate rows felled as shown in layout Fig.2. The pruning was done for lower branches depending the height of the tree. The trees were felled by cutting at ground level. After 8 years, performance of remaining (maximum 8) trees of every species from each replication was recorded annually. Biomass production at 20 years of growth was recorded after felling 3 randomly selected trees of every species from each replication. Total biomass of trees harvested at 5, 8 and 20 years of growth was segregated into timber (>31.5 cm tree bole and >20 cm girth of thick branches) and fuel-wood (remaining twigs). Dry biomass of different components was recorded after keeping the samples in oven at 70°C till constant weight achieved. Biomass production at respective stages of growth was computed as Mg ha^{-1}.

Plantation water use and water use efficiency

Periodic water use of plantation was measured starting from 3rd year of growth from April 1998 to October 2015. It was calculated using soil water balance method i.e. $E = I + P - R + G + S$; where E, I, P, R, G and S represent evaporation from soil surface + transpiration from plantation canopy, water applied through irrigation, precipitation received, run-off, water contribution from or to water table and change in soil water storage, respectively. In this study, R and G were assumed insignificant, because experimental field was properly bund to avoid run off and water table was deep (~13 m) to contribute towards plantation water use. Total amount of irrigation water applied every year (from 3rd to 8 years of growth) was measured by multiplication of tube well discharge rate with its running time for each irrigation of 7.0 cm depth and number of irrigations applied during the period under consideration; while precipitation was recorded from Choudhary Charan Singh Haryana Agricultural University Hisar meteorological observatory situated at ~3.0 km distance from the experimental site.

Though the drainage flux was not measured directly, but it was accounted for by measuring changes in soil moisture at monthly interval. Change in soil profile (up to 3.5 m) moisture was measured from four neutron probe access tubes at monthly interval up to 8 years of growth and 3 months interval during remaining period of 12 years. These access tubes were installed at 0.6 m lateral distance (2 in channel and 2 between rows in either side) around the 2nd tree of 4th row of each species in every block. Change in soil moisture below 0.3 m depth was calculated from depth wise (0.3 m interval up to 3.0 m) measurements recorded from access tubes using already calibrated neutron probe (CPN Hydroprobe) count ratio readings. Surface (0.3 m) soil moisture was simultaneously measured gravimetrically. Water use efficiency of respective tree species was calculated by dividing the total biomass production (Mg ha^{-1}) by total water use (m) of respective tree species. Aggregate of water use by different species during period of supplemental irrigation (April 97 to Jan 2001) and remaining period (Jan 2001 to Oct 2015) of no irrigation along with respective water use efficiency are presented here.

Experimental design and statistical analysis

The experiment comprising 31 forestry species was laid out in randomised block design with 3 replications. Individual treatment plot of 16 m × 10 m size consisted of 32 plants of each species planted in 4 rows with 8 plants per row. Significance of differences in mean values of the recorded growth parameters of 18 tree species which survived till 2014-15 was evaluated by ANOVA using (SAS) for randomised incomplete block design at confidence level of 0.05 following Gomez and Gomez (1984). The statistical analysis regarding growth parameters was done every year independently after taking observations but included here for the relevant year of report only.

Results

Growth performance of tree species *Survival*

During the initial 3 years, when plants received saline water irrigation, the most of tree species recorded >70% survival, except *Syzygium cuminii* which failed in second year only. *Crescentia alata, Cassia glauca* and *Bauhinia variegata* did not survive after third year of planting, while *Acacia auriculaeformis* also died after fifth year. Survival of *Albizia lebbeck, Casuarina equisetifolia, Dalbergia sissoo,* and *Terminalia arjuna* reduced to <25% after discontinuation of supplemental irrigation of saline water. Mortality in *Samanea saman* reached ~50% in 6th year of growth and the species failed completely afterwards. Nevertheless, tree survival >73% was recorded in *Acacia farnesiana, A. nilotica, A. tortilis, A. tortilis* (hybrid), *Azadirachta indica, Cassia siamea, Eucalyptus tereticornis, Feronia limonia, Pithecellobium dulce, Prosopis cineraria, P. juliflora* and *Ziziphus mauritiana* even after 8 years (Table 4). Tree species like *Guazuma ulmifolia, Cassia javanica, C. fistula, Callistemon lanceolatus* and *Tamarix articulata* recorded 41-67% survival at 8 years of growth. *Eucalyptus tereticornis* maintained highest (83%) survival at 20 years of growth followed by *Feronia limonia* and *Azadirachta indica* recording ~75%, and species such as *Acacia nilotica, A. tortilis, Prosopis juliflora, Tamarix articulata* and *Ziziphus mauritiana* >65%. The most of tree species

Table 4. Survival* (%) of tree species in experimental plots during different periods of growth after transplanting

Tree species	After years									
	2	4	6	8	10	12	14	16	18	20
Acacia auriculaeformis	72	10	0	0	0	0	0	0	0	0
A. farnesiana	97	97	97	97	75	75	67	67	67	50
A. nilotica	99	97	97	97	75	75	75	67	67	67
A. tortilis	97	97	96	94	83	75	67	67	67	67
A. tortilis (hybrid)	98	98	98	88	75	67	58	58	50	50
Albizia lebbeck	85	72	24	8	8	8	8	8	8	8
Azadirachta indica	100	100	92	90	75	75	75	75	75	75
Bauhinia variegata	20	0	0	0	0	0	0	0	0	0
Callistemon lanceolatus anceolatus	89	79	67	56	42	42	33	33	33	33
Cassia fistula	72	72	72	56	50	42	33	33	33	33
C. glauca	54	0	0	0	0	0	0	0	0	0
C. javanica	93	93	93	67	50	42	42	25	25	25
C. siamea	85	85	81	81	75	67	58	42	42	42
Casuarina equisetifolia	90	73	23	6	0	0	0	0	0	0
Crescentia alata	66	0	0	0	0	0	0	0	0	0
Dalbergia sissoo	67	64	24	20	12	0	0	0	0	0
Eucalyptus tereticornis	98	94	88	88	83	83	83	83	83	83
Feronia limonia	82	82	82	77	75	75	75	75	75	75
Guazuma ulmifolia	71	71	59	41	33	33	25	25	25	25

Contd...

Melia azedarach	100	100	75	73	50	33	25	25	25	25
Moringa oleifera	92	75	72	56	50	42	33	17	8	8
Pithecellobium dulce	100	98	92	77	67	58	50	42	42	42
Pongamia pinnata	94	89	76	29	0	0	0	0	0	0
Prosopis cineraria	97	97	95	92	75	75	67	50	50	50
Prosopis juliflora	96	96	96	94	83	75	67	67	67	67
Samanea saman	82	78	50	13	0	0	0	0	0	0
Syzygium cuminii	0	0	0	0	0	0	0	0	0	0
Tamarix articulata	92	88	67	67	67	67	67	67	67	67
Terminalia arjuna	97	92	24	3	0	0	0	0	0	0
Tecomella undulata	86	78	53	39	17	12	0	0	0	0
Ziziphus mauritiana	100	100	96	75	75	67	67	67	67	67
LSD ($p \leq 0.05$)	8	19	16	25	28	31	26	29	31	31

*Survival after 8 years onwards is based on trees left after harvest i.e., from 8 trees per plot

Table 5. Height (m) of tree species during different periods of growth

Tree species	Height (m) after years								
	4yr	8yr	+	12yr	+	16yr	+	20yr	+
Acacia farnesiana	3.7	4.6	0.22	4.9	0.07	5.2	0.07	5.2	0.0
A. nilotica	5.4	7.5	0.52	10.9	0.85	12.5	0.40	13.9	0.35
A. tortilis	4.1	6.6	0.62	9.5	0.72	11.2	0.40	12.9	0.42
A. tortilis (hybrid)	3.9	6.9	0.75	9.2	0.57	10.9	0.42	12.8	0.50
Azadirachta indica	3.2	4.7	0.40	6.8	0.52	8.4	0.40	10.6	0.55
Cassia siamea	4.9	7.3	0.60	9.4	0.52	10.6	0.30	12.1	0.55
C. javanica	2.9	3.9	0.25	7.0	0.78	8.9	0.47	9.6	0.18
C. fistula	3.2	5.3	0.75	9.0	1.27	11.2	0.55	11.8	0.15
Callistemon lanceolatus anceolatus	2.6	4.3	0.42	7.1	0.70	8.2	0.29	9.7	0.38
Eucalyptus tereticornis	6.7	10.9	1.05	16.8	1.50	19.0	0.56	20.6	0.40
Feronia limonia	1.7	3.5	0.45	7.2	0.92	9.2	0.50	11.0	0.50
Guazuma ulmifolia	3.1	5.8	0.67	8.6	0.70	9.7	0.27	11.4	0.42
Melia azedarach	4.5	6.3	0.45	7.7	0.35	8.6	0.27	8.9	0.07
Pithecellobium dulce	3.7	4.7	0.25	5.4	0.18	8.9	0.9	11.5	0.7
Prosopis cineraria	1.9	2.9	0.25	4.8	0.47	6.5	0.42	7.8	0.3
P. juliflora	4.9	6.7	0.45	7.9	0.30	8.8	0.22	9.2	0.10
Tamarix articulata	6.7	12.0	1.32	16.4	1.10	19.0	0.65	21.0	0.50
Ziziphus mauritiana	2.3	3.7	0.35	7.5	0.95	8.6	0.27	9.2	0.15
LSD ($p \leq 0.05$)	1.1	1.9	-	2.6	-	3.7	-	4.3	-

+ indicates temporal annual increase in height. The data is based on all surviving trees
Only 18 species are included as 11 died and 2 recorded <10% survival (see Table 3)

exhibited good survival till continuation of supplemental irrigation even though with saline water.

Temporal increase in tree height

Tree species differed significantly in their height gained with age over the years (Table 5). *Acacia farnesiana* remained bush and attained the maximum height of only 5.2 m with an average annual increment of <0.22 m per year. While species like *Acacia nilotica, A. tortilis, A. tortilis* (hybrid), *Cassia siamea, C. fistula, Eucalyptus tereticornis* and *Tamarix articulata* recorded greater increase in height ranging from 0.5 to 1.3 m per year during 3 years of supplemental irrigation with saline water. *Tamarix articulata* and *Eucalyptus tereticornis* attained significantly greater height than all other species at all stages of growth and

Table 6. Girth at breast height of tree species during different periods of growth

Tree species	Girth at breast height after years (cm)								
	4yr	8yr	+	12yr	+	16yr	+	20yr	+
Acacia farnesiana	17.9	22.3	1.1	34.0	2.9	37.8	1.0	39.0	0.3
A. nilotica	26.7	36.4	2.4	56.6	5.0	74.0	4.35	90.3	4.1
A. tortilis	19.5	34.2	3.7	50.9	4.2	58.1	1.8	67.0	2.22
A. tortilis (hybrid)	16.0	33.3	4.3	46.5	3.6	56.1	2.4	61.9	1.45
Azadirachta indica	24.8	30.8	1.5	52.8	4.4	77.5	6.2	98.3	5.2
Cassia siamea	25.1	36.5	2.9	51.9	3.8	61.9	2.5	71.7	2.45
C. javanica	19.8	26.7	1.7	47.1	5.1	62.5	3.8	67.6	1.3
C. fistula	20.1	29.5	2.4	35.2	1.4	38.7	0.9	41.5	0.7
Callistemon lanceolatus anceolatus	15.7	22.0	1.6	39.0	4.2	53.7	3.7	63.3	2.4
Eucalyptus tereticornis	17.4	28.6	2.8	44.3	3.9	62.2	4.5	69.2	1.75
Feronia limonia	10.0	14.8	1.2	30.2	3.8	50.3	5.0	59.4	2.3
Guazuma ulmifolia	18.9	30.8	3.0	49.6	4.7	72.0	5.6	78.5	1.6
Melia azedarach	27.6	44.3	4.2	54.0	2.4	57.8	1.0	61.3	0.9
Pithecellobium dulce	18.9	24.8	1.5	40.8	4.0	62.9	5.5	67.3	1.1
Prosopis cineraria	10.7	14.1	0.9	27.3	3.3	37.7	2.6	44.0	1.6
P. juliflora	22.0	33.6	2.9	44.3	2.7	54.8	2.6	61.8	1.7
Tamarix articulata	50.0	78.3	7.1	114.1	8.9	162.8	12.2	181.7	4.72
Ziziphus mauritiana	9.4	17.6	2.0	34.6	4.2	53.4	4.7	62.2	2.2
LSD ($p \leq 0.05$)	4.4	17.3	-	18.5	-	21.2	-	19.8	-

+ indicates temporal increase in annual girth. The data is based on all surviving trees

recorded the maximum height of 19 m after 16 years of growth. Species such as *Acacia nilotica, A. tortilis, A. tortilis* (hybrid), *Cassia siamea, C. fistula, Guazuma ulmifolia, Pithecellobium dulce* and *Feronia limonia* recorded lower height gain as compared to that of *Eucalyptus tereticornis* and *Tamarix articulata. Tamarix articulata* attained the maximum height of 21 m at 20 years of age, followed by *Eucalyptus tereticornis* (20.6 m), *A. nilotica* (14 m), *A. tortilis* (13 m), *Cassia siamea, C. fistula* (12 m) and *Guazuma ulmifolia, Pithecellobium dulce* and *Feronia limonia* (11m). While rest of the tree species like *Cassia javanica, Callistemon lanceolatus, Ziziphus mauritiana, Prosopis juliflora, P. cineraria* and *Melia azedarach* attained even lower height ranging from only 7.8-9.7 m.

Periodic changes in tree girth

Gains in bole girth at breast height (1.35 m; GBH) in most of the tree species followed a trend similar to that of the average gains in their heights (Table 6). In the initial stage (up to 4 years of growth), *Tamarix articulata* attained a GBH of 50 cm. It was significantly *(p*≤0.05) greater than that of the GBH of *Melia azedarach* (27.6 cm), *Acacia nilotica* (26.7 cm), *Cassia siamea* (25.1 cm), *Prosopis juliflora* (22.0 cm), *Cassia fistula* (20.1 cm), *C. javanica* (19.8 cm), *A. tortilis* (19.5 cm), and *Pithecellobium dulce* (18.9 cm). Some of these species continued to attain comparatively more increase in girth throughout the experimentation period of 20 years. After 20 years, the GBH of 6 top ranking species in terms of GBH followed the order; *Tamarix articulata* (181.7cm), *Azadirachta indica* (98.3 cm), *Acacia nilotica* (90.3 cm) and *Guazuma ulmifolia* (78.5 cm), followed by *Cassia seamea* (71.7 cm) and *Eucalyptus tereticornis* (69.2 cm). GBH of tree species such as *Acacia tortilis, A. tortilis* (hybrid), *Cassia javanica, Callistemon lanceolatus, Melia azedarach, Pithecellobium dulce, Prosopis juliflora,* and *Ziziphus mauritiana* were also comparable to the last two of the above-mentioned six species. Among the surviving species, *Acacia farnesiana, Prosopis cineraria* and *Cassia fistula* exhibited GBH ranging from 39 cm to 44 cm.

Biomass accumulation

Prosopis juliflora, Azadirachta indica, Cassia javanica and *Tamarix articulata* produced significantly more (0.56 to 0.43 Mg ha^{-1}) pruning biomass at 2 years of growth as compared to < 0.25 Mg ha^{-1} in *Cassia fistula, Guazuma ulmifolia, Ziziphus mauritiana, Melia azaderach, Cassia siamea, Feronia limonia and Prosopis cineraria*. While all four species of *Acacia*, *Eucalyptus tereticornis* and *Pithecellobium dulce* produced pruned biomass ranging from 0.28 to 0.32 Mg ha^{-1} (Table 7). After 5 years of age; *Tamarix articulata, Acacia nilotica, Prosopis juliflora* and *Melia azedarach* attained significantly highest (16.90 to 10.73 Mg ha^{-1}) aboveground biomass as compared to that of *Acacia tortilis, A. tortilis* (hybrid), *Eucalyptus tereticornis, Pithecellobium dulce, Cassia siamea* and *Azadirachta indica* (5.50 to 8.27 Mg ha^{-1}). While the remaining species exhibited aboveground biomass less than 4.27 Mg ha^{-1}. After 8 years of planting, *Tamarix articulata* produced the highest biomass of 73.5 Mg ha^{-1} followed by *Acacia nilotica* (22.4 Mg ha^{-1}), *Prosopis juliflora* (20.2 Mg ha^{-1}) and *Eucalyptus tereticornis* (14.8 Mg ha^{-1}). Trend in the total biomass accumulation after 20 years of growth followed the order *Tamarix articulata* (391 Mg ha^{-1}) > *Acacia nilotica* (230 Mg ha^{-1}) > *A. tortilis* (184 Mg ha^{-1}) > *Eucalyptus tereticornis* (145 Mg ha^{-1}) > *Prosopis juliflora* (153 Mg ha^{-1}) and > *Azadirachta indica* (123 Mg ha^{-1}).

Plantation water use and water-use-efficiency

Water use of plantations varied significantly among different species during the period (1997-2001) when supplemental irrigations were applied. However, variation in water use was lesser among the species, during later period from January 2001 to October 2015, when no supplemental irrigation was given. During later period of 15 years, *Cassia siamea* and *Cassia fistula* recorded the highest (7.71 and 7.16 m, respectively), while *Ziziphus mauritiana* and *Guazuma ulmifolia* had the lowest (5.42 and 5.45 m, respectively) water use (Table 8). When overall aggregate water use of the species was compared, *Cassia siamea* recorded the highest (12.16 m) followed by *Azadirachta indica* (11.68 m) and the lowest by *Acacia farnesiana* (9.07 m) preceded by *Tamarix articulata* (9.79 m).

The WUE varied markedly among different tree plantations. The highest WUE of 42.79 Mg m^{-1} was recorded in *Tamarix articulata* followed by

Table 7. Pruned and harvested biomass of different tree species at different stages of their growth

Tree species	Biomass (Mg ha^{-1}) after years				
	2yr (P)	5yr (H)#	8yr (H)$	20yr (H)•	Total
Acacia farnesiana	0.32	8.10	8.66	22.12	39.20
A. nilotica	0.32	16.07	22.43	190.51	230.33
A. tortilis	0.31	8.27	11.53	165.45	184.56
A. tortilis (hybrid)	0.35	8.31	11.65	156.24	176.55
Azadirachta indica	0.48	5.50	6.23	111.16	123.37
Cassia siamea	0.23	6.27	13.70	101.87	122.07
C. javanica	0.46	2.80	2.27	34.60	40.13
C. fistula	0.07	4.27	2.17	50.63	57.14
Callistemon lanceolatus	0.08	2.27	2.03	17.39	21.77
Eucalyptus tereticornis	0.28	7.70	14.81	122.36	145.15
Feronia limonia	0.21	4.87	7.85	43.2	56.13
Guazuma ulmifolia	0.14	1.30	3.03	15.90	20.37
Melia azedarach	0.19	10.73	6.30	28.80	46.92
Pithecellobium dulce	0.28	5.70	3.47	51.09	60.54
Prosopis cineraria	0.16	2.02	3.25	21.23	26.66
Prosopis juliflora	0.56	14.10	20.23	118.97	153.86
Tamarix articulata	0.43	16.90	73.50	300.70	391.53
Ziziphus mauritiana	0.20	1.73	3.13	55.12	60.18
LSD ($p = 0.05$)	0.20	4.02	3.36	12.06	7.84

P= pruned biomass, H=harvested biomass
# Biomass after harvesting alternate rows; $ Biomass after harvesting alternate trees from the left over after 5 years of harvest; • Biomass based on remaining trees after 8 years.
All these treatments are part of management for optimizing biomass production

Table 8. Salinity (ECe), sodicity (pHs and ESP) and $CaCO_3$ in soil depth (0-1.2 m) after 20 years of growth of different species of forestry plantations, and their water use efficiency (up to 3.0 m depth) (Mean of 3 random soil samples taken with augers)

Tree species	ECe ($dS\ m^{-1}$)	pHs	ESP (%)	$CaCO_3$ (%)	*Water use (m) 1994-97*	98-2011	Overall WUE ($Mg\ m^{-1}$)
Acacia farnesiana	2.1±0.2	8.3±0.1	9.2±0.4	6.7±1.2	2.45	6.63	4.86
A. nilotica	2.3±0.2	7.9±0.3	7.6±0.2	5.7±1.5	4.41	7.07	21.98
A. tortilis	2.2±0.1	8.1±0.4	8.9±1.7	6.0±2.0	4.65	6.82	17.63
A. tortilis (hybrid)	2.3 ±0.3	8.2±0.3	8.7±1.5	6.1±1.9	4.52	6.88	17.95
Azadirachta indica	2.0±0.3	8.4±0.1	8.3±0.6	5.9±0.7	4.74	6.94	11.55
Cassia siamea	2.4±0.1	8.2±0.2	8.7±0.1	6.3±1.3	4.45	7.71	12.01
C. javanica	2.2±0.2	8.0±0.3	9.8±0.8	6.8±0.5	4.56	6.33	4.06
C. fistula	2.0±0.2	8.3±0.2	10.1±1.0	7.2±2.4	3.47	7.16	6.62
Callistemon lanceolatus	2.5±0.3	8.1±0.1	9.6±0.6	7.8±1.1	4.56	6.02	2.06
Eucalyptus tereticornis	1.9±0.1	8.4±0.1	8.2±0.5	6.1±1.8	4.79	5.99	13.46
Feronia limonia	1.8±0.3	7.9±0.2	8.9±0.4	6.0±1.1	4.65	5.72	5.97
Guazuma ulmifolia	2.6±0.3	8.0±0.2	9.5±0.7	7.5±1.0	4.67	5.45	2.01
Melia azedarach	2.6±0.1	8.2±0.1	9.4±1.3	7.3±1.2	4.80	5.80	4.43
Pithecellobium dulce	1.7±0.4	7.8±0.2	8.6±0.5	6.2±0.9	4.63	5.68	5.87
Prosopis cineraria	1.6±0.3	6.4±0.2	7.6±0.5	5.8±0.7	4.53	4.64	3,26
Prosopis juliflora	2.3±0.2	8.2±0.1	7.2±0.1	5.8±0.6	4.86	5.91	14.29
Tamarix articulata	2.4±0.2	8.1±0.2	8.5±0.8	6.3±1.0	3.79	5.06	42.79
Ziziphus mauritiana mauritiana	2.1±0.2	8.4±0.1	7.4±0.2	5.9±0.5	4.71	5.42	5.94
LSD (p = 0.05)	0.24	0.34	0.35	0.34	0.11	0.11	0.29

ECe and pHs are electrical conductivity and pH of soil saturation extract; ESP is exchangeable sodium percentage, while WUE stands for water use efficiency.
*Irrigation period

21.98, 17.63, 14.29, 13.46, 12.01 and 11.55 $Mg\ m^{-1}$ by *Acacia nilotica, Acacia tortilis, Prosopis juliflora, Eucalyptus tereticornis, Cassia siamea* and *Azadirachta indica*, respectively. Remaining species produced less than 10 $Mg\ m^{-1}$ with lowest (2.01 $Mg\ m^{-1}$) being in *Guazuma ulmifolia* followed by 2.06, 4.06, 4.43 and 4.86 $Mg\ m^{-1}$ in *Callistemon lanceolatus, Cassia javanica, Melia azedarach* and *Acacia farnesiana,* respectively.

Changes in soil salinity, sodicity, calcareousness and organic carbon

Soil salinity tended to rise during the period when saline irrigations were applied. After one year of plantations growth; soil salinity (EC_e) in 0-1.2 m soil profile ranged between 5-10 $dS\ m^{-1}$ with an average of 6.8 $dS\ m^{-1}$. Soil profile salinity decreased to 6-5 $dS\ m^{-1}$ during 2000 to 2005 and continued to decrease further with passage of time reaching < 3.0 $dS\ m^{-1}$ after 20 years of tree growth (Figure 3). Soil salinity did not differ significantly ($p \leq 0.05$) among different tree species at any given depth and/or time. Hence only four values, i.e. two highest and two lowest recorded at specific time and soil depth, were included for simplifying interpretations (Fig. 3). Though tree species did not have marked effect on soil salinity and soil reaction, but soil profile sodicity (ESP) and $CaCO_3$ content decreased after 20 years of growth under different forestry species (Table 7). Respective decrease in the two parameters was the maximum (31 and 23%) under *Prosopis juliflora,* followed by *Ziziphus mauritiana* (29 and 21%), *Acacia nilotica* (27 and 23%), *Eucalyptus tereticornis* (21 and 19%), *Azadirachta indica* (20 and 21%) and *Tamarix articulata* (18 and 16%). Other species had relatively lesser effect on decreasing soil sodicity and $CaCO_3$.

Soil organic carbon increased under all the surviving tree species. It was significantly higher (>0.5%) under *Acacia nilotica, A. tortilis, Azadirachta indica, Eucalyptus tereticornis, Feronia limonia, Tamarix articulata* and *Guazuma ulmifolia* as compared to other tree species (Fig. 4).

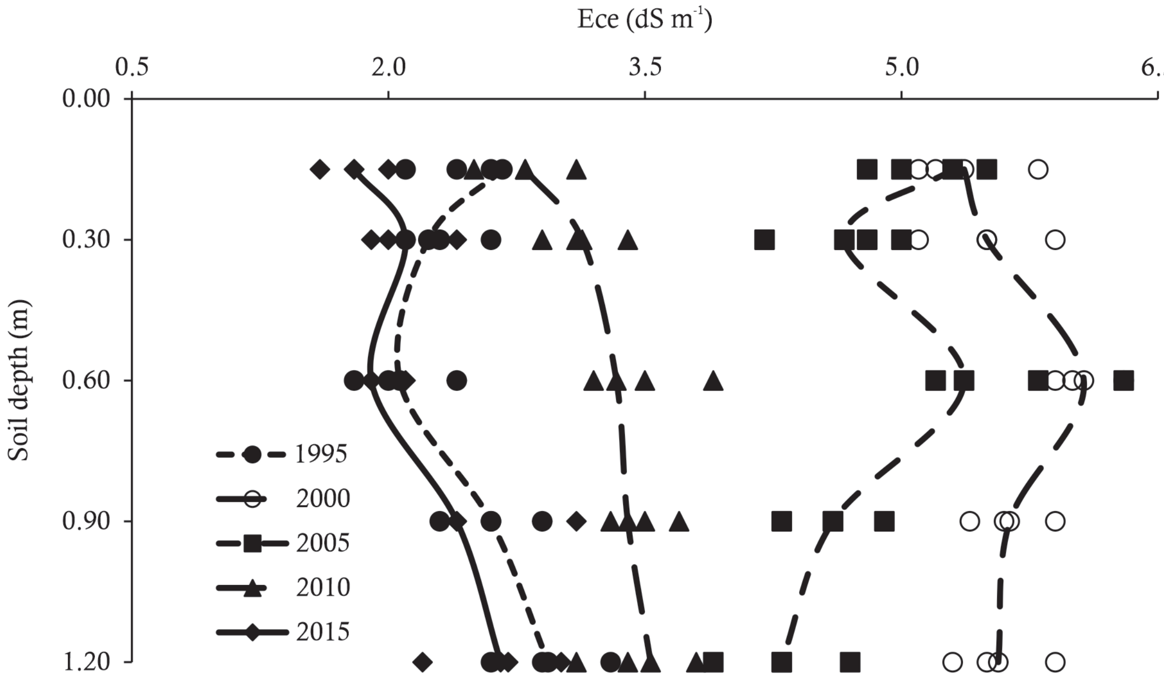

Fig. 3 Soil salinity during different periods of time across the tree plantations. (LSD ($p \leq 0.05$) at 0-0.15, 0.15-0.30, 0.30-0.60, 0.60-0.90 and 0.90-1.20 m depths was 0.53, 0.65, 0.81, 0.58 and 0.72, respectively). Only four values, i.e. two highest and two lowest recorded at specific time and soil depth, were included for simplifying interpretations

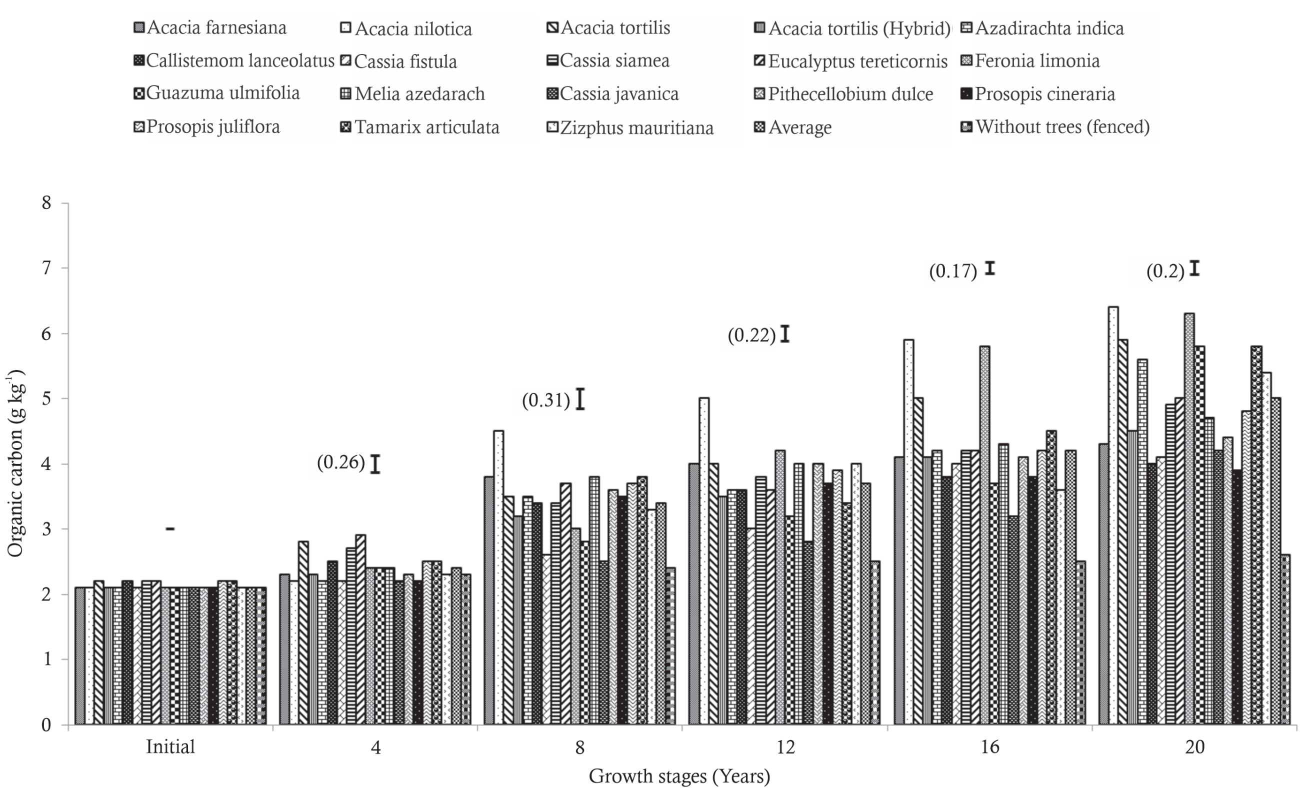

Fig.4 Soil organic carbon (gC kg^{-1} soil) in 30 cm soil layer at successive growth periods of different tree species. The error bars shown are LSD (at confidence level of 0.05) of respective years

Discussion

Sensitivity of tree saplings to water and salt stress during establishment phase, paucity of fresh water and inefficient management of available saline groundwater for irrigation usually result in failure of afforestation programmes in rainfed arid and semi-arid areas underlain with saline groundwater (Armitage, 1984; Barrett-Lennard, 2003; Dagar and Minhas, 2016). Selection of suitable tree species and adoption of efficient pre- and post-management practices, as per the site-specific conditions, are the key factors to success of plantations (Yadav and Dagar, 2016; Yadav *et al*., 2016). Therefore, in present study, tree species were selected on the basis of their tolerance to water and salt stress, and adaptability to monsoon type subtropical semi-arid climatic conditions (Table 1) besides having their economic value in terms of fuel wood, timber, fodder and fruit and medicinal value in some species (Table 3). These results can be applicable in other arid and semi-arid conditions having saline aquifers of ECiw up to 10 dS m^{-1}. Further to improve establishment and performance of trees, the saplings were planted at closer spacing in the sill of furrows and pruned and harvested periodically. Selecting salt and water stress tolerant tree species (Armitage, 1984; Tomar *et al*., 1998; Minhas *et al*., 2015), planting them in sill of furrows (Tomar *et al*., 1998, 2003; Dagar *et al*., 2016b) and using saline groundwater for irrigation in furrows (Minhas *et al*., 1997a, b; Tomar *et al*., 1998, 2003; Dagar *et al*., 2008, 2016b) have been also recorded to improve establishment, growth and biomass production of forestry species under monsoonal semi-arid conditions (Gupta *et al*., 1995; Barrett-Lennard, 2003). Tanwar (2003) reported significant information on management of saline water in irrigation globally but very little information made available on tree cover development.

Although tree species differed in their temporal growth pattern but *Tamarix articulata, Acacia nilotica, A. tortilis*, *A. tortilis* (hybrid), *Prosopis juliflora, Eucalyptus tereticornis, Azadirachta indica* and *Cassia siamea* recorded relatively greater survival, establishment and growth (height, GBH) and total biomass production (391 to 124 Mg ha^{-1}) as most of these have stress tolerant capability (Minhas *et al*., 1998; Hari-Bhagwan and Dagar, 2004; Dagar and Minhas, 2016). Thus, these species could be preferred for success of afforestation on calcareous dry lands underlain with saline groundwater 'the only available source of irrigation'. These species continued to add biomass regularly throughout the study period of 20 years showing their potentiality during stress conditions. Earlier Rogers (1985), Morris *et al*. (1994) and Minhas *et al*. (1998) also observed similar findings for some of the species and thereby implied for the need of long-term trials on evaluating suitability of the tree species to site specific conditions. Species such as *Pithecellobium dulce, Ziziphus mauritiana, Cassia fistula, Melia azaderach, Cassia javanica and Acacia farnesiana* with comparatively lower survival, growth and biomass production (60 to 40 Mg ha^{-1}) ranked second choice for afforestation under these eco-edaphic conditions. But performance of *Feronia limonia, Callistemon lanceolatus, Guazuma ulmifolia* and *Prosopis cineraria* was very poor and were not suitable for afforestation under such situations using saline water for irrigation. Though species such as *P. cineraria* and *Ziziphus mauritiana* have been judged as the boon for dry regions (Dagar, 2018) but could not perform under saline irrigation.

Differences in growth performance of the species tested could be due to variations in their genetic potential and adaptation to prevailing eco-edaphic conditions. Several other workers have also reported species of *Eucalyptus, Prosopis*, *Tamarix*, *Salvadora* and *Casuarina* for afforestation of saline waterlogged soils (Ahmad and Ismail, 1992; Marcar *et al*., 1993; Davidson and Galloway, 1993; Tomar *et al*., 1994, 1998; Barret-Lennard, 2003; Dagar, 2014; Dagar *et al*., 2016a). Further, Garrett (1993), Bowman and Ruprecht (2000), Dagar *et al*. (2001), Singh and Dagar (2005), Dagar *et al*. (2020 a, b) and Banyal *et al*. (2017) have listed some useful trees suitable for dry land salinity. Tolerance of tree species to the interactive effect of salt and water stress has been observed to determine their performance under arid situations where only saline groundwater is available for irrigation (Marcar *et al*., 1993; Dagar and Minhas, 2016; Dagar *et al*., 2016b). Wood *et al*. (1975)

suggested local provenances of *Acacia nilotica*, *A. tortilis*, *Prosopis spicigera* and *Ziziphus spina-christi* for saline water irrigated forestry. Similarly, our results are comparable to Jain *et al.* (1983) who observed that *P. juliflora* and *T. articulata* could tolerate irrigation water salinity of 8 dS m^{-1}.

Water use of different tree species varied markedly during initial period (up to 8 years) till irrigations were supplied, but to lesser extent during later period of growth. Initially, plantation water use varied because of availability of water with irrigations, though saline, which helped the high genetic potential trees to produce more leaf area resulting in more transpiration and thus higher water use. However, the extent of variation in water use of different species decreased during post irrigation cessation period. Since water use is mainly a function of evaporative demand induced by climatic conditions and availability of water; and as both of the factors were similar during post irrigation cessation period, so water use of different species during this period differed to lesser extent. Marcar *et al*. (1993) and Hubbard *et al*. (2010) also reported the positive effects of saline irrigation on growth and water use by *Eucalyptus* trees. Similarly, Dagar *et al*. (2004, 2005, 2006) attributed changes in water use and successful performance of *Salvadora persica*, *Catharanthus roseus*, *Cordia rothii* and *Adhatoda vasica* to saline water irrigation (up to EC 12 dS m^{-1}). *Tamarix articulata* used lesser water (9.79 m) but produced highest WUE of 42.79 Mg m^{-1}. It was followed by *Acacia nilotica, Acacia tortilis, Prosopis juliflora, Eucalyptus tereticornis, Cassia siamea* and *Azadirachta indica*, which produced WUE > 11.55 Mg m^{-1}. Variation in WUE among species was the result of wide variation in their biomass production without any appreciable differences in their water use. Contrary to lesser differences in overall WUE of these species, Tomar *et al*. (2003) observed wide variability in their WUE during initial period of 8 years when saline water irrigation was applied. It may be pointed here that trees with higher WUE along with higher salt and water stress tolerance should be preferred for afforestation of dry land areas because even the saline groundwater resources in these areas are very limited to sustain long-term irrigation requirement of plantations. Moreover, salt input into soil has to be the minimum to ensure a better growth of trees as also reported earlier by Minhas *et al*. (2015) and Yadav *et. al*. (2016).

Soil salinity increased in proportion to the salts added with application of saline irrigations with average salinity in soil profile (up to 1.2 m depth) increasing to 6.8 dS m^{-1} after one year of growth. But after cessation of irrigation, profile salinity consistently decreased <3.0 dS m^{-1} due to leaching of salts with monsoon rains during consecutive years and tree growth. Planting saplings in sill of furrows and irrigating with saline groundwater in furrows that to only during early establishment period minimized the salt load in root zone. Additionally harvesting higher runoff in furrows from inter- row area with concentrated infiltration through furrow sill zone further increased leaching of salts accumulated with saline irrigation as also reported earlier by Tomar *et al*. (2003), Dagar (2014) and Yadav and Dagar (2016). It is pertinent to mention here that based on preliminary observations some results of this experimentation were published by Tomar *et al*. (2003) but to keep continuity of this long-term study those results are mentioned here in this article.

Prosopis juliflora proved the most effective in decreasing ESP and $CaCO_3$ content followed by *Ziziphus mauritiana*, *Acacia nilotica*, *Eucalyptus tereticornis*, *Azadirachta indica* and *Tamarix articulata.* Other species had relatively lesser effect on reduction of these two parameters. In addition to decrease in ESP and $CaCO_3$, all the surviving tree species also increased soil organic carbon. The increase in soil organic carbon (>5.0 g kg^{-1}soil) was observed under *Acacia nilotica, A. tortilis, Azadirachta indica, Eucalyptus tereticornis, Feronia limonia, Tamarix articulata* and *Guazuma ulmifolia* as compared to other species. The effect of tree species on soil organic carbon was more conspicuous in the surface (0.3 m) soil as compared to the lower soil depths. Decrease in soil profile ESP and $CaCO_3$ content and increase in soil organic carbon might be mainly due to dissolution of native $CaCO_3$ with excretion of root exudates, reaction with organic acids produced with decomposition of roots and litter fall and root proliferation activities as observed earlier by Singh and Dagar (2005) and Dagar (2014). Dissolution of native $CaCO_3$ has dual benefits *viz.*, supply of Ca^{2+} for soil exchange complex and nutrition to plantations.

Planting trees on these degraded lands of arid areas would be helpful in augmenting fodder, food, timber and fuel wood. These studies become more significant when we find that due to uncertainty of climate there is frequent failure of annual crops. Tree-based farming systems involving salt-tolerant woody and herbaceous crops including halophytes have better scopes of sustaining agriculture production as is advocated recently by Dagar *et al*. (2024) in their very important contribution on halophytes and also by Minhas and Qadir (2024) who have given a detailed account of irrigation sustainability with saline and alkali waters.

Conclusions

After 20 years of performance, it could be concluded that *Tamarix articulata, Acacia nilotica, A. tortilis*, *A. tortilis* (hybrid), *Prosopis juliflora, Eucalyptus tereticornis* and *Azadirachta indica* performed best in terms of survival, height, GBH and total biomass production and thus are the preferred choice for afforestation of calcareous dry lands with saline groundwater. Most of these have high economic importance in terms of timber, fuel wood, edible gum (*Acacia nilotica*) and medicine (*Azadirechta indica*) and also pulp wood (*Eucalyptus tereticornis*). Many of these species have wider phyto-geographical distribution, especially in dry regions, hence may be planted in other regions across dry climates using saline ground water. Planting tree saplings in sill of furrows and supplementing with saline water [EC ~9.0 dS m^{-1} and SAR ~20 $(mmol\ L^{-1})^{1/2}$] irrigation during initial 3 years created favourable water and salt regimes in root zone for better establishment and growth of trees in such arid and semi-arid areas. These species produced not only biomass (120-390 Mg ha^{-1}), but also improved soil conditions in terms of increase in soil organic carbon and decrease in soil sodicity and calcium precipitation. Thus, growing recommended salt and water stress tolerant tree species with suggested planting and saline water irrigation strategies would help in productive utilization of abandoned degraded calcareous dry lands and improving long-term ecological sustainability of these and similar areas of dry ecologies through enhanced carbon sequestration. These studies become more relevant in the scenario of changed climate when agricultural sustainability is more vulnerable.

Acknowledgements

Authors are grateful to number of anonymous staff members of the Haryana State Forestry Department for their help in carrying out this experiment. In particular, thanks are due to Sultan Singh, initiator of the project, and M. Ram, Mehi Pal, Jeet Ram and P. Singh for supply of seedlings, occasional field help and for showing keen interest in the study. The contribution of V.K. Sharma and Y.P. Singh to take observations during initial stage of experiment and of Raj K. Gupta and N.T. Singh for encouragement and healthy criticism during initial years of experiment is acknowledged. The help rendered by Mr. Brij Mohan, YK Shukla, Hari Bhagwan and Mukesh Kumar in monitoring various growth parameters and analytical work at different periods of time is thankfully acknowledged. Authors are thankful to all Directors of CSSRI, Karnal who extended the facilities from time to time. The study was a part of the project funded by National Wasteland Board, Ministry of Rural Development, Government of India, New Delhi at initial stage.

References

Ahmad R and Ismail S (1992) Studies on selection of salt tolerant plants for food, fodder and fuel from world flora. In: Lieth H and Al Masoom AA (eds) *Towards the Rational Use of High Salinity Tolerant Plants,* Vol. 2: *Agriculture and Forestry Under Marginal Soil Water Conditions.* Kluwer, Academic Publishers, London, pp 295-304.

Armitage FB (1984) *Irrigated Forestry in Arid and Semi-Arid Lands: A Synthesis*. Ottawa, Canada, IDRC, pp 160.

Ayers RS and Westcot DW (1985) *Water Quality for Agriculture*. FAO Irrigation and Drainage paper **29** (1):173

Banyal R, Rajkumar, Kumar M. Yadav RK and Dagar JC (2017) Agroforestry for rehabilitation and sustenance of saline ecologies. In: Dagar JC and Tewari VP (eds) *Agroforestry: Anecdotal to Modern Science.* Springer, Singapore. https://doi.org/10.1007/978-981-10-7650-3_16.

Barrett-Lennard EG (2003) *Saltland Pastures in Australia: A Practical Guide* (2nd ed) Land, Water and Wool-Sustainable Grazing on Saline Lands Sub-Program, State of Western Australia, pp 176.

Bowman S and Ruprecht J (2000) *Blackwood River Catchent Flood Risk Study*. Report No. SWH 29, Surface Water Hydrology Report Séries, Water and Rivers Commission, East Perth, pp 36.

Dagar JC (2014) Greening salty and waterlogged lands through agroforestry systems. In: Dagar, JC, Singh AK and Arunachalam A (eds) *Agroforestry Systems in India: Livelihood Security & Environmental Services-Advances in Agroforestry* Vol 10, Springer Publishers, pp 333-344.

Dagar JC (2018) Utilization of degraded saline habitats and poor-quality waters for livelihood security. *Scho J Food & Nutr*. 1(3)-2018. SJFN.MS.ID.000115.

Dagar JC, Gupta SR and Kumar A (eds) (2024) *Halophytes vis-à-vis Saline Agriculture: Perspectives and Opportunities for Food Security.* Springer Nature Singapore https://doi.org/10.1007/978-981-97-3157-2.

Dagar JC**,** Gupta SR and Teketay D (eds) (2020a) *Agroforestry for Degraded Landscapes: Recent Advances and Challenges.* Vol 1 Springer Nature Singapore Pte Ltd, p 554.

Dagar JC**,** Gupta SR and Teketay D (eds) (2020b) *Agroforestry for Degraded Landscapes: Recent Advances and Challenges* Vol 2. Springer Nature Singapore Pte Ltd, p 475.

Dagar JC, Hari-Bhagwan and Yogesh-Kumar (2004) Effect on growth performance and biochemical contents of *Salvadora persica* when irrigated with water of different salinity. *Indian Journal of Plant Physiology* 9(3):234-238.

Dagar JC, Kumar Y and Tomar OS (2005) Performance of ornamental and medicinal periwinkle under saline environment. *Indian Journal of Horticulture* 62(2):175-180

Dagar JC, Lal K, Mukesh-Kumar, Jeet-Ram, Chaudhari SK, Yadav RK, Singh G, Sharif- Ahamad, and Amarinder-Kaur (2016a) Impact of eucalyptus geometry on biomass production, water table drawdown, carbon sequestration and inter-crop yield on waterlogged saline soils of North-West India. *Agriculture, Ecosystem & Environment* **233**: 33-42.

Dagar JC and Minhas PS (2016) Saline irrigation for productive agroforestry systems. In: Dagar JC and Minhas PS (eds) *Agroforestry for the Management of Waterlogged Saline Soils and Poor-quality Waters, Advances in Agroforestry*13, :145-162 .

Dagar JC and Singh G (2000) Evaluation of fruit tree species for sodicity tolerance. *Indian Journal of Forestry* **23**(4):390-396.

Dagar JC, Singh G and Singh NT (2001) Evaluation of forest and fruit trees used for rehabilitation of semiarid alkali-sodic soils in India. *Arid Land Research & Management* **15**:115-133.

Dagar JC, Tomar OS, Kumar Y, Yadav RK and Tyagi NK (2006) Performance of some under–explored plants under different treatments of saline irrigation in semi-arid climate of northwest India. *Land Degradation & Development* 17:285-299.

Dagar JC, Tomar OS, Minhas PS, Singh G and Jeet-Ram. (2008) *Dryland Biosaline Agriculture –Hisar Experience*. Techanical Bulletin 6: CSSRI, Karnal, pp 28.

Dagar JC, Yadav RK, Tomar OS, Minhas PS, Gajender and Lal K (2016b) Fruit-based agroforestry systems for saline water-irrigated semi-arid hyperthermic camborthids soils of north-west India. *Agroforest Syst* **90**: 1123-1132.

Davidson N and Galloway R (1993) *Productive Use of Saline Land*. ACIAR Proceedings No. 42, Australian Centre for International Agricultural Research, Canberra, pp 123.

Garrett B (1993) Agroforestry for salinity control. In: Race D (ed) *Agroforestry: Trees for Productive Farming*. Daratech Pvt Ltd, East Melbourne, Australia, pp 109-113.

Gomez KA and Gomez AA (1984) *Statistical Procedures for Agricultural Research* (Second Edition). Wiley, New York, USA, 680.

Gupta RK, Tomar OS and Minhas PS (1995) *Managing Salt-affected Soils and Waters for Afforestation,* Bulletin No. 7/95, Central Soil Salinity Research Institute, Karnal, pp 23.

Hari-Bhagwan and Dagar JC (2004) Vegetation ecology of halophytic communities of saline arid regions of North-Western India. *Bulletin of the National Institute of Ecology* **14**: 1-24.

Hubbard RM, Stape JI, Ryan MG, Almieida AC and Rojas J (2010) Effects of irrigation on water use and water use efficiency in two fast growing Eucalyptus plantations. *Forest Ecol Manage* **259**:1714-1721.

Jackson, ML (1967) *Soil Chemical Analysis,* Asia Publishing House, New Delhi, pp 498.

Jain BL, Goyal RS and Muthana.KD (1983) Performance of some tree species in relation to irrigation with saline waters. *Annals of Arid Zone* **22**:233-238.

Koutroulis AG (2019) Dryland changes under different levels of global warming. *Sci. Total Environ* 655: 482–511,

Marcar NE, Craford DE and Leppert PM (1993) The potential of trees for utilization and management of salt affected land. In: Proc Nat: Workshop on *Productive Use of Saline Land.* ACIAR Proc. No. 42, Perth, Western Australia, 1-14 May, Austrailia, pp 17-22.

Minhas PS (1996) Saline water management for irrigation in India. *Agric Water Manage* **30**: 1-24.

Minhas PS and Qadir M (2024) *Irrigation Sustainability with Saline and Alkali Waters. Extent, Impact and Management Guidelines*, pp 305.

Minhas PS, Sharma OP and Patil G (1998) *25 Years of Research on Management of Satt-affected Soils and Use of Saline Water in Agriculture*. Central Soil Salinity Research Institute, Karnal, India, p 220.

Minhas PS, Singh YP, Tomar OS, Gupta RK and Gupta RK (1997a) Saline-water irrigation for the establishment of furrow-planted trees in north-west India. *Agroforestry Systems* **35**:177–186.

Minhas PS, Singh YP, Tomar OS, Gupta RK and Gupta Raj K (1997b) Effect of saline irrigation and its schedules on growth, biomass production and water use by *Acacia nilotica* and *Dalbergia sissoo* in a highly calcareous soil. *J Arid Environments* **36**:181-192.

Minhas PS, Yadav RK, Lal K and Chaturvedi RK (2015) Effect of long-term irrigation with wastewater on growth, biomass production and water use by Eucalyptus (*Eucalyptus tereticornis Sm.*) planted at variable stocking density. *Agricultural Water Management* **152**:151–160.

Morris J, Bickford R and -Collopy J (1994) *Tree and* Res Report *Shrub Performance and Soil Conditions in Plantation Irrigated with Saline Ground Water*. Report No. 357. Dept Conservation and Natural Resource, Victoria, pp 37.

Piper CS (1967) *Soil and Plant Analysis*. Asia Publishing House, New Delhi.

Qureshi RH and Barrett-Lenard EG (1998) *Saline Agriculture for Irrigated Land in Pakistan: A Handbook.* ACIAR Mon No. 50, Canberra, pp 142.

Richards LA (1954) *Diagnosis and Improvement of saline and Alkali Soils.* USDA, Washington D.C.

Rogers AL (1985) Foliar salt in Eucalyptus species*. Australian Forest Research* 15:9-16.

Schofield, N.J. 1992. Tree planting for dryland salinity control in Australia. *Agroforestry Systems* **20**:1-23.

Singh G and Dagar JC (2005) *Greening Sodic Lands: Bichhian Model*. Technical Bulletin No.2/2005. Central Soil Salinity Research Institute, Karnal, India, pp 51.

Singh YP, Mishra VK, Arora S, Dagar JC and Lal K (2022) Restoration of degraded sodic soils through silvipastoral systems in the Indo-Gangetic Plains. *Land Degradation Development,* **33**: 1459-1473

Tanwar BS (2003) *Saline Water Management for Irrigation*. International Commission on Irrigation and Drainage (ICID) New Delhi, India, p 140.

Tomar OS and Yadav JSP (1985) Effect of saline irrigation and fertilizer application on growth of tree seedlings. *Annals of Arid Zone* **24**: 94-100.

Tomar OS and Minhas PS (1998) Afforestation of salt-affected soils. In: Tyagi NK and Minhas PS (eds) *Agricultural Salinity Management in India*. Central Soil Salinity Research Institute, Karnal, pp 453-472.

Tomar OS, Minhas PS and Gupta Raj K (1994) Potentialities for afforestation of waterlogged saline soils. In: Singh P, Pathak PS and Roy MM (eds) *Agroforestry Systems for Degraded Lands.* Oxford and IBH Publishing Co Pvt Ltd, New Delhi, India, pp 111-120.

Tomar OS, Gupta RK and Dagar.JC (1998) Afforestation techniques and evaluation of different tree species for waterlogged saline soils in semiarid tropics. *Arid Soil Research & Rehabilitation* **12**(4):301-316.

Tomar OS, Minhas PS, Sharma VK, Singh YP and Gupta RK (2003) Performance of 31 tree species and soil condition in a plantation established with saline irrigation. *Forest Ecology and Management* **177**:333-346.

Walkley AI and Black A (1934) An examination of digestion method for determining soil organic carbon and a proposed modification of the chromic acid titration method. *Soil Science* **63**:29-38.

Wood PJ, Willens AF and Willens GA (1975) An irrigated plantation project in Abu Dhabi. *Commonwealth Forestry Review* **54**(2):139-146.

Yadav JSP (1991) *Problems and Potentials of Reforestation of Salt Affected Soils of India.* Regional Wood Energy Development Programme in Asia. CGP/RAS/111/ NET Field Document No. 14, Bangkok, FAO, pp 54.

Yadav RK and Dagar JC (2016) Innovations in utilization of poor-quality water for sustainable agricultural production. In: Dagar JC, Sharma PC, Sharma DK and Singh AK (eds*). Innovative Saline Agriculture*. Springer, pp 291-263.

Yadav RK, Minhas PS, Khajanchi-Lal and Dagar JC (2016) Potential of wastewater disposal through tree plantations. In: Dagar JC and Minhas PS (eds). *Agroforestry for the Management of Waterlogged Saline Soils and Poor-quality Waters. Advances in Agroforestry*, vol 13. Springer, New Delhi.

Received: October 20, 2024; Accepted: October 30, 2024

Journal of Soil Salinity and Water Quality 16(2), 307-316, 2024
DOI: https://doi.org/10.56093/jsswq.v16i2.156426

Development of Sensor and Decision Support System (DSS)-based Automated Irrigation System for Enhancing Water Productivity of Tomato Crop

Jitendra Kumar[1]*, Neelam Patel[2], Pramod Kumar Sahoo[3], Susama Sudhishri[4], Rashmi Yadav[5], Sagar Vibhute[1] and Awani Kumar Singh[6]

[1]*Division of Irrigation and Drainage Engineering, ICAR-CSSRI, Karnal-132 001, Haryana, India*
[2]*Knowledge and Innovation Hub (KIH), NITI Aayog, New Delhi-110 001, India*
[3]*Division of Agricultural Engineering, ICAR-IARI, New Delhi-110 012, India*
[4]*Water Technology Centre, ICAR-IARI, New Delhi-110 012, India*
[5]*Guest faculty (Agricultural Engineering), MGUVV, Durg, Chhattisgarh-491 111, India*
[6]*Centre for Protected Cultivation Technology, ICAR-IARI, New Delhi-110 012, India*
**Corresponding author's E-mail: Jitendra.Kumar3@icar.gov.in*

Abstract

In India, given the rising trend of population growth, climate change and the need to increase agricultural production with efficient utilization of water, It is crucial to execute precise water management strategies in the farmland. In this study, efforts were made towards development of an automated system for irrigation scheduling on real-time basis considering the soil moisture conditions and crop parameters, and evaluation of performance under different irrigation methods in tomato crop. The soil moisture sensor was integrated with decision support system (DSS) and microcontroller using internet and global system for mobile communication (GSM) module for automated irrigation. The developed sensor was compared with Frequency Domain Reflectometer (FDR), tensiometer, and watermark sensor and was calibrated using the gravimetric method. The irrigation water productivity of tomato crop ranged from 5.2–12.6 kg m^{-3} for control and 7.7–18.7 kg m^{-3} for automated system under different methods of irrigation. By using an automated drip irrigation system instead of a manually operated check basin irrigation system, cultivators of tomatoes were able to save 39.61% of the water. In terms of economics analysis, highest benefit cost ratio was obtained under manually operated drip irrigation (2.61) followed by automated drip irrigation system (2.50) in tomato crop.

Key words: Automated System, Irrigation scheduling, Soil moisture sensor, Water productivity

Introduction

The burgeoning population of India with increasing food demand along with competing water demand for both urban and environmental needs are leading towards the decrease in the availability of water for agriculture with time. This necessitates the increased efforts in judicious use of irrigation water to fulfil the requirement of crop needs. Adopting precise water application by sprinkler and drip irrigation can lead to higher irrigation efficiency, ranging from 75 to 95 percent (CWC, 2017). Promoting new and broad access to the state-of-art technologies and adopting "more crop per drop" is vital for improving water productivity in the country (Ojha *et al*., 2015). Therefore, precise irrigation water management is the need of the hour (Yadav *et al.,* 2024). The advent of precision irrigation method such as micro irrigation system which includes drip irrigation, sprinkler irrigation, and microjets have played a major role in reducing the water requirement in agricultural and horticultural crops (Marazky *et al*., 2011).

Efforts have been made by many researchers in this direction by using tensiometer for irrigation scheduling in automated irrigation system. The tensiometer is one of the efficient instrument for irrigation scheduling. Significant developmental changes have been done by many researchers over the years in terms of diameter, length, pressure sensing and automation. At IIT Kharagpur, Joshi *et al.* (1999) developed an automatic irrigation controller based on soil moisture. To detect the potential for automated watering, the controller interfaces with a tensiometer that is coupled to a U-tube manometer. An automatic valve for an automated irrigation system was developed (Luthra *et al.,* 1997). This system used a modified manometer to measure the soil water tension, and it used a timer that the user had programmed to operate irrigation at predetermined intervals. Pinmanee *et al.* (2011) developed a tensiometer for scheduling of irrigation and tested under field crops and reported that its reliability in maintaining a favourable moisture regime in soil with higher fruit weight and yield and saving labour costs. Efficient irrigation scheduling using tensiometer based on soil matric potential for enhancing water productivity (Meron *et al.,* 2001; Muoz-Carpena *et al.,* 2005; Dukes and Scholberg, 2005). Similar research was conducted to design a software for sensor network based management of irrigation (Chauhan *et al.,* 2013; Kim *et al.,* 2009; Repullo *et al.,* 2015). DSS based fertigation system was designed and developed for criterial selection of scheduling of fertigation based on plant needs (Xin *et al.,* 1995). Automated irrigation system monitoring status of soil and plant using sensor which integrated with decision support advisories and control irrigation application as per crop needs. The extension of automation system for irrigation in India are very limited and not much popularize among the farmers due to high cost and required technical skills for its monitoring in Indian conditions. Thus, research is needed to develop an automated irrigation system that may turn on the irrigation when the soil moisture content reached at threshold point and option to set predetermined limit using sensor and simplicity nature of operation. Thus, an effort was undertaken to create an indigenous automated irrigation system for real-time irrigation monitoring to bridge the gap between conventional irrigation system and need based irrigation system for enhancing water productivity.

Material and Methods

Basic properties of soil at site

The experiments were conducted in the Precision Farming Development Centre (PFDC), Water Technology Centre, and ICAR-Indian Agricultural Research Institute (IARI) in New Delhi, India, as seen in Fig. 1. In order to characterise the soil, soil samples were taken using a soil auger from various depths, including 0–20

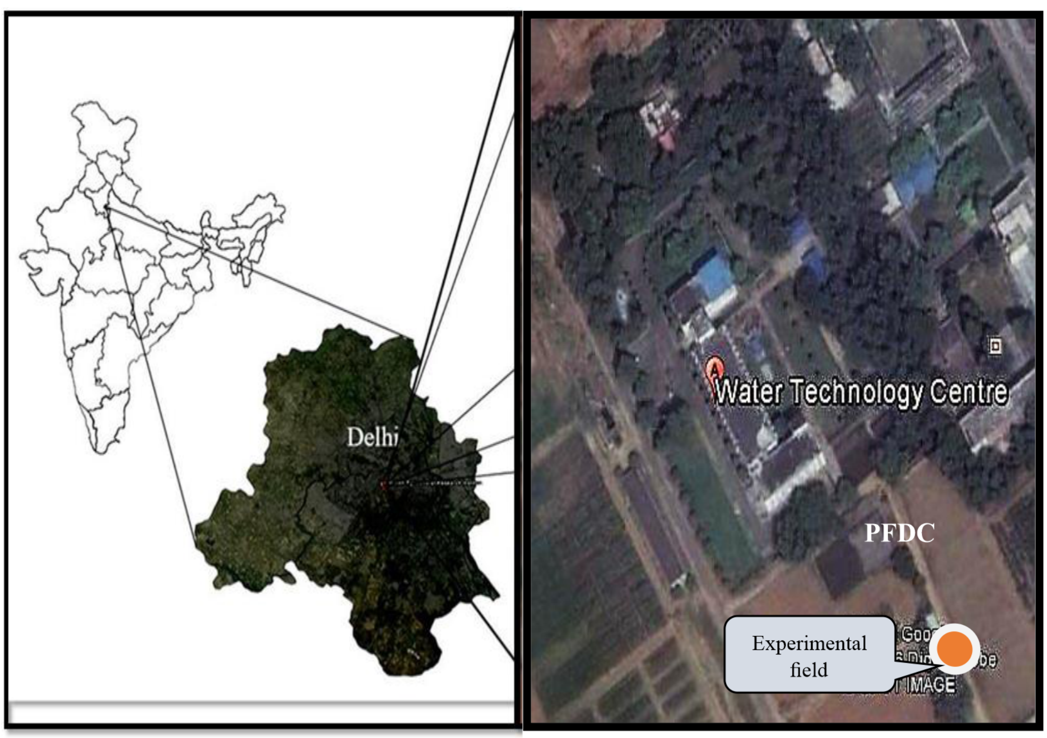

Fig. 1 Location map of experimental area

cm, 20–30 cm, 30-45 cm, and 45–60 cm. Sand, silt, and clay had average values of 69.1%, 13.15%, and 17.78%, respectively, in the sandy loam soil of the experimental region. The soil bulk density was 1.56 g cm^{-3}, and the saturated hydraulic conductivity was 1.17 cm h^{-1} (Table 1). The pH and EC of the soil was 7.14 and 0.1325 dS m^{-1}, respectively. The available nitrogen, phosphorous and potassium in experimental plot were 72.8, 11.3 and 131.3 kg ha^{-1} respectively. The soil was medium in organic carbon, low in nitrogen and medium in available phosphorus and potassium.

Assessment of crop water requirement

The Penman-Monteith semi-empirical method was used to estimate the water requirement for the tomato crop based on reference crop evapotranspiration (ETo) programmed in decision support system. Tomato (*Lycopersicum esculentum var. Pusa rohini)* was chosen for a 150-day field experiment and split into four growth stages: 30 days for the early stage, 40 days for the development stage, 45 days for the mid-season, and 35 days for the late-season. According to Allen *et al*. (1998), the crop coefficient values for the early, development, mid-season, and late stages were 0.60, 0.90, 1.20, and 0.90, respectively. These values were given as crop information in the webpage of decision support system. The automated weather station, which is close to the trial location, provided the necessary meteorological data, including minimum and maximum temperatures, rainfall, daylight hours, wind speed, etc. Based on crop growth phases, the crop evapotranspiration ($ET_c = ET_o \times K_c$) for each month was calculated by multiplying the crop coefficient (K_c) by the reference evapotranspiration (ET_o). The estimation of water requirement and pumping time was estimated using formulas (eq 1-6) programmed in decision support system.

The time of irrigation for operating the drip system per application was calculated as per equation (7-9):

$$\text{Irrigation water requirement} = \frac{ET_0 \times Kc \times \text{Crop area} \times \text{Wetted area}}{\text{Efficiency of drip irrigation}} \quad \ldots(1)$$

$$\text{Total no. of emitter per lateral (TEL)} = \frac{\text{Total length of lateral (m)}}{\text{Spacing of emitter along lateral (m)}} \quad \ldots(2)$$

$$\text{Total no. of lateral per sub main line (TLSm)} = \frac{\text{Total length of submain line (m)}}{\text{Spacing of lateral along the submain line (m)}} \quad \ldots(3)$$

Area cover by submain at specific plot (sq. m) =

$$\frac{\text{Spacing of lateral along the submain line (m)} \times \text{Spacing of emitter along lateral (m)} \times TEL \times TLSm}{100 \times \text{Number of emitter per plant}} \quad \ldots(4)$$

Time taken to irrigate at specific plot (hours) =

$$\frac{ET_0 \times Kc \times \text{Crop area} \times \text{Wetted area} \times 1000}{\text{Discharge rate of one emitter (lph)} \times \text{total no. of emitter per lateral} \times TLSm \times \text{efficiency of drip irrigation}} \quad \ldots(5)$$

Total time taken to irrigate the given area (hours) =

$$\text{Total time to irrigate at specific plot} \times \frac{\text{Total cropped area}}{\text{Area covered by submain at specific plot}} \quad \ldots(6)$$

Irrigation time (hours) =

$$\frac{\text{Crop evapotranspiration} \times \text{Area covered by one lateral}}{\text{Efficiency of drip irrigation system} \times \text{Discharge of each emitter (lph)} \times \text{no. of emitter per lateral}} \quad \ldots(7)$$

$$\text{Discharge capacity of pump (lps)} = 2780 \times \frac{\text{Area to be irrigated (ha)} \times \text{Net depth of water application (cm)}}{\text{Total day required for one irrigation} \times \text{Operating hours in a day} \times \text{Water application efficiency}} \quad ...(8)$$

$$\text{Motor horse power (hp)} = \frac{\text{Discharge capacity of pump (lps)} \times \text{Total head required at the pump (m)}}{75 \times \text{Pump efficiency (in fraction)}} \quad ...(9)$$

Table 1. Physical properties of soil

Depth (cm)	Particle size distribution: Clay (%)	Silt (%)	Sand (%)	Textural class	Hydraulic conductivity ($cm\ h^{-1}$)	Bulk density ($gm\ cm^{-3}$)	Field capacity (%)	Wilting point (%)
0-20	15.3	13.1	71.6	Sandy loam	1.28	1.52	21.78	7.81
20-30	17.5	13.5	69	Sandy loam	1.33	1.61	25.69	9.35
30-45	18.9	12.7	68.4	Sandy loam	0.93	1.54	26.33	11.72
45-60	19.4	13.3	67.3	Sandy loam	1.15	1.57	28.31	12.83

Results and Discussion

Development of soil moisture sensor for irrigation scheduling

The sensor development for soil moisture measurement was done by modifying the tensiometer components and interface with micro controller for management of irrigation on real time basis. Efforts have been made to detect threshold point of water column inside tensiometer by using capacitance sensor. Identifying the threshold point for positioning the capacitance sensor within the acrylic pipe of the tensiometer could be a promising approach for regulating irrigation under soil moisture deficit conditions.

The rate at which the water column rises and falls in the modified tensiometer was adopted for measuring moisture content of the soil which comprises of sensing variation in water level using level sensor, conversion of the capacitance sensed value to electromagnetic signal, analysis and computation of received data and precise irrigation scheduling in field remotely. This system has option to control supply of irrigation at the pre-defined soil moisture content and programmed timer by the user. Irrigation starts when the height of water column is lower than the pre-set lower limit, and stops when it reaches set upper limit of soil moisture content or duration of irrigation completed which was programmed in timer.

The developed system consisted of sensor, a hardware input/output (interfacing circuit), a GSM transmitter and receiver and drip head works. The developed system had an alternative of SMS based and soil moisture based irrigation scheduling. Under SMS based irrigation scheduling, there were two alternatives of operating irrigation either at regular time interval or at particular date and time. User could also turn on/off the irrigation pump and valve using GSM based technology. The soil moisture sensor was developed using indigenously available material including electronic components and its easy way to assembled and installation in field. Therefore, farmers could use this system for efficient irrigation scheduling and enhancing water productivity. The characteristic curve of the modified tensiometer calibrated with gravimetric method was compared with frequency domain reflectometry (FDR), tensiometer, and watermark sensor. The results showed that the performance of the developed system was satisfactory for efficient management of irrigation. The developed sensor with control unit can be proposed to be in several commercial agricultural production systems in country because of its reasonable cost (Rs. 13,500/unit) and reliable operation.

Performance evaluation of soil moisture sensor

A 21 m × 21 m size of plot selected for performance evaluation of the designed system at site. The plots were kept apart from one another by a buffer strip of 1.0 m. The field layout was prepared in split plot design and tomato crop grown under three irrigation methods *i.e.* check basin, furrow and drip irrigation. The three plots were irrigated through manual control and remaining three were controlled by sensor based automated system. In each plot, soil moisture sensor developed by modification of tensiometer was installed for irrigation scheduling. The developed sensors were tested in field plot irrigated with electric motor driven irrigation pump. The modified tensiometer had the potential to improve water productivity by maintaining soil moisture at the threshold level. It was observed that average depth of water column for installation of level sensor in modified tensiometer was 26-30 cm at 20 cm soil depth and 24-28 cm at 30 cm soil depth in tomato crop at 50% MAD value of field capacity under different irrigation methods. This might be due to the variation of soil texture, physiological characteristics of crop, its growth stage, different ground coverage, stomatal variation and seasonal effects. Moreover, irrigation method also had an influence on the water column of modified tensiometer. Water level fluctuation in soil moisture sensor provides a rapid visual means of observing trends in soil moisture as inclined by rainfall and irrigation application. However, a certain degree of training and experience is required to determine the set of level sensors inside the modified tensiometer. Sensor site is highly significant for soil moisture monitoring. Some factors to be considered are location of the dripper, depth of installation, soil variability and topography. Therefore, a precise setting point of level sensor was determined and tested under different crops and soil moisture deficit conditions.

The probable explanation lies in the lower irrigation frequency and higher initial moisture content in the check basin compared to furrow and drip systems. However, each irrigation in the check basin involved a larger water volume, resulting in a significant amount of water eventually moving beyond the root zone. The justification might be due to more percolation losses due to gravity force. The moisture content at 30 cm depth was considerably more than 20 cm depth, therefore, suction range was less at the same depth. The layout of developed system for automated irrigation is shown in Fig. 2.

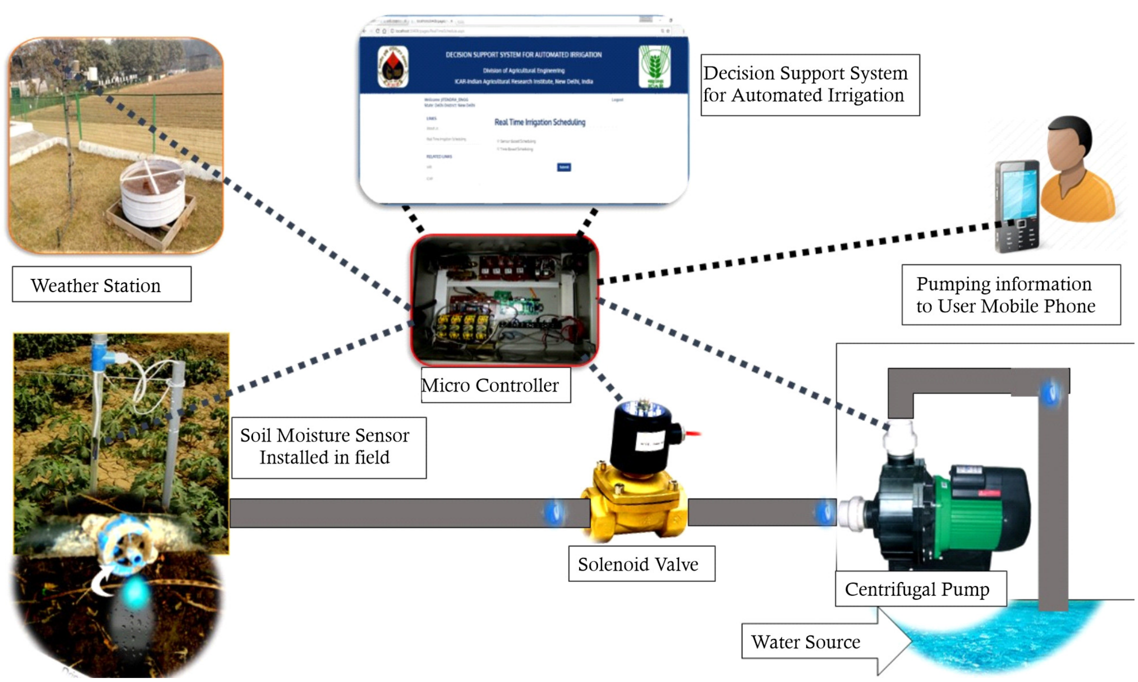

Fig. 2 Layout of automated system for efficient irrigation management

Webpage of decision support system (DSS) for automated irrigation

The DSS was developed under ASP.NET programming language and different database of soil, crop, irrigation information were developed in Microsoft SQL server 2008. The decision support system was designed for irrigation scheduling either on time basis or/on soil moisture sensor basis as shown in Fig. 2. In context of estimation of irrigation scheduling, user feeds input parameters such as area, soil, crop and irrigation information and weather information acquired from weather station installed at experimental field of PFDC, WTC, IARI, New Delhi. After taking values from selected database and dynamic weather information, the output results were obtained as crop water requirement and pumping time under different methods of irrigation. In sensor based irrigation scheduling, user uses same procedure as time based but user has to feed input parameters such as MAD value of available water and code of installed soil moisture sensor at which sub plot irrigation is to be done.

Fig. 3 shows the association between water column and water content of soil in tomato crop under different methods of irrigation at 20 cm and 30 cm depth, respectively. The coefficient of determination (R^2) ranged from 0.83-0.82, and 0.76 for the relation between water column and soil moisture content measured by gravimetric method and FDR, respectively. Slight variation of water column range between 26-30 cm, was observed at 20 cm depth and 24-28 cm at 30 cm depth, respectively. The relationship between water column along with soil water potential was

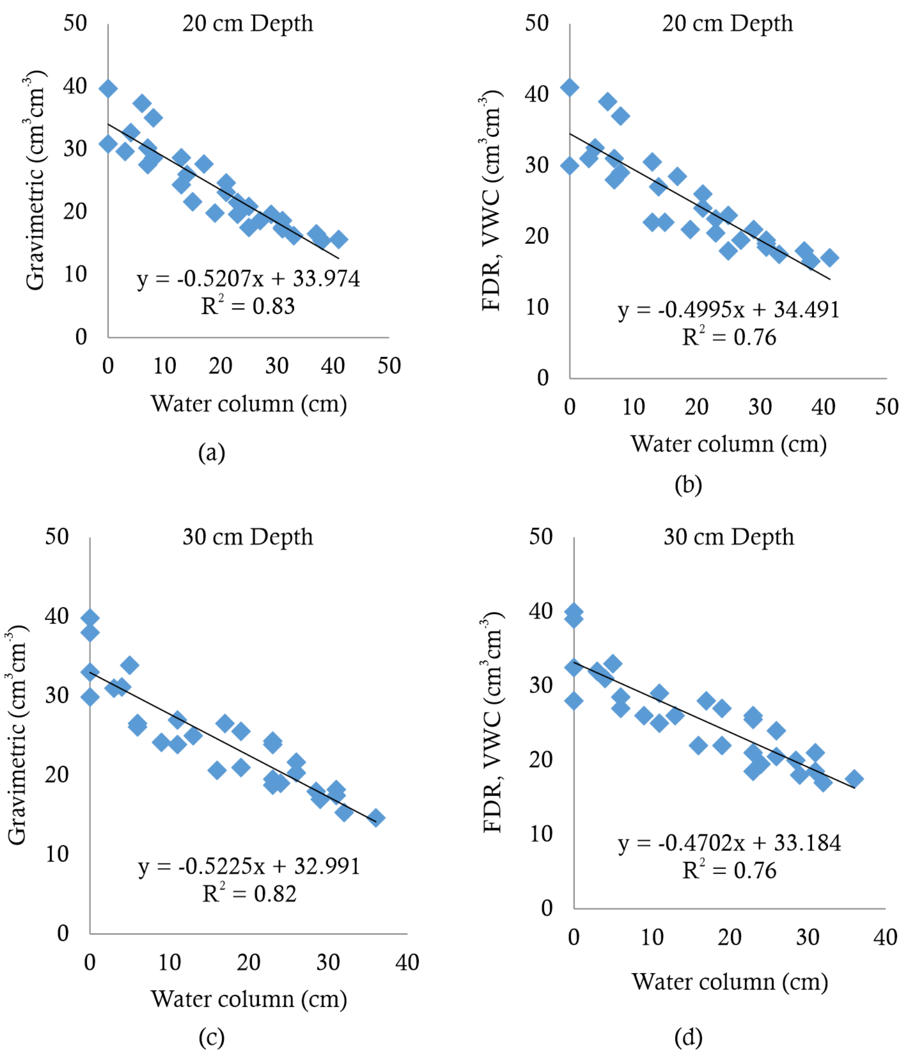

Fig. 3 Relationship between water column of modified tensiometer in tomato crop with (a) Gravimetric method (GM) at 20 cm soil depth (b) Frequency Domain Reflectometer (FDR) at 20 cm soil depth (c) GM at 30 cm soil depth (d) FDR at 30 cm soil depth.

measured by tensiometer and watermark, respectively in tomato crop as shown in Fig. 4. The coefficient of determination ranged from 0.94-0.90 and 0.91-0.82 using tensiometer and watermark at 20 cm and 30 cm depths, respectively. Slight variation of soil water suction was found to be approximately 29 centibar and 36 kPa at 20 cm depth and 30 centibar and 37 kPa at 30 cm depth respectively.

Remote control of irrigation pump using GSM module

The transfer of information regarding the status of soil moisture content in the field was the most important factor using GSM and SMS technologies. Once the transmitter/receiver receives data from all the sensor nodes, It develops a database to organize the data and then an SMS would be triggered and sent via GSM modem through the cellular network to the user's mobile phone. GSM technology has a wide range of coverage and provides advantages over the other technologies. The SMS technology used in the experiment provided an efficient information delivery service to the user. Car *et al.* (2007 & 2012) suggested an alternative option of getting efficient irrigation informatics using Short message service (SMS) for improving water use efficiency. The micro controller receive command from sensor based on moisture content present in soil and perform the preset necessary control operations i.e. switch on/off the solenoid valve and pump simultaneously. Similar research to improve the performance of soil moisture sensor was carried out by few researchers (Al Smadi, 2011; Zotarelli

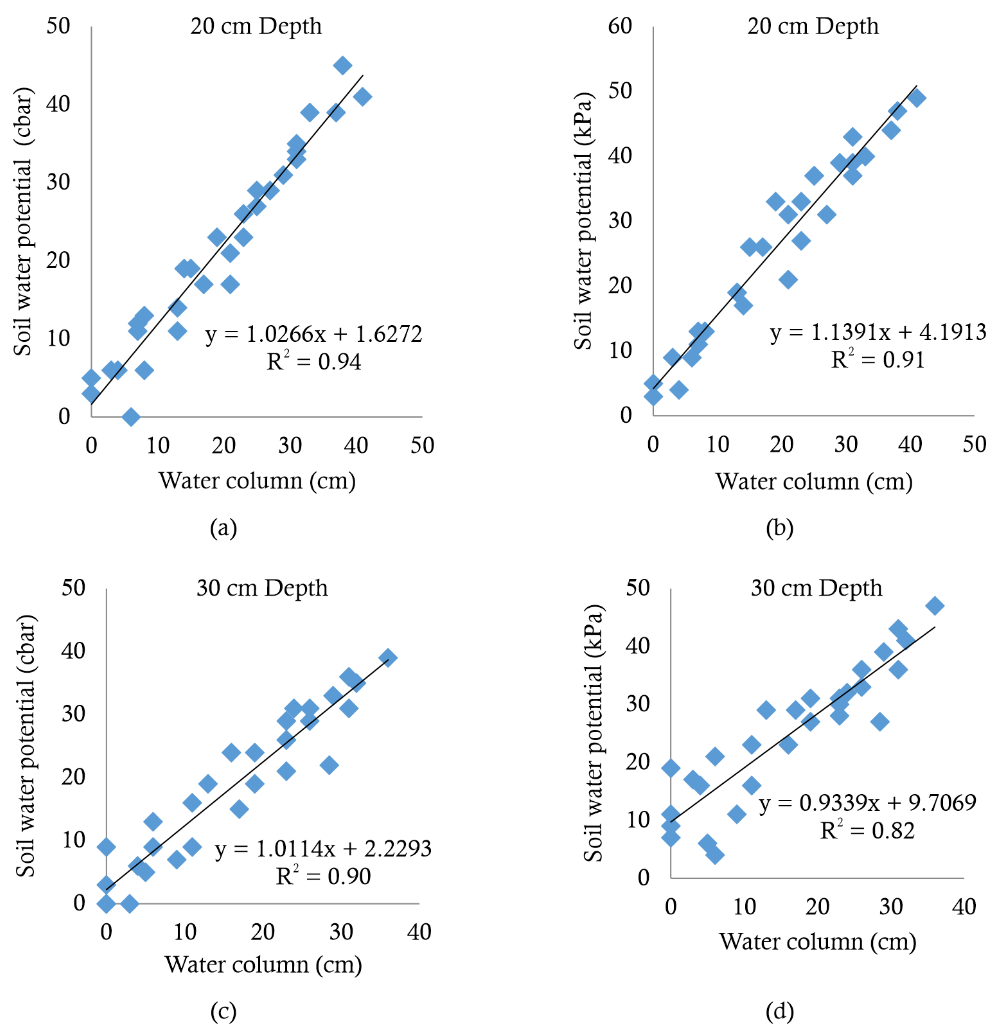

Fig. 4 Relationship between water column of modified tensiometer in tomato crop with (a) Tensiometer at 20 cm soil depth (b) Watermark at 20 cm soil depth (c) Tensiometer at 30 cm soil depth (d) Watermark at 30 cm soil depth

Table 2. Crop evapotranspiration and water productivity of tomato crop under different methods of irrigation

Crop Name	ET_c (mm)	Effective rainfall (mm)	Method of irrigation	Irrigation water productivity ($kg\ m^{-3}$)		Crop water productivity ($kg\ m^{-3}$)	
				Control irrigation	Automated irrigation	Control irrigation	Automated irrigation
Tomato	446.0	217.6	Check basin	5.2	7.7	5.4	7.0
			Furrow irrigation	6.8	9.0	6.4	7.9
			Drip irrigation	12.6	18.7	9.3	11.6

et al., 2009; Cardenas-Lailhacar and Dukes, 2010).

Water productivity and cost economics of tomato crop

Water productivity may be defined as the ratio of crop yield to the amount of water utilised per unit of crop growth. As shown in Table 2, the irrigation water productivity and crop water productivity of the tomato crop were determined in this study under irrigation techniques, including check basin, furrow and drip irrigation, with both manual and automated control systems.

Crop water productivity of tomato crop ranged from 5.4 kg m^3 to 11.6 kg m^3, whereas irrigation water productivity varied from 5.2 kg m^{-3} to 18.7 kg^{-3} under manual and automated operated irrigation methods i.e. check basin, furrow and drip system as shown in Table 2. Zhou

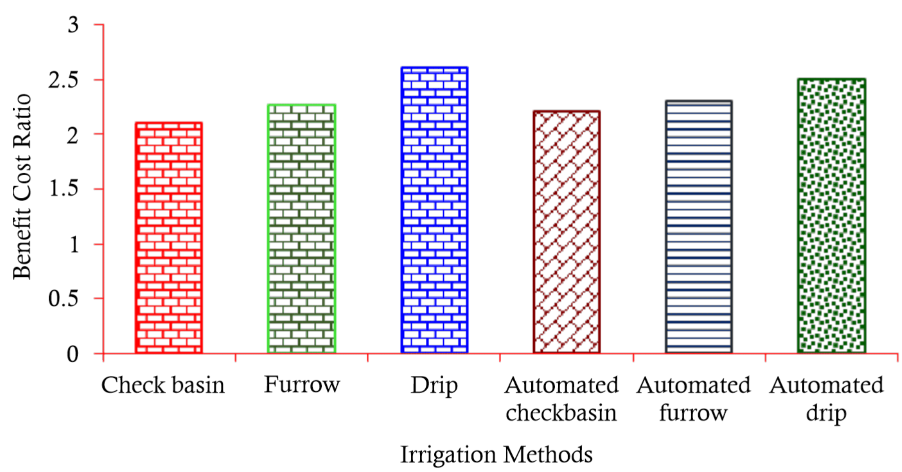

Fig. 5 Benefit cost ratio under different irrigation methods in tomato crop for 1 ha area

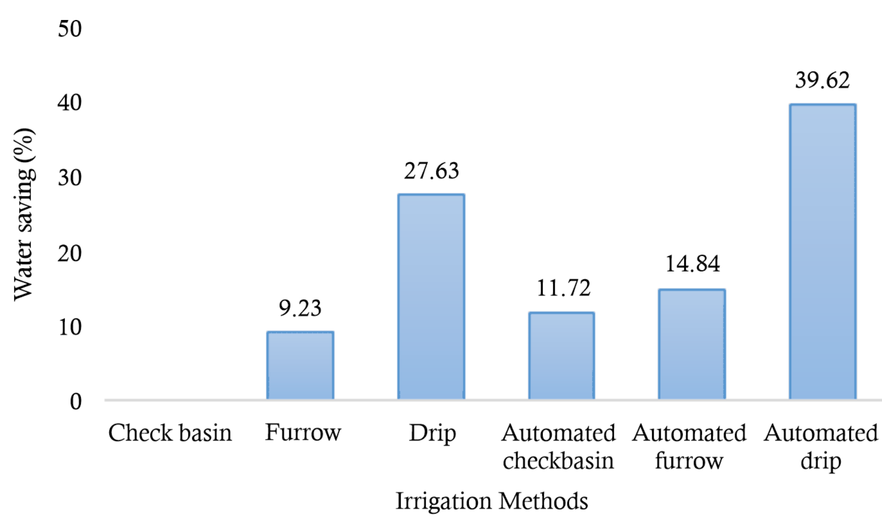

Fig. 6 Water saving under different irrigation methods in tomato crop for 1 ha area

(2010) reported similar findings, which indicated that, greater yields with equivalent level of water extraction consequently resulted in greater CWP and IWP. In case of crop water productivity, two combinations were found non-significant, first one between automated and manual drip and, second one between automated check basin and automated furrow irrigation. The treatment mean of irrigation water productivity was found to be significant with each other in case of tomato crop. The crop water productivity under automated drip was not significant with manual drip system. However, it was significant over other treatments. CWP of automated furrow irrigation was significant over manual furrow irrigation. However, this treatment was not statistically significant with automated check. In case of automated check and manual check, the value of CWP was found significant. The manual drip irrigation system achieved the highest benefit-cost ratio of 2.61, while the automated drip irrigation method resulted in the greatest water savings of 39.62% compared to manual check basin irrigation for tomato cultivation.

Conclusions

The automated irrigation system is the need of hour to enhancing agricultural water productivity and water saving for future use. This study focused on development of sensor based automated system for real time irrigation scheduling and enhancing water productivity. The developed sensor control water application according to crop demand and/or preset soil moisture content, and DSS assisted to estimate crop water requirement and pumping time under different irrigation methods. The water column attained under developed sensor was calibrated with the soil water content data acquired by gravimetric method and same was compared with FDR, watermark and tensiometer derived volumetric water content. The benefit cost ratios (2.5) and highest water saving (39%) obtained under automated drip system compared with check basin irrigation. Therefore, even though the initial cost of a drip irrigation system is high, it may be decided to invest in sensor-based automated irrigation for major agricultural crops in order to achieve optimal production and maximum returns while saving water, energy, and labour costs in comparison to conventional irrigation systems. This technology makes sure that efficient irrigation scheduling on real time basis considering a set of soil moisture, weather parameters and plant demand which eliminates the need for frequent farm visits of users.

Acknowledgements

The authors wish to acknowledge the support and guidance given by the faculty of Division of Agricultural Engineering, Water Technology Centre and Post Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, for assistance in experimental work.

References

Allen RG, Pereira LS, Raes D and Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper no. 56 Rome, Italy.

AL-Smadi TA (2011) Low cost smart sensor design. *American Journal of Engineering and Applied Sciences* **4**(1): 162-168.

Car NJ, Christen EW, Hornbuckle, JW and Moore GA (2012) Using a mobile phone short messaging service (SMS) for irrigation scheduling in Australia– farmer's participation and utility evaluation. *Computer and Electronics in Agriculture* **84**:132-143.

Car NJ, Moore G, Christen EW, Hornbuckle JW and Bartlett C (2007) Tool for improving water use efficiency: irrigation informatics implemented via SMS. *International Congress on Modeling and Simulation*. Modeling and Simulation Society of Australia and New Zealand. University of Melbourne, Victoria. ISBN: 978-0-9758400-4-7. pp 135-141

Cardenas-Lailhacar B and Dukes MD (2010) Precision of soil moisture sensor irrigation controllers under field conditions. *Agricultural Water Management* **97**: 666-672.

Central Water Commission (2017) Water and Related Statistics. (Available at: http://www.cwc.nic.in).

Chauhan YS, Wright GC, Holzworth D, Rachaputi RCN and Payero JO (2013) AQUAMAN: a web-based decision support system for irrigation scheduling in peanuts. *Irrigation Science* **31**: 271-283.

Dukes MD and Scholberg JM (2005) Soil moisture controlled subsurface drip irrigation on sandy soils. *Applied Engineering in Agriculture* **21**(1): 89-101.

Joshi A, Tiwari KN and Banerjee S (1999) Automated Irrigation controller Patent Application No. 6/Cal/99 dated 04-1-1999, IIT Kharagpur.

Kim Y and Evans RG (2009) Software design for wireless sensor-based site-specific irrigation. *Computers and Electronics in Agriculture* **66**: 159-165.

Luthra SK, Kaledhonkar MJ, Singh OP and Tyagi NK (1997) Design and development of an auto-irrigation system. *Agricultural Water Management* **33**:169-181.

Marazky MSAE, Mohammad FD and Al-Ghobari HM (2011) Evaluation of soil moisture sensors under intelligent irrigation systems for economical in arid regions. *American Journal of Agricultural and Biological Sciences* **6**(2): 287-300.

Meron M, Hallel R, Bravdo R and Wallach R (2001) Tensiometer actuated automatic micro irrigation of apples. *Acta Horticulturae* **562**: 63-69.

Munoz-Carpena R, Dukes MD, Yuncong CLi and Klassen W (2005) Field comparision of tensiometer and granular matrix sensor automatic drip irrigation on tomato. *HortTechnology* **15**: 584-590.

Ojha T, Mishra S and Raghuwanshi NS (2015) Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges. *Computer and Electronics in Agriculture* **118**: 66-84.

Pinmanee S, Spreer W, Spohrer K, Ongprasert S and Müller J (2011) Development of a low-cost Tensiometer driven irrigation control unit and evaluation of its suitability for irrigation of lychee trees in the uplands of Northern Thailand in a participatory approach, *Journal of Horticulture and Forestry* **3**: 226-230.

Repullo JAV, Penalver LRP, Buendia MJ, Rosillo JJ and Martinez JMM 2015. Software for the automatic control of irrigation using weighing-drainage lysimeters. *Agricultural Water Management* **151**: 4-12.

Xin JN, Zazueta FS, Smajstrla AG and Wheaton TA (1995) Real time expert system for citrus micro irrigation management. *Proceedings of the 5th International Microirrigation Congress,* 2-6 April at Orlando, **pp** 787-91.

Yadav R, Kushwah A, Sangeeta Soren J, Ganachari H and Singh I (2024) Innovative Module Design for Advanced Automated Irrigation Systems. *Journal of Scientific Research and Reports* **30**(5): 547–555

Zhou Q, Kang S, Zhang L and Li L (2007) Comparison of APRI and Hydrus-2D models to simulate soil water dynamics in a vineyard under alternate partial root zone drip irrigation. *Plant and Soil* **291**: 211-223.

Zotarelli L, Scholberg JM, Dukes MD, Munoz-Carpena R and Icerman J (2009) Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. *Agricultural Water Management* **96**: 23-34.

Received: September 12, 2024; Accepted: October 14, 2024

Application Form for Life/Annual/Associate/Institutional Membership*

Indian Society of Soil Salinity and Water Quality

(Registered under Societies Act. XXI of 1860)

(Registration No. ROS-088, Dated : 6-8-2008)

Registered Office: Central Soil Salinity Research Institute; Zarifa Farm, Karnal-132001, Haryana, India

1. Name of the Applicant ______________________________
   (In Block Letters) (Surname) (First name) (Middle name)
2. Designation or Position: ______________________________
3. Name & Address of the Organisation: ______________________________
   ____
4. Mailing Address : ______________________________
   ____

Telephone No. (Prefix ISD/STD code) Office : ______________ Residence : ______________

Fax: ______________ Mobile : ______________ Email: ______________

5. Permanent Address : ______________________________
   ____
6. Date of Birth : ______________ Nationality: ______________
7. Academic Qualifications: ______________________________
8. Field of Specialization: ______________________________

I/We hereby apply for Life/Annual/Associate/Institutional Membership of the Indian Society of Soil Salinity and Water Quality. The details of the Demand Draft are as follows:

Demand Draft No. ______________ Drawn on Bank ______________

Dated ______________ Amount Rs. ______________

I/We testify that the above statements are correct and agree that if admitted. I/we shall be governed by the Rules and Regulations of the Indian Society of Soil Salinity and Water Quality as long as I am /we are member(s). I/we further agree to promote the objectives of the society as far as shall be within my/our power and that, if my/our membership is discontinued, I/we shall return any means of new membership identification I/we may have received from the society and remit upon resignation any unpaid fees or dues owing to the society. I/we further undertake to abide by either professional conduct rule or code that the Society may frame from time to time. **(Strike through which are not applicable)**

Date ______________ Signature of the Applicant

Category of Membership*	Subscription Rate		Admission fee (only one time)	
	Inland (₹)	Foreign($)	Inland(₹)	Foreign ($)
Life Member	4,000	250	50	-
Annual Member	450	50	50	-
Student Member (for one year)	250	25	50	-
Institutional Members (Lump sum for 30 years)	25,000	-	-	-
Institutional Members (Annual)	3,500	-	-	

DD/Cheques (Crossed) are payable to "Indian Society of Soil Salinity and Water Quality" Karnal. Please add Rs. 100/- for outstation cheques.

Please mail the completed form along with remittance bank draft/local cheque to: **Dr. Gajender Yadav, General Secretary, Indian Society of Soil Salinity and Water Quality, Central Soil Salinity Research Institute, Zarifa Farm, Kachhwa Road, Karnal-132001, Haryana, India**

Tel: +91 -184-2209380,2209310 (O); Fax: +91-184-2290480; E-mail: salinitysocietykarnal@gmail.com; gajender.icar@gmail.com

For Office use only

Proposed by :

Seconded by: Admitted on General Secretary