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CONTENTS

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Diagnosis, Classification and Management of Black Sodic Soils of Indian Deccan: An Overview

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Abstract

Black sodic soils pose a significant challenge in agricultural production, particularly in arid and semi-arid regions where high sodium content degrades soil structure and fertility. These soils suffer from nutrient deficiencies such as iron, manganese, zinc, copper, and phosphorus, along with poor physical properties, and increased susceptibility to erosion, leading to reduced crop productivity and economic losses. Sodicity is exacerbated by poor irrigation practices and the rising demand for water. This review explores the characteristics, diagnosis, and classification of black sodic soils, alongside strategies for their sustainable management, focusing on amelioration techniques such as the use of soil amendments and organic materials. This review highlights critical insights into the diagnosis, classification, and sustainable management practices of black sodic soils in the Indian Deccan, emphasizing the unique challenges and solutions pertinent to Southern Indian Vertisols.

Key words: Black sodic soils, crop productivity, nutrient deficiencies, organic materials, sodic soil classification, soil amelioration, soil amendments, soil degradation, soil diagnosis, soil fertility, soil sodicity

Black (swell-shrink) sodic soils

Black soils, oftenly referred to swell-shrink or cracking clay soils including Vertisols and their intergrades , are prevalent in multiple regions worldwide. In Indian landscape, these soils found in extensive areas of 72.9 million hectares (Mha) (Murthy *et al.,* 1982), primarily located in the low-lying piedmont areas, valleys, and micro-depressions, which from the alluvial sediments resulting from the weathering of Deccan basalt. In Peninsular India, naturally degraded black sodic Vertisols, impacted by subsoil sodicity from pedogenic processes, suffer structural and hydraulic issues due to pedogenic calcium carbonate (Pal *et al.*, 2006). Concentrated in states like Maharashtra and Gujarat, about 3.77 million hectares in India are affected by sodicity, with Maharashtra accounting for 36% of Vertisol areas impacted by high sodium and specific clay minerals (Mohanapriya *et al.,* 2022). The Purna Valley in Maharashtra (4.49 lakh hectares) is especially notable for its inherent sodicity (Bhowate and Bansod, 2017). Sodic soils, characterized by high sodium content, are especially problematic for agriculture, as they deteriorate in structure, suffer from poor aeration, unfavorable water to air ratios, and have unstable aggregates. This makes them prone to runoff, erosion, and ultimately, loss of fertility (Levy and Nachshon, 2022). The physical properties of these soils, including their cracking behavior during dry periods and swelling when wet, further complicate their management, particularly in regions with distinct wet and dry seasons. These properties are not only inherent but also intensified by poor management practices and the increasing use of effluents rich in sodium or utilization of brackish water for irrigation practices (Levy and Nachshon, 2022).

Globally, alkali soils occupy 581 million hectares (Shin *et al.,* 2016), a number that is expected to rise due to increasing food production demands and the growing need for good quality water. This competition for water between agricultural, urban, and industrial sectors often results in the allocation of poor-quality irrigation water, which worsens sodicity. In India, nearly 46% of the land is classified as degraded (Katyal, 2012), with salinization and alkalization affecting over 10 million hectares (Suri, 2007). Particularly troubling is the 6.7 million hectares of salt-affected soils concentrated in states like Uttar Pradesh, Gujarat, and Maharashtra, where sodicity is a major issue. These sodic soils are defined by a high concentration of sodium on cation exchange sites, which causes clay dispersion and weakens the soil's structural stability. This reduces the soil's capacity to absorb and retain water, leading to hard setting and the formation of soil crusts after drying (Amezketa *et al.*, 2005).

The processes contributing to sodic soil degradation-such as clay dispersion and decreased hydraulic conductivity-result in reduced water movement and poor leaching of sodium (Awedat *et al.*, 2021). This contributes to further erosion and makes it difficult to restore soil health. However, the structural degradation of sodic soils can be addressed through understanding the key processes that stabilize aggregates and reduce clay dispersion. Moreover, wetting and drying cycles-common in arid regions-can induce intense changes in Vertisols, especially those dominated by smectitic clays (Utomo and Dexter, 1982). These cycles cause shrink-swell behavior, leading to the term "self-mulching soils" (Pal *et al.*, 2012). These soils formed during wetter climatic periods, and the drying conditions of the Holocene led to the emergence of the distinctive cracking soils that shape much of India's agricultural landscape (Pal *et al.*, 2001; Pal *et al.*, 2006). However, what makes these soils so unique also presents serious challenges. Their swelling and shrinking behavior complicates farming, and when sodicity-the excessive buildup of sodium-sets in, it only worsens the situation. Sodicity damages the soil structure, restricts water movement, and stunts plant roots, leading to dramatic losses in crop productivity.

Material and Methods

This review used a structured approach to analyze literature on black sodic soils, focusing on characteristics, classification, and sustainable management. Keywords like "black sodic soils" and "soil amendments" were used across databases like Scopus, Google Scholar, and IARI repositories for region-specific data. Studies from the last 10–15 years on sodic Vertisols in arid and semi-arid areas were selected, with findings organized by themes like "Formation Mechanisms" and "Management Practices." Tables and figures summarized data on amendments and soil structure, enabling a focused synthesis on managing sodic soils effectively.

Characteristics of black sodic soils

Black sodic soils, are clay-rich soils exhibiting shrink-swell properties. Characterized by their high sodium content, these soils experience severe structural degradation, poor aeration, and low hydraulic conductivity. Globally, sodic soils span regions including India, where they are concentrated in states like Uttar Pradesh, Gujarat, and Maharashtra . The Purna Valley in Maharashtra is one example of black sodic soils, where salinity, poor drainage, and groundwater quality present ongoing challenges. Bhattacharyya *et al.* (2018), the characteristics of black sodic soils in Maharashtra, specifically identified as Calciusterts, are highlighted by the presence of the fibrous mineral palygorskite. This mineral is unique to sodic black soils in the region and is unaffected by soil modifiers, indicating that it is a natural component rather than a result of soil amendments. This mineral presence significantly influences the hydraulic and physical properties of these soils, which are typically characterized by poor structural stability, high clay content, and challenges in water movement.

The high smectite content in these soils increases bulk density, which in turn leads to a a rigid and consolidated soil structure. . Even at minimal levels of sodicity with ESP values of 4.8-11.1, the soils in the Purna Valley in India were found to suffer from severe drainage problems, as the saturated hydraulic conductivity was drastically reduced (Kharche *et al.*, 2012).Kadam *et al.* (2013) also observed inadequate internal drainage at significantly lower ESP values than the traditional threshold, with the soils exhibiting pH values ranging between 7.0 to 9.5, ECe values between 0.44 to 2.74 dS m^{-1}, and ESP levels of 4.8 to 11.1. Another factor contributing to the subsoil sodicity in these calcareous soils is the precipitation of calcium carbonate ($CaCO_3$) at greater depths, driven by the washing out of bicarbonates in the wet season. This precipitation process results in the formation of sodicity levels in subsoils as well as compact soil structures (Kadam *et al.*, 2013).

The interaction between sodicity and climate also plays a significant role in the classification of these soils. In humid environment, the soil undergoes leaching, which deplets essential cations and anions by water movement and deposited in lower landforms or groundwater aquifers (Zinck and Metternicht, 2009). In arid, semi-arid, and sub-humid climates, however, cations generally remain within the soil's exchangeable complex or form secondary minerals. When the concentration of ions in the soil solution reaches a saturation point, salts such as calcium carbonate ($CaCO_3$), gypsum ($CaSO_4.2H_2O$), and magnesite ($MgCO_3$) precipitate (Bui, 2017). The presence of Na^+ ions increases in the soil solution, resulting in the replacement of Ca^{2+} and Mg^{2+} with sodium, thus contributing to sodification.

The dependency The impact of electrical conductivity (EC) on hydraulic conductivity (HC) has an important implications for stability of soil structure under sodic conditions. In well-structured soils, large pores and cracks allow water to flow easily. However, in sodic soils, the swelling and dispersion of clays in response to low EC drastically reduce pore size, causing a sharp decline in hydraulic conductivity (Chi *et al.*, 2012). This reduction in HC can lead to anaerobic soil conditions, thereby limits plant growth and slows the decomposition of organic matter.

During the wet season,, the existing salts in the soil are leached with the initial rainfall, causing a further reduction in HC and resulting in water logging. In soils with high clay content, HC is particularly sensitive to sodic conditions, as clay swelling significantly reduces pore size, leading to poor drainage. On the other hand, in sandy soils, where clay content is low, HC is less affected by sodicity. The addition of calcium (Ca^{2+}) and magnesium (Mg^{2+}) salts helps mitigate these effects by competing with sodium (Na^+) for binding sites on clay particles, thereby reducing soil dispersion and improving soil structure (Schultz *et al.*, 2017).

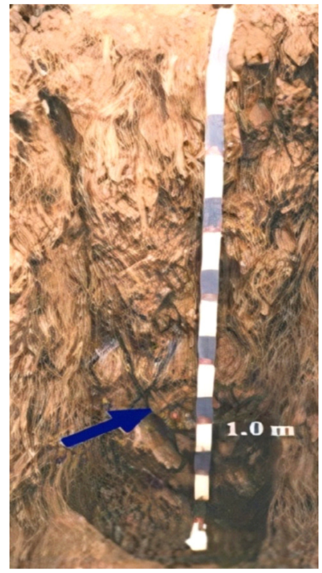

Fig. 1 Soil profile of sodic Haplusterts (Vertisols) from Paral, Akola, Maharashtra. Adapted from Pal *et al.* (2003)

Diagnosis of black sodic soils

Black sodic soils, particularly Vertisols, are predominantly found in river valleys and basins, especially in semi-arid regions. These soils are often degraded due to both natural factors (such as primary salinity) and historical mis-management. A key example is the Purna Valley located in the Vidarbha area of Maharashtra, India, where a combination of native salinity, poor drainage, and suboptimal groundwater quality has created a challenging environment for sustainable agriculture. In the Purna Valley, Vertisols extend across the districts of Amravati, Akola, and Buldhana, have been extensively studied due to their high clay content, which makes them particularly prone to water logging and poor drainage. Despite the lack of visible salt efflorescence on the surface, these soils suffer from significant subsurface sodicity and salinity issues.

These soils, derived from basaltic parent material, exhibit high pH levels (above 9.0), elevated calcium carbonate ($CaCO_3$) content (9.5-16.2%), and high electrical conductivity (EC_e ranging from 4.84 to 13.89 dSm^{-1}). The exchangeable sodium percentage (ESP) also increases with depth, reaching values between 14.3

and 23.1. These characteristics make the soils structurally unstable and impede water movement, further aggravating soil degradation (Kharche *et al*., 2004; Dongare, 2010). The biological health of these soils has also been compromised. Mane (2012) reported a decline in soil microbial biomass carbon, along with reduced respiration rates and diminished activity of critical enzymes like dehydrogenase and urease. Additionally, Kadu *et al*. (2003) observed that these soils are deficient in organic carbon and have an inverted calcium-magnesium ratio. The Ca/Mg imbalance, coupled with high sodium and magnesium concentrations, further impairs soil structure, particularly in deeper soil layers.

Microtopographic features play a crucial role in the development of sodicity. For example, (IGP), Pal *et al*. (2003) observed that in the Indo–Gangetic Plains (IGP), meander-forming rivers have created microhigh (MH) and microlow (ML) positions on otherwise smooth surfaces. Soils in ML depressions frequently experience flooding and wetting–drying cycles, which promote the dissociation of alkali salts and result in sodium saturation and high pH levels (≥8.4). In contrast, MH areas are more prone to sodicity resulting from accumulation of calcium carbonate formed through pedogenesis and the resulting increase in pH. This process is also observed in Vertisols of Peninsular India, where non–pedogenic calcium carbonate (NPC), derived from the weathering of basaltic rocks, dissolves and reprecipitates as pedogenic calcium carbonate (PC), leading to the formation of sodicity in the of subsoil layer (Srivastava *et al*., 2002; Pal *et al*., 2006).The parent material, particularly the plagioclase feldspar–rich alluvium, plays a significant role in this process (Thakare *et al*., 2013).Remote sensing is emerging as a powerful tool for diagnosing soil conditions, particularly in semi–arid regions. While remote sensing has traditionally been used to monitor soil salinity, its application in soil sodicity diagnosis is gaining traction. For instance, Bai *et al*. (2016) found a strong association between Landsat 8-OLI bands and soil pH level in alkali soils, demonstrating its potential for assessing sodicity in large areas.

Excessive irrigation, particularly in semi-arid climates, has worsened the sodicity problem in many regions, including the Purna Valley. Research by Kharche *et al*. (2004) and Dongare (2010) highlighted that poor drainage conditions, combined with high ESP values, result in severe soil degradation. The lack of proper water management further exacerbates the problem by raising the water table and promoting the accumulation of salts, which are drawn to the surface through evapotranspiration. Despite these challenges, the application of gypsum and calcium-zeolites has shown promise in reducing sodicity and improving soil hydraulic properties. Pal *et al*. (2006) found that these amendments helped arrest the increase in soil pH thereby stabilize the Ca:Mg ratio, particularly in regions

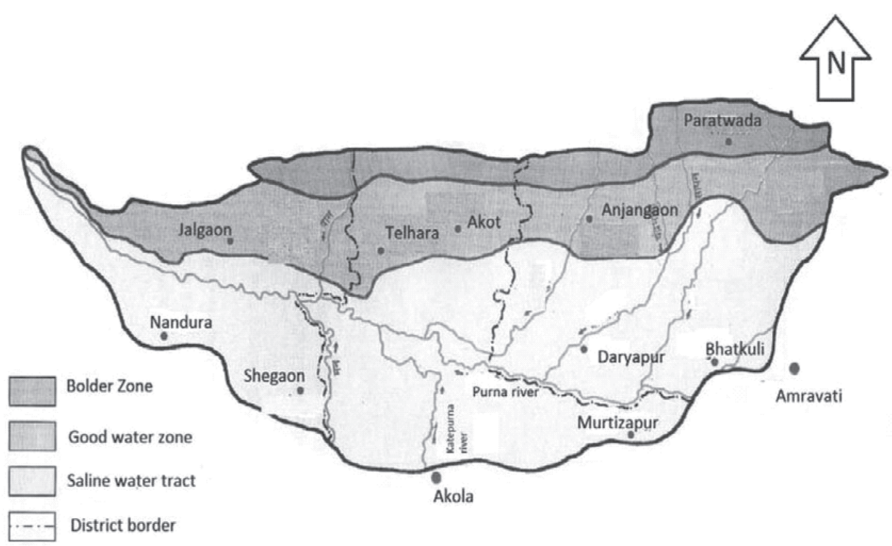

Fig. 2 Map of Purna Valley tract in Vidarbha region of Maharashtra. Adapted from Kadam *et al*., 2013

where ESP levels were less than 15. However, long–term reclamation requires a combination of soil amendments and sustainable irrigation practices.

Impact of water quality on sodic vertisols

Poor-quality irrigation water, especially with high sodium levels, greatly impacts the structure and productivity of sodic Vertisols. Dang *et al.* (2018) found that saline-sodic water reduces hydraulic conductivity, causing compaction, poor drainage, and limited water infiltration. Yadav *et al*. (2024) demonstrated in India's rice-wheat system that sodic water increases soil sodium, displacing calcium and magnesium and reducing organic carbon and wheat yields by 31.7%. Using gypsum or sulfur helps, but full soil recovery requires high-quality water. Alternating sodic and canal water, as shown by Choudhary *et al.* (2019), can improve soil structure and increase yields by 7-26%. Sundha *et al.* (2022) highlighted that low-electrolyte water raises phosphorus leaching risks, which organic amendments like gypsum and compost can help control. Ozer and Köklü (2019) stressed the need to manage SAR and EC in irrigation water to prevent sodic soil degradation, emphasizing ongoing water quality monitoring for sustainable productivity.

Classification of black sodic soils

Sodic soils are primarily classified based on their electrical conductivity (ECe), pH, and exchangeable sodium percentage (ESP). According to the United States Salinity Laboratory (USSL) Staff (1954), sodic soils typically exhibit low electrical conductivity (EC_e, electrical conductivity of saturation extract) (< 4 dS m^{-1}), high pH_s (pH of saturation extract) (> 8.2), and high ESP (> 15). These soils contain significant amounts of carbonate(CO_3^{2-})and bicarbonate (HCO_3^-) salts (Sharma *et al*., 2016), distinguishing them from saline soils, which have excessive levels of chlorides and sulfates of sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in soil water saturation paste extract. In extreme cases, sodic soils can have pH levels as high as 10.5 or more, further deteriorating their physical properties. High sodicity results in the surface accumulation of dissolved organic matter (OM), imparting a dark hue to the soils, earning them the moniker "black sodic soils". The upper soil surface hardens and become nearly impervious to water, leaving sub-surface soil layers waterlogged, often exhibiting poor drainage. Upon drying, these soils form deep cracks (1-2 cm wide), characteristic of sodic Vertisols (Abrol *et al*., 1988).

Challenges with existing ESP thresholds

The conventional classification of sodic soils, based on an ESP threshold of 15, is increasingly being regarded as inadequate for Vertisols with high clay content and low permeability. Several studies have demonstrated that soil degradation occurs at much lower ESP values in such soils. For instance, Balpande *et al*. (1996) advocated an ESP threshold of 5 for Vertisols with a high content of smectite clays, as soils with even moderate ESP levels experience significant structural degradation. This is further supported by research showing that soil degradation can occur at ESP values as low as 5 or 6 (Sharma *et al*., 1997). Therefore, it is evident that ESP 15 is too high a threshold for heavy clay soils with swell-shrink properties, such as black sodic Vertisols. A lower ESP limit, coupled with saturated hydraulic conductivity (SHC) values, is increasingly being considered for these soils. For example, an SHC value lower than 10 mm hr{ ^{1} has been recommended as an effective diagnostic criterion for sodic Vertisols, especially in the India's central peninsular regions (Kharche *et al*., 2012).

Recent studies, such as those conducted by Pal *et al*. (2006), advocate for a lower ESP threshold to classify black sodic soils more accurately. These findings emphasize the importance of considering both ESP and hydraulic conductivity when categorizing sodic soils, assoil performance deteriorates significantly below the traditional ESP threshold of 15 (Pal, 2004; Kadam, 2011).

Management of black sodic soils

Chemical and organic amendments

Reclaming of sodic soils typically aims on lowering the exchangeable sodium percentage by substituting Na with Ca. Gypsum ($CaSO_4.2H_2O$) acts as an effective amendment due to its soluble

Ca^{2+} ions, which promote the flocculation of clay minerals. This process enhances soil structure by increasing the hydraulic conductivity and soil permeability, facilitating better movement of irrigation water and leaching of Na^+ from the soil (Alhammadi and Miller, 2006; Dontsova and Norton, 2002). The primary management practices to reduce sodicity involve application of gypsum to promote better soil structure thereby enhance the wasing out of soluble salts and exchangeable Na. Often, gypsum application is combined with deep tillage ("deep ripping") to further aid water entry and leaching (So and McKenzie, 1984; McKenzie and So, 1989; McKenzie *et al*., 1990, 1993). However, deep ripping alone may have transient benefits in sodic Vertisols if not accompanied by gypsum, owing to soil compression and re–compaction (McKenzie *et al*., 1990).Various types of amendments used for sodic soil reclamation are described in Table 1.

The addition of organic amendments to soils, including sodic soils, has been widely observed to enhance soil aggregation and the stability of aggregates (Abiven *et al*., 2009; Clark *et al*., 2009; Ghosh *et al*., 2010; Tisdall and Oades, 1982). Soil aggregation results from the action of various stabilizing agents that operate simultaneously across multiple spatial and temporal scales. Introducing fresh organic materials stimulates microbial activity, which promotes the production of fungal hyphae and microbial compounds such as lipids and polysaccharides that serve as binding agents (Abiven *et al*., 2009; Holatko *et al.,* 2021). These binding agents act as "glues," bonding primary mineral particles into microaggregates, which are then joined to form larger macro-aggregates (Tisdall and Oades, 1982). A range of organic amendments-including crop residues, agricultural by-products, peat, and compost-are commonly applied to improve overall soil health (Clark *et al*., 2009; Ghosh *et al*., 2011; Gill *et al*., 2009; Six *et al*., 2004; Tejada *et al*., 2006; Guo *et al*., 2019). Many studies report a quick and beneficial impact on soil aggregate stability following organic amendments. However, inconsistent effects of these additions have also been noted in some cases (Albiach *et al*., 2001; Spaccini *et al.,* 2002; Guo *et al.,* 2018),

Table 1. Amendments used for sodic soil reclamation

Amendment	Mechanism of reclamation	References
Gypsum ($CaSO_4$)	Provides soluble calcium that replaces sodium ions in soil, improving permeability and reducing clay dispersivity.	Basak *et al*. (2023)
Gypsiferous Material (GM)	Faster dissolution than mined gypsum; decreases clay dispersivity, increases aggregate stability and soil permeability.	Pal *et al.* (2006); Trimurtulu *et al.* (2000)
Calcium chloride ($CaCl_2$)	Provides soluble calcium more efficiently than gypsum; however, effects may be short-term and leaching may occur.	Basak *et al*. (2015); Vaidya *et al*. (2002)
Magnesium Chloride ($MgCl_2$)	Provides magnesium; easier to apply through irrigation water, but may leach below the root zone.	Basak*et al*. (2015); Vaidya *et al*. (2002)
Sulfuric Acid (H_2SO_4)	Combines with calcium carbonate in the soil converting it into soluble form of calcium ($CaSO_4$.2/ H_2O or $CaCl_2$).	Minhas *et al*. (2021)
Fly Ash	Providing a readily available concentration of calcium ions in the soil.	Lokeshapp and Dixit (2011); Veeresh *et al*. (2003); Mishra *et al*. (2019)
Elemental Sulfur (S)	Microbial oxidation produces sulfuric acid, which then reacts with calcium carbonate to release soluble calcium.	Jaggi *et al*. (2005)
Flue Gas Desulfurization Gypsum (FDG)	Byproduct of coal-fired power plants, it is more soluble than mined gypsum thus, improves soil structure.	Sundha *et al*. (2023)
Phosphogypsum (PG)	Byproduct from the phosphorus industry, it is used as a as a cost effective soil amendment to provide soluble calcium.	Sundha *et al*. (2023)
Acid waste Products	React with calcium carbonate to release soluble calcium, used in combination with gypsum or GM.	Rashmi *et al.* (2024)

underscoring the importance of a deeper understanding of the mechanisms underlying soil aggregate stability.

In India, the application of farmyard manure has also been reported to reduce sodicity. This effect may be attributed to the dissolution of native $CaCO_3$, sodium (Na) displacement by calcium (Ca) on exchangeable sites, , increased electrical conductivity (EC), and overall improvement in soil structure and Na leaching (More, 1994; Dubey, 1996; Chorom and Rengasamy, 1997). Organic amendments, such as composted cotton stalk, biomulch, and green manures (*e.g.*, dhaincha, sunhemp), have shown significant improvements in microbial biomass carbon, dehydrogenase activity, and soil health, often outperforming gypsum in enhancing biological properties and carbon sequestration (Shirale *et al.*, 2018; Mubarak and Nortcliff, 2010; Qadir *et al.*, 2007).

Tree plantations and agroforestry

In sodic lands, tree plantations and agroforestry offer alternative methods for soil restoration. Plant roots exude CO_2 and protons directly into the soil matrix, increasing acidity and dissolving Ca-bearing minerals, which in turn replaces Naz from the exchange sites. For example, Kallar grass scientifically known as *Leptochloa fusca* has been effectively used to reclaim soils affected by salinity, sodicity, and combined saline sodic conditions in Pakistan (Nadeem *et al.*, 2017). In northern Indian states, species such as mesquite (*Prosopis juliflora*), tamarisk (*Tamarix articulata*), and gomaarábiga (*Acacia nilotica*) have proven effective in restoring sodic soils, while other species like forest red gum (*Eucalyptus tereticornis*) and Indian rosewood (*Dalbergia sissoo*) exhibit strong survival rate but lower yield (Dagar *et al.*, 2001; Singh *et al.*, 2012). Reforested lands with a mix of species, including arjuna (*Terminalia arjuna*), neem (*Azadirachta indica*), and lebbeck (*Albizialebbeck*), have been reported to restore sodic croplands and improve soil properties.

Drainage

Drainage in sodic swell-shrink soils is challenging due to poor hydraulic properties. Tile drains are often ineffective, so vertical drainage via boreholes or wells is more promising. Successful reclamation includes installing 80 mm PVC corrugated pipes spaced 75 meters apart, combined with sugarcane trash or green manuring to improve drainage and increase crop productivity. Managing monsoon rains is also tricky; a three-tier system of rainwater storage, shallow ponds, and surface drains helps balance excess water and drought conditions (Chaudhary and Kharche, 2015). The study by Chinchmalatpure *et al*. (2020) highlights that subsurface drainage significantly improves saline Vertisols in Gujarat's Ukai-Kakrapar Canal Command by lowering the water table and reducing soil salinity. This drainage system enhances soil aeration, root growth, and nutrient uptake, leading to higher sugarcane yields and sustainable soil health in waterlogged, saline conditions.

Deep Tillage and Subsoiling

While conventional tillage offers advantages like loosening the soil and improving aeration, it also brings certain unintended drawbacks. These include harm to soil structure, increased oxidation of soil organic carbon, disintegration of macro-aggregates, reduced hydraulic conductivity, and heightened soil susceptibility to erosion (Blanco-Canqui and Ruis, 2018). Tillage can be beneficial for reclaiming sodic soils, as it breaks down compacted soil layers, enhances overall porosity-particularly larger pore spaces-lowers bulk density, and facilitates root penetration into deeper soil layers (Mu *et al.*, 2016; Mosaddeghi *et al.*, 2009; Nitant and Singh, 1995). Additionally, tillage has been shown to boost microbial diversity, support rhizosphere microorganisms, and increase the soil's water retention capacity, thereby creating favorable conditions for root growth and delaying plant aging (Djm *et al.*, 2010; Liang *et al.*, 2010; Qin *et al.,* 2008). Modern reclamation methods for sodic soils include tillage practices designed to enhance soil physical properties and facilitate fine tilth. Conventional tillage practices, such as deep plowing (1–2 m), can enhance soil structure, increase porosity, decrease bulk density, and enhance root extension. However, deep tillage may also bring sodic subsoil to the surface, leading to potential issues with logging and infiltration. In such cases, ridge cultivation and surface mulching can be beneficial. Surface mulching, such as with crop residues, decreases evaporation rates, which helps lower soil salinity and sodicity, particularly in drylands and areas with saline irrigation water (Bezborodov*et al*., 2010; Stavi, 2020; Verhulst *et al*., 2009).

Conclusion

Black sodic soils, especially the expansive Vertisols in the arid and semi-arid Indian Deccan, present a significant challenge to sustainable agriculture. Characterized by high sodium levels, poor permeability, and structural instability, these soils hinder crop productivity and soil health. Climate factors, suboptimal irrigation practices, and the rising use of low-quality water sources exacerbate the sodicity issues. Addressing these challenges requires a comprehensive approach that combines soil diagnosis, classification, and sustainable management strategies. Key amelioration techniques, such as gypsum, phosphogypsum, compost, and organic mulches, help improve soil structure by replacing sodium with calcium, stabilizing aggregates, and enhancing water infiltration. In addition, agroforestry and tree plantations offer long-term restoration solutions, while practices like targeted tillage and subsoiling can improve root penetration and physical soil properties.

Moreover, better water management practices-such as alternating between high-quality and sodic water and implementing effective drainage solutions-are essential to mitigate sodicity's adverse effects. Further research into the specific impacts of sodicity on Vertisols, especially under changing climate conditions, will enhance our ability to manage these soils effectively. Through the development of region-specific practices and optimized amendment applications, there is strong potential for reclaiming black sodic soils in ways that improve their productivity and resilience, contributing to greater food security and supporting sustainable agricultural livelihoods.

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Potential of Conservation Agricultural Practices on Soil Quality, Carbon Sequestration, Salinity Management and Productivity of Rainfed Areas

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Abstract

Intensive cropping, traditional tillage practices, and crop residue removal are the major factors of soil organic carbon (SOC) depletion. Restoration of SOC levels would improve the soil's aggregate ability, physical, chemical, and biological properties, low greenhouse gas emission, and environmental sustainability. The importance of rainfed farming in India is increasing continuously with the increasing demand for feed, fodder, and fiber. It is technologically estimated that at any point in time, 50% of cropped area in India will remain under the rainfed system. The major challenges in rainfed areas include water scarcity, climate variability, and the lack of suitable technologies and practices resulting in half of SOC being present in arid soils than in moist environments. That's why the carbon sequestration in these soils requires a wide range of management practices to restore SOC levels. Conservation agriculture (CA) practices such as minimum tillage (MT), reduced tillage (RT), and zero tillage (ZT) may help in carbon sequestration and restoring SOC levels. The results of different studies revealed that ZT, MT and RT recorded higher total organic carbon, microbial biomass carbon, and particulate organic carbon as compared with conventional tillage and these are now established methods for promoting carbon sequestration and reducing greenhouse gas emissions in soils. The continuous tillage practices are a major threat to soil health, productivity, and fertility in dry areas. The tillage technology showed direct and indirect benefits in resource-saving ability and carbon sequestration. Long-term conservation tillage, judicious nutrient, and residue management practices increase the SOC content and enhance soil aggregation, hydraulic conductivity, soil porosity, and moisture retention capacity. Generally, the soil quality index (SQI) is used as a quantitative parameter to measure the effect of crop management practices on soil health. In tropical areas, the changes in different tillage practices, input, and residue management technologies offer a conclusive statement regarding the feasibility and sustainability of CA cropping systems. The SQI indicators are highly location and purpose-specific, as directly correlated with an ecosystem, physical, chemical, and biological processes, crop management variations, and properties of soil. This review aims to highlight the impact of conservation tillage practices that have potential possibilities for carbon sequestration in soils including salt-affected soils of rainfed areas.

Keywords: Carbon sequestration, Minimum tillage, Rainfed areas, Reduced tillage, Soil organic carbon, Zero tillage, Salinity management

Introduction

Rainfed agriculture is a major crop production system across the world (Wang *et al*., 2007). After the second era of the green revolution, main issues in rainfed agriculture have occurred like low water availability, dry spells, and prominent high temperatures. Intensive cropping systems with conventional tillage and imbalanced use of fertilizers lead to soil degradation in dryland agriculture and Indo-Gangetic Plains (Parihar *et al*., 2016). Shifting from a conventional tillage-based production system to Conservation Agriculture (CA) necessitates a transitional period. During this transition, the promotion of the three core CA practices alongside other sound agricultural techniques, encompassing integrated management of crops, soil, nutrients, water, pests, and energy, is crucial. The feasibility of adopting or integrating CA practices hinges on various factors, including biophysical, economic, socio-cultural, managerial, and developmental aspects pertinent to the local agricultural context. No singular methodology applies to the introduction, execution, and evolution of CA in different environments. This variability extends to the scalability and organization of CA adoption to leverage territorial-level benefits for rural communities and society.

The adoption of CA in diverse conventional production systems depends upon its suitability and necessity in rainfed areas. This CA approach aids in enhancing soil health, mitigating erosion, and augmenting biomass production. In rainfed areas demonstrated that CA gave superior grain yield production compared to conventional tillage (CT). Wheat yield increased by 43%, barley by 8%, lentil by 11%, and chickpea by 19% in CA. Moreover, over a five-year cereal-legume rotation cycle, CA led to a 20% boost in system yield, a 40% increase in total benefits, a 13% rise in precipitation use efficiency, 14% augmentation in available soil moisture along with the production costs reduction by 14.5% (Devkota *et al.,* 2015). The CA system exhibited higher levels of soil organic matter (up by 7%), available phosphorus (up by 3%), and exchangeable potassium (up by 15%) compared to CT, albeit these disparities were not statistically significant. Both our field experiment and long-term simulations underscore that adopting CA enhances various agronomic, economic, and soil fertility metrics in clay soil within a rainfed Mediterranean setting when juxtaposed with CT (Devkota *et al.,* 2022).

Traditional cultivation practices lead to land mismanagement and faulty production practices in these rainfed regions have critically low SOC levels. Restoring degraded soils with depleted SOC reserves presents significant potential for SOC storage and sustainable agriculture (Lal, 2009). Conservation agriculture (CA) characterized by minimal soil disturbance, crop rotation, and retention of crop residues, is widely recommended to mitigate soil degradation and enhance agricultural sustainability. CA practices are endorsed by the Intergovernmental Panel on Climate Change (IPCC) for their role in mitigating climate change and increasing carbon sequestration in soils (Luo *et al*. 2010). Conservation tillage, a key component of CA significantly influences plant growth, environmental conditions, and soil health. Practices such as reduced tillage (RT) zero tillage (ZT) subsoil mulching and residue retention are commonly integrated into conservation tillage systems (Lampurlanes *et al*., 2002). In rainfed regions of the Pothobar plateau in Pakistan covering 1.8 million hectares, farmers often practice summer following using moldboard plowing, with limited adoption of zero tillage (ZT) or minimum tillage (MT) methods. Soil is a significant reservoir of terrestrial carbon sequestration (Schlesinger and Andrews, 2000). Soil organic carbon (SOC) is essential for maintaining soil quality and supporting sustainable crop production (Lal, 2004). Insufficient SOC level can lead to challenges in agriculture and the environment including nutrient deficiencies (Ashagrie *et al*., 2007), reduced water retention (Resck *et al*., 2008). Agricultural activities, soil environment, and soil organic matter quality can have varying impacts on carbon storage as SOC (Nyawade *et al*., 2019). Agrarian practices contribute significantly (9.4%) to greenhouse gas emissions (Smith *et al*., 2008). Carbon sequestration in soils is a promising strategy to mitigate CO_2 emissions (Mancinelli and Yang, 2010). Efforts are underway to promote sod carbon sequestration as a means to mitigate anthropogenic carbon emissions and combat climate change (Lenka and Lal, 2013). Agricultural soils globally have the potential to sequester around \$500-6000 Mg CO_2 per year by 2030 (Smith and Conen, 2004). The main aim of this review paper is to identify the effective production techniques pertaining to rainfed areas, that have the potential to sustain the production, productivity, fertility, and climatic vulnerability of these regions. The CA-based approaches related to rainfed areas have a wide scope for efficient resource utilization for crop production. Using ZT, NT, or Intercropping with short-duration crops like cowpea, pearl millet, caster, and moong are viable options for the farmers of rainfed areas. It is the best strategy option to make resilience to changing climatic conditions in water stress areas.

Basic principles of conservation agriculture

Population growth, shifting dietary preferences, and climate change are propelling a transformation in global food production toward greater efficiency, reliability, and sustainability. In India, arable land for crop cultivation comprises approximately 51% of the total land area (Anonymous, 2022). Conservation tillage is an agricultural strategy designed to reduce the frequency or intensity of tillage operations, aiming to achieve various economic and environmental advantages. These benefits encompass a decline in carbon dioxide and greenhouse gas emissions, reduced dependency on farm machinery and equipment, and overall savings in fuel and labor expenses. Furthermore, conservation tillage techniques have demonstrated enhancements in soil health, mitigation of runoff, and minimization of erosion. With its potential to yield both environmental and economic advantages, a meticulously developed and effectively integrated conservation tillage approach can play a pivotal role in fostering the sustainability of agricultural systems. This is particularly critical in a country grappling with a severe water deficit in rainfed areas. The three major principles involved in the successful adoption of CA are, i) Minimal soil disturbance, ii) crop management, and iii) permanent soil cover. There are a number of practices involved with these principles which are shown in Table 1.

Climate change is anticipated to intensify climate variability, further straining rainfed dryland production systems. Conservation Agriculture (CA) offers a comprehensive framework of principles aimed at fostering sustainable, dependable, and climate-resilient farming practices. While initially conceived as guidance for grain farmers, the principles of CA are applicable across various agricultural commodities. These principles have been widely advocated and successfully adopted. This review underscores the outcomes of research conducted thus far and the challenges associated with implementing rainfed conservation agriculture in India.

Impact of conservation tillage on soil health

The conventional tillage involves extensive mechanical soil manipulation to enhance soil aeration, and field workability, seedbed preparation, fertilizer incorporation, and weed control (Gajda *et al.*, 2018). To address these challenges, ZT has emerged as a potential practice

Table 1. Principles of conservation agriculture (AGRA, 2024)

I) Minimal soil disturbance	II) Crop management	III) Permanent soil cover
Preserve soil structure, reducing soil degradation	Crop rotation to increase soil fertility and productivity	Minimize raindrop impact
Shield soil from wind, water and anthropogenic erosion	Enhances crop plant nutrient uptake efficiency	Decreasing runoff and facilitating infiltration rate of soil
Enhances infiltration rates, improving water retention	Intercropping various crops with distinct nutrient needs can prevent hard pan formation	Lowers evaporation and conserve moisture
Slow organic matter decomposition and enhance its accumulation	Minimizes the risk of crop failure during drought, rain and disease outbreak	Reducing competition for resources by suppressing weed growth
Promoting soil organisms, soil health and organic matter mineralization	Efficient weed, disease and pest management by disturbing their life cycle through new crop introduction	Enhances soil quality by augmenting organic matter levels and nutrient richness
Minimizes soil disturbance, save energy, save time	Prevent soil erosion events	Provides conducive habitat for diverse range soil organisms
Mitigates soil compaction by leaving roots undisturbed	Efficient water use	Regulates soil temperature, promoting optimal conditions for plant growth

for achieving agricultural sustainability (Ussiri *et al.*, 2009; Ruan and Robertson, 2013; Mangalassery *et al.*, 2014). The research conducted in China indicates that zero tillage (ZT) offers the potential to increase food production, minimizing soil depletion, degradation, and environmental pollution in direct seeded rice (DSR) (Ahmad *et al.*, 2009).

The nutrient availability status, microbial biomass, respiration, and humic acid concentrations are effective indicators for assessing the long-term effects of improved management practices on soil quality (Years *et al.*, 2014; Biswas *et al.*, 2017). Bhadur *et al.* (2014) and Sharma *et al.* (2016) monitored changes in the Soil Quality Index (SQI) by non-linear or linear method of termination based on methodological systems and analytical objectives under Conservation Agriculture (CA) in temperate regions. Zero tillage practices and application of N fertilizer with organic manure have positive impacts on SOC. The combination of conservation agriculture and balanced input management enhances carbon (SOC) concentration and SOC stability (Dey *et al.*, 2020). The impact of balanced input management in soil enhanced microbial diversity, microbial biomass, and enzymatic activities (Ghosh *et al.*, 2017). Therefore, it becomes crucial to comprehensively compare the advantages and disadvantages of both systems-ZT and CT regarding their impacts on natural resources, agricultural productivity, and climate change to provide a clear understanding of their respective contributions. The results of 3-years study with ZT-ZT, CT-CT, ZT-CT, ZT-CT and CT-ZT in rice-wheat cropping system indicated that enzyme alkaline phosphatase and protease activity was higher (9.3-48.1%) in the zero-tillage as compared to conventional tillage system (Mina *et al.*, 2008). Saho and his coworkers (2016) revealed that the conservation tillage practices, viz. no-tillage, subsoiling, and ridge planting-led to significant improvements in soil nutrient levels in the topsoil (0-20 cm) in rainfed environments. Available phosphorus increased by 3.8%, 37.8% and 36.9% available potassium by 13.6% 37.5% and 25.0%, soil organic matter by 0.17% 5.65% and 4.77%, respectively, under these practices. In the first four years of tillage, Rhoton (2000) observed that soils under no-tillage contained higher organic matter content compared to soils under conventional tillage. Soils subjected to plough tillage experienced an estimated 10% loss of initial soil organic matter content. Zero tillage significantly increased organic carbon to depths of 10, 15, and 25 cm in sandy loam, loam, and clay loam soils, respectively, indicating deeper organic carbon accumulation with finer soil textures. The infiltration rate also increased under ZT compared to CT, with a notable 28% increase in clay loam soil (Singh *et al.*, 2014). Stanek-Tarkowska *et al.* (2018) found that SOC content, soil water content, and bulk density in the 0-5 cm and 5-10 cm layers were significantly higher under reduced tillage (RT) than conventional tillage, though no significant differences were observed in deeper soil layers.

Soil organic carbon (SOC) content

Soil organic carbon (SOC), carbon sequestration rate and cumulative carbon sequestration were notably affected by tillage practices and crop production methods (Yadav *et al.*, 2021). Conservation tillage has consistently enhanced soil organic carbon in the top soil layers. Ten years of field studies have demonstrated that no-till management with moderate to high rates of nitrogen fertilizer application effectively increased the SOC levels. Partial removal of crop residues decreased SOC over time while leaving all crop residues in the soil increased SOC annually. This Long-term increase in SOC can influence soil hydraulic properties, potentially affecting surface runoff, soil sedimentation, and slope stability (Alvaro-Fuentes *et al.*, 2007).

Traditional cultivation practices in the Indo-Gangetic Plains (IGP) region involve intensive tillage methods to prepare a loose seedbed (Hobbs *et al.*, 2008). However, conventional tillage practices can accelerate the breakdown of soil aggregates and loss of soil organic carbon (Six *et al.*, 2000). There is potential to reduce intensive tillage operation and incorporation of legumes in rice-based rotations to improve soil aggregation and carbon sequestration (Venkatesh *et al.*, 2013). The N fertilizer application under NT enhances

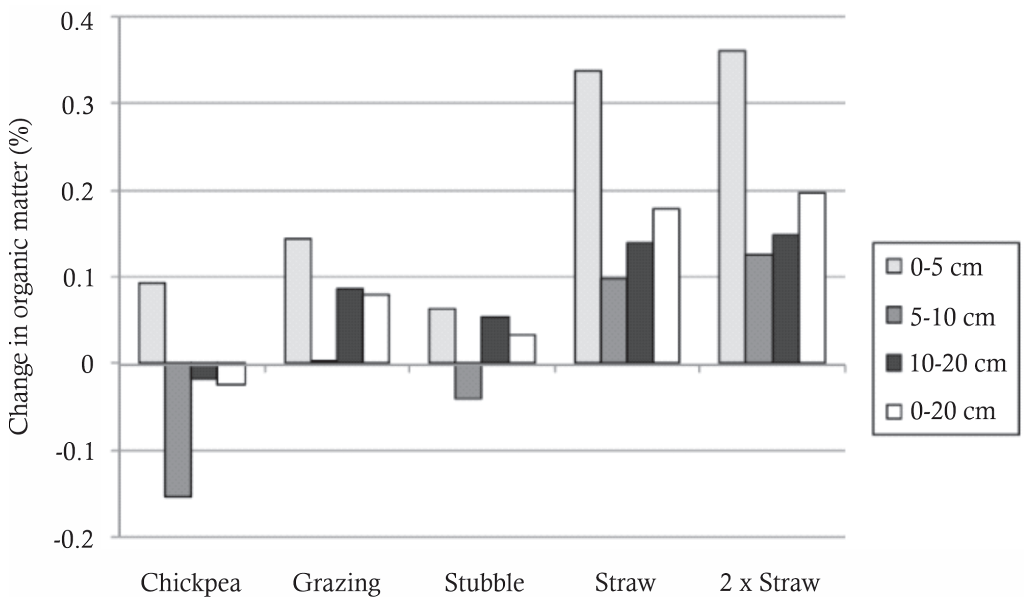

Fig. 1 Impact of crop and residue management on soil organic matter (*Source:* Basch *et. al.,* 2010)

soil C sequestration, and especially decreases nitrate leaching risks, particularly during long fallow periods. The conservation tillage practices mitigate this risk by promoting weed cover and reducing bare soil exposure compared to conventional tillage. However, N fertilizer usage also contributes to N_2O emissions, offsetting its CO_2 mitigation benefits, though this may be minimal in soils with low SOC content typical of Mediterranean rainfed agriculture.

Basch *et al*. (2010) observed a notable trend in soil organic matter (SOM) dynamics across different soil layers after residue incorporation. They recorded the greatest increase in SOM in the lower soil layer (10-20 cm), followed by the topsoil layer (0-5 cm), with the lowest increase observed in the middle layer (5-10 cm). This pattern underscores the potential of no-till practices combined with the return of crop residues to facilitate SOM accumulation in Mediterranean rainfed agriculture. Laamran and his co-worker (2020) reported that total carbon concentrations in topsoil responded to tillage and crop rotation treatments, and no-till plots had higher values of total carbon as compared to mouldboard tillage (Fig. 1).

Salinity reclamation

Incorporating straw into agricultural soils has proven to be an effective strategy for mitigating soil salinization. One of the primary benefits of straw incorporation is its ability to increase the soil's organic matter content. Being rich in carbon, straw is an essential food source for soil microorganisms, which decompose organic matter, release crucial nutrients, and improve soil structure. This enhanced organic matter boosts the soil's water-holding capacity, reducing the concentration of soluble salts and preventing their accumulation in the root zone (Amini *et al*., 2016). The process encourages the formation of stable soil aggregates, which create pore spaces for better air and water movement, facilitating the leaching of excess salts deeper into the soil profile and away from plant roots. Despite its advantages, straw incorporation presents several challenges. Effective implementation requires technical expertise to ensure proper incorporation depth. Variability in straw quality and quantity may affect its performance, and excessive residue can hinder crop sowing, germination, and early growth. Additionally, the practice may increase soil methane emissions and slow straw decomposition, posing environmental and operational concerns that need to be addressed for sustainable management of degraded soils (Ma *et al*., 2008). The major impact of conservation agriculture on soil salinity would be the reduction in soil electrical conductivity (EC) due to the moderating effect of organic carbon added through good crop rotation soil cover and not allowing accumulated carbon to get lost through decomposition. The application of organic amendments significantly enhances soil health by increasing soil organic carbon levels and improving macro-aggregation and structural formation. These improvements boost soil permeability, facilitating the leaching of salts away from the root zone and reducing evaporation rates, which helps to minimize salt buildup in the surface soil layer (Lakhdar *et al.*, 2009). This synergistic tillage conservation approach of organic amendments helps address both soil structure and chemical imbalances in sodic soils (Goncalo *et. al.*, 2020). The tillage management of crop residue plays a critical role in influencing soil health, resilience and effectively reduces evaporation rates, thereby mitigating soil salinity and sodicity (Bezborodov *et al.*, 2010). This CA approach is particularly beneficial in arid and semi-arid regions, where water loss through evaporation is a major concern. By conserving soil moisture and reducing salt accumulation, ground surface mulching offers a practical and sustainable strategy for managing soil salinity, especially in challenging environmental conditions (Stavi, 2020) and sodicity (Verhulst *et al.*, 2009).

Soil nutrient status

There was a close relationship between crop yield and soil CN, CP, CK, and NP ratios. A structural equation model demonstrated that C, N, and P levels influenced CN and CP ratios, enhancing crop yield under long-term conservation tillage. Long-term conservation tillage practices enhance soil-stoichiometry balance leading to improved crop yields and substantial C sequestration potential. The CA effect of balanced nutrition through improving microbial biomass carbon (MBC), soil microbial diversity, and enzymatic activities. The major effect of the CA-based scenarios was the higher accumulation of organic carbon (OC) and total N at the soil surface compared to conventional tillage. The CA-based systems have a distinct influence on soil quality and N:P:K dynamics compared to traditional agriculture based on intensive tilled systems (Jat *et al.*, 2011). The adoption of CA provides opportunities to significantly decrease NO_3-N loss (14% to 44%) and PO_4-P (33% to 50%) in the leachate as compared to conventional tillage (Belay *et al.*, 2020). Zero tillage exhibited significantly higher enzymatic activity, including urease (31.76 µg NH_4-N g^{-1} soil hr^{-1}), dehydrogenase (183.79 µg TPF g^{-1} soil 24 hr^{-1}), acid phosphatase (34.34 µg PNP g^{-1} soil), and alkaline phosphatase (35.11 µg PNP g^{-1} soil). This enhanced activity can be attributed to an improved microbial population in zero-tillage systems compared to minimum tillage and conventional tillage practices. Zero-tilled practices recorded maximum total N uptake by lentil grain and stover (103.16 and 115.09 kg ha^{-1}) followed by relay cropped and conventionally tillage systems during 2018–19 and 2019–20, respectively (Mukherjee *et al.*, 2023).

Water availability

Soil organic carbon, greenhouse gas (GHG) emissions, and water footprint (WF) serve as pivotal indicators of environmental sustainability within agricultural systems. Enhancing SOC levels while concurrently mitigating GHG emissions and reducing WF are integral strategies for achieving high crop productivity with minimal environmental impact. This multi-faceted approach encompasses sustainable intensification (SI) and climate-smart agriculture (CSA), crucial for ensuring food security. Conventional agricultural practices, characterized by intensive soil tillage and crop residue removal, often exacerbate negative environmental outcomes by diminishing SOC levels, increasing climatic variability, and elevating water consumption. In contrast, conservation agriculture, specifically conservation tillage system (CTS) emphasizing crop residue retention, emerges as a resource-conserving alternative. CTS offers the potential to boost crop productivity while safeguarding soil health and upholding the environmental sustainability of cereal cropping systems.

Tillage treatments affected soil water intake, with the infiltration rate (IR) increasing in the order of ZT > RT > CT in rainfed conditions. The highest mean IR was observed in the ZTM-ZTW treatment (2.67 cm hr^{-1}), while the lowest was in the CTM-CTW treatment (2.36 cm hr^{-1}). Table 2 clearly shows that the IR increased as the frequency of tillage practices decreased for both

Table 2. Impact of various tillage methods on soil physical properties in a mung bean-wheat cropping system after two years of study (Kumar *et al.*, 2024)

Treatments	Infiltration rate (cm hr^{-1})
ZTM-ZTW	2.67
ZTM-RTW	2.63
ZTM-CTW	2.55
RTM-ZTW	2.64
RTM-RTW	2.58
RTM-CTW	2.41
CTM-ZTW	2.46
CTM-RTW	2.37
CTM-CTW	2.36
LSD (p=0.05)	NS

ZTM- Zero-tillage mung bean, ZTW- Zero-tillage wheat, RTM- Reduced tillage mung bean, RTW- Reduced tillage wheat, CTM- Conventional tillage mung bean, CTW- Conventional tillage wheat

crops under the mung bean-wheat cropping system (Kumar *et al.*, 2024). Conservation tillage methods exhibit superior soil infiltration compared to conventional tillage methods, as illustrated in Fig. 2. At the Mareko site, two-times tillage showed a 56% increase, no-tillage demonstrated a 21% increase, and one-time tillage exhibited a 12.9% increase in soil infiltration rate compared to conventional tillage. Similarly, at the Mito site, no-tillage displayed a 44.4% increase, one-time tillage showed a 73.6% increase, and two-times tillage had a 24.3% increase in infiltration rate compared to conventional tillage. These differences in soil infiltration rates under conservation tillage, particularly after crop harvest, may be attributed to residue management practices each year, which contribute to enhanced soil infiltration. Notably, the current soil infiltration rates fall within the range outlined by the Horton infiltration curve (Bekele *et al.*, 2022). Reduced tillage resulted in increased water content and stability of soil. In addition, RT recorded higher soil microbial activity and decreased the content of readily dispersible clay in comparison with conventional tillage in the top layer of the soil (Gajda *et al*, 2018).

Conservation tillage is one of the best options to combat the water scarcity and land degradation problems. The soil moisture content (SMC) in a 2-year study in Ethiopia recorded a rising pattern across different tillage methods. Conventional tillage recorded an average SMC of 13.73%, while zero tillage showed a slightly higher SMC at 15.08%. Reduced and strip tillage demonstrated similar trends, with SMC values of 15.11% and 18.61%, respectively (Handiso *et al.*, 2023). Notably, zero tillage, two-times tillage, and strip tillage showcased significant advantages in soil moisture conservation compared to conventional tillage, with respective advantages of 9.25%, 10.05%, and 35.54% (Fig. 3).

Soil water infiltration depends significantly on soil structure and the stability of soil aggregates. Research has consistently shown the beneficial impact of conservation ullage systems on

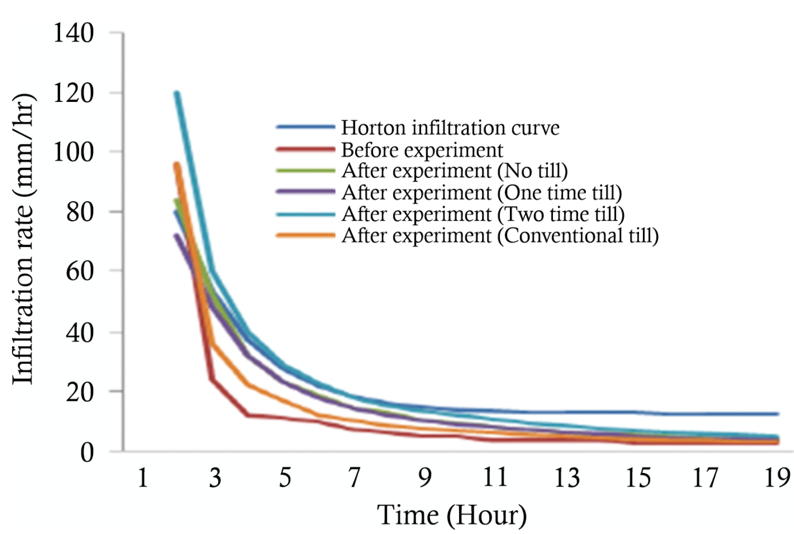

Fig. 2 Soil infiltration rate (mm h^{-1}) in Mareko and Mito sites (*Source:* Bekele *et. al.*, 2022)

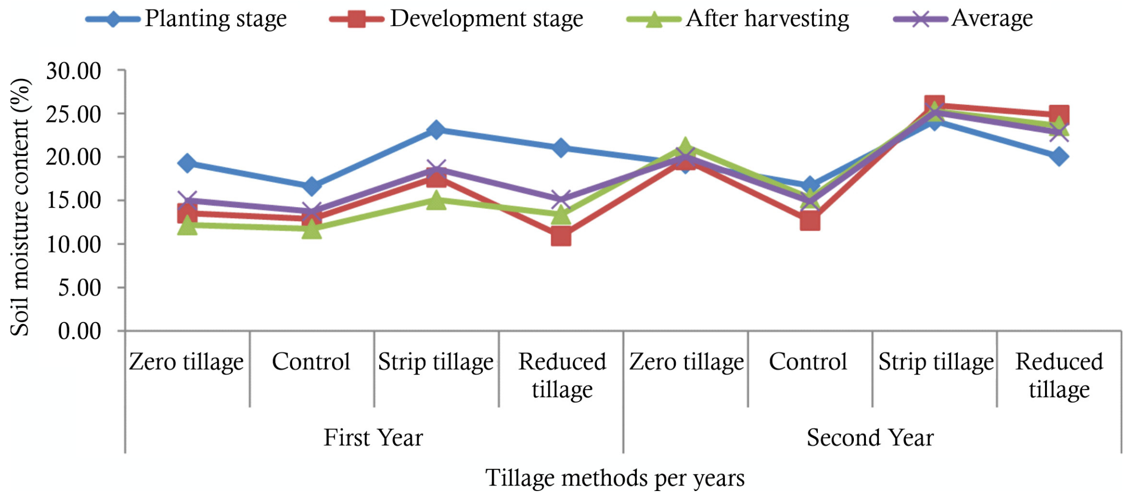

Fig. 3 Impact of periods of different tillage methods on soil moisture content (*Source:* Handiso *et al.*, 2023)

enhancing soil structure across various soil types and climates (Oyedele *et al.*, 1999). The no tillage subsoiling, and ridge planting methods enhanced water use efficiency over conventional tillage by 24.6%, 15.9% and 15.7% in wheat, maize, and annual crops, respectively (Saho *et al.*, 2016). Research studies showed that mulching reduces evaporation, increases infiltration, and effectively conserves water resulting in improved water use efficiency and crop yields (Wang *et al.*, 2007). A 13-year comprehensive study conducted on the Loess Plateau revealed notable benefits of adopting no-till with stubble retention (NTS), particularly regarding soil organic carbon, soil water content, and grain yield improvement. Under NTS, water stored in surface layers became more readily available for crops than deeper layers. Surface soil water content (0-10 cm) witnessed a remarkable enhancement of up to 90% when contrasted with conventional tillage methods. Additionally, there was a notable improvement in soil organic carbon levels. Crops cultivated under NTS exhibited superior growth and yield outcomes. Furthermore, NTS led to enhancements in soil quality, water use efficiency, and nitrogen use efficiency; while concurrently reducing soil erosion significantly (Li *et al.*, 2015).

Impact of conservation tillage on crop production and system productivity

The conventional tillage-based soil management for intensive crop production often leads to soil degradation and increased cost of production due to fuel, labor, fertilizers, and agrochemical inputs. This method also contributes to greenhouse gas emissions and climate change. In contrast, conservation agriculture offers a sustainable alternative with improved soil health, reduced environmental impact, lower energy consumption and emissions, and enhanced biodiversity. Conservation agriculture fosters a healthier ecosystem, supporting a greater abundance of various organisms compared to conventional systems. Despite these benefits, there remains skepticism, particularly in India, about the suitability of conservation practices in local soil and climate conditions. However, as concerns about environmental sustainability grow, it's increasingly important for farmers to adopt practices like conservation agriculture that balance economic viability with environmental stewardship.

Aboveground biomass yield and plant-derived carbon inputs to soil are significantly influenced by tillage and crop establishment methods. The study on summer maize grown under no-tillage with residue burning (NT-RB) and no-tillage with residue retention (NT-RR) produced notably higher biomass compared to conventional tillage with residue burning (CT-RB) treatments (Yadav *et al.*, 2021). The initial soil organic carbon (SOC) content and grain yield were notably enhanced in conservation tillage than conventional tillage (Jiang *et al.*, 2022). Conservation tillage methods were instrumental in maintaining balanced soil stoichiometry particularly concerning C:N and C:P ratios, thereby augmenting crop yield with reduced soil disturbance (Mooshammer *et al.*, 2014; Liu *et al.*, 2023;). The higher system productivity was recorded in summer maize and dry season field pea under NT than that under conventional tillage systems in drylands due to the availability of soil moisture content and nutrients for a longer duration (Monneveux *et al.*, 2006; Saha *et al.*, 2010).

The maximum moisture conservation under ridge farming tillage (RFT) recorded higher yields in pigeon pea, cowpea and castor as crops benefited from conserved soil moisture. Mean pigeon pea yields under stubble mulch farming tillage (SMFT) and RFT were 88% and 67% higher than conventional tillage (CT) in eleven years of study (Kurothe *et al.*, 2014). The outcomes of extensive farmer-led trials conducted across the Indo-Gangetic Plain (IGP) revealed promising results regarding no-till wheat cultivation within the rice-wheat cropping system (RWCS) and no-till wheat achieved comparable productivity to conventionally tilled wheat cultivation (RWC, 2006). Economic analysis of a study in rainfed areas of China demonstrated that profitability of spring wheat-field pea cropping system under no-tillage with stubble retention surpassed the conventional tillage, no-till without stubble retention, conventional tillage with stubble incorporated, conventional tillage with plastic mulch, and no-till with plastic mulch by margins of 81%, 38%, 75%, 165% and 66%, respectively (Li *et al.*, 2015). Tillage is one of the labor-intensive operations as primary tillage practices account for 70-75% of the total energy consumed before planting. While minimum and zero-tillage can save energy, these savings are often counter-balanced by increased input demands for herbicides and nitrogen fertilizers. Zero-tillage (ZT) in wheat, across various cropping systems and landscapes, is now widely recognized as a method to enhance productivity, profitability, soil health, input-use efficiency, and overall system sustainability. It also contributes to effectively managing crop residues, natural resources, and environmental pollution (Yadav *et al.*, 2012: Yadav *et al.*, 2020).

Green house gas emission

Agriculture is acknowledged as a significant contributor to greenhouse gas (GHG) emissions, a trend that escalates with intensive crop production. Agriculture contributes significantly to this issue, accounting for up to 20% of total emissions. Consequently, there is a pressing need to adopt sustainable agricultural techniques that prioritize maximum crop yield while minimizing the global warming potential. Assessing the net global warming potential (NGWP) and greenhouse gas intensity (GHGI) of agricultural activities serves as a valuable method for gauging their potential to mitigate climate impact. Conservation agricultural practices like no-tillage (NT) and minimum tillage (MT) have the potential to mitigate these emissions while enhancing carbon sequestration in rainfed tropical agroecosystems. A 23-year long-term study demonstrated that CO_2 emissions from CT practices were consistently lower compared with intensive tillage (IT). Cumulative CO_2 emissions per season for NT, MT, and IT were recorded at 10, 15, and 20 Mg CO_2-C ha^{-1}, respectively (Utomo, 2014). Partibha *et al.* (2016) reported that zero-tillage and reduced tillage practices contributed 26% and 11% lower indirect GHG emissions over CT, respectively, in the five years of study.

Rahman and his co-workers (2021) revealed that the total greenhouse gas (GHG) emissions were estimated as 1987/ kg CO_2 eq ha^{-1}, 1992/ kg CO_2 eq ha^{-1}, and 2028/ kg CO_2 eq ha^{-1} for zero tillage, minimum tillage, and conventional tillage practices in wheat crop, respectively. Conservation tillage systems with residue retention significantly reduce GHG emissions in wheat cultivation. Figures 4 and 5 present the total life cycle GHG emissions associated with inputs used in wheat crop production. The maximum GHG emissions originated from nitrous oxide (N_2O), with average emissions of approximately 562/ kg CO_2 eq ha^{-1} in wheat cultivation. This accounted for 28.28%, 28.21%, and 27.71% of total GHG emissions for ZT, MT, and CT practices, respectively. Nitrogen (N) fertilizer emerged as the second largest contributor, accounting for 24.98%, 24.92%, and 24.47% of emissions for ZT, MT, and CT practices, respectively.

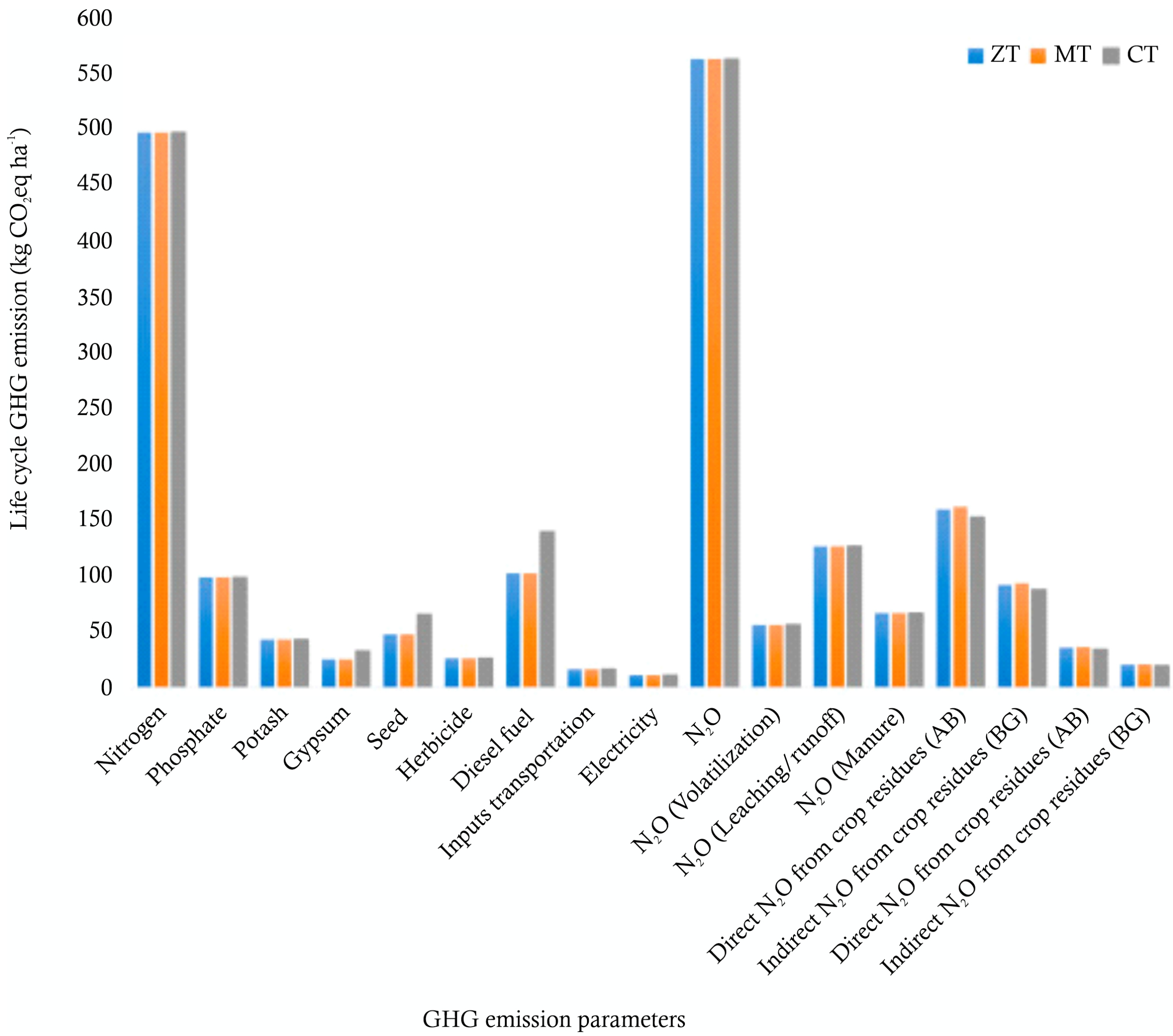

Fig. 4 Influence of different tillage practices on different parameters of greenhouse gas emission (*Source:* Utomo, 2014)

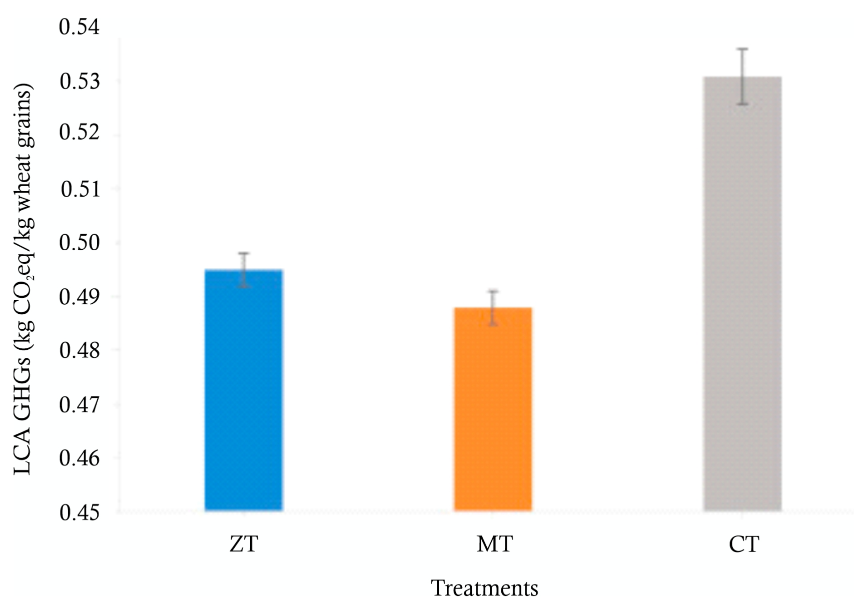

Fig. 5 Green house gas emissions under different different tillage methods (*Source:* Utomo, 2014)

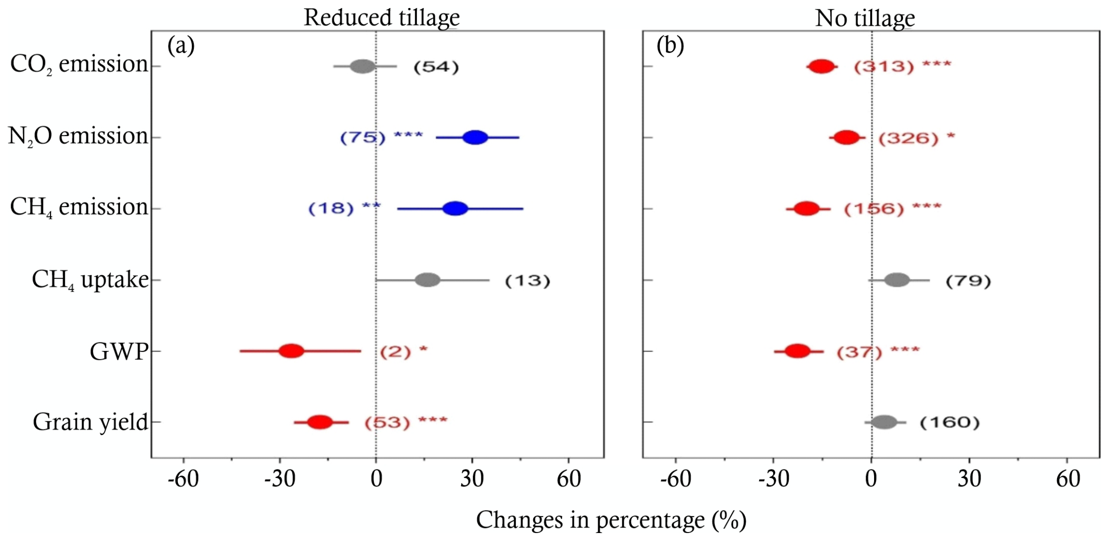

Fig. 6 Impact of zero-tillage and reduced tillage on CO_2, N_2O, CH4 emission, CH_4 uptake, gross warming potential (GWP) and grain yield of wheat (Source: Yue *et. al.*, 2023)

Yue and his co-workers (2023) revealed that reduced tillage leads to a 31.0% increase in N2O emissions and a 24.7% rise in CH4 emissions, while crop yields decline by 17.4%, with no impact on CO2 emissions or CH4 uptake. They also reported that no tillage reduces CO2, N2O, and CH4 emissions by 15.1%, 7.5%, and 19.8%, respectively, and decreases the global warming potential (GWP) by 22.6%, without affecting CH4 uptake. The effects of reduced and no-tillage are influenced by factors such as crop residue retention, cropland type, crop rotation, crop species, and soil physicochemical properties, with the degree of impact varies depending on the greenhouse gas and tillage methods, as depicted in Figure 6. Maucieri *et al.* (2021) and Shakoor *et al.* (2021), after working on previous large meta-analysis datasets, concluded that the reduced tillage did not affect CO_2 emissions, whereas in no-tillage CO_2 emissions reduced by 15.1% as compared to CT. These lower CO_2 emissions under no-tillage management may be attributed to slower rates of organic matter decomposition, due to reduced soil aeration and breakdown of soil aggregates that restrict access to decomposers (Six *et al.*, 2004).

Positive impacts of conservation tillage in rainfed conditions

- Site specific soil water conservation and availability (Lampurlanes *et al.,* 2016).
- Reduced wind and water erosion, (Unger *et al.*, 1988).
- Reduced temperature variability in agricultural systems, (Blanco-Canqui and Lal, 2009).
- Increased soil health and fertility, (Blanco-Canqui and Lal, 2009).
- Improved soil aggregation, enhancing soil structure and stability, (Govaerts *et al.*, 2009).
- Reduced fuel usage, cost savings and environmental benefits, (Hobbs *et al.*, 2008).
- Improved timeliness of agricultural operations, ensuring efficiency, (Hobbs *et al.*, 2008).
- Increased soil biological activity, fostering nutrient cycling, (Hoyle and Murphy., 2006).
- Increased populations of beneficial insects, (Witmer *et al.*, 2003).
- Better use of cover crops and mulches, in mitigating weed–crop interference, weed management strategies, enhancing overall crop productivity, (Kaschuk *et al.*, 2010; Cordeau, 2021).
- Reduced incidence of plant diseases contributing to crop health and yield stability, (Kirkegaard *et al.*, 2008).
- Reduced populations of insect-pests, reducing the need for chemical pest control methods, (Witmer *et al.*, 2003).

- Reduced weed resistance, mitigating challenges associated with herbicide resistance, (Chauvel *et al*., 2009).
- Increased root exploration at various soil depths, enhancing nutrient uptake and overall plant health (Hobbs *et al*., 2008).
- Increased soil biological diversity, contributing to ecosystem resilience and sustainability (Hobbs *et al.,* 2008: Kaschuk *et al*., 2010).
- Increased incorporation of crop residues, better crop rotations, and nutrient cycling, (Fillery, 2001).

Negative impacts of conservation tillage

- Residue handling management at seeding stage, higher reliance on herbicides (Lafond *et al*., 2006)
- Poor seed germination and establishment in the absence of proper machinery (Boomsma *et al*., 2010)
- Higher insect-pest population in certain situations (Harrison *et al*., 1980)
- Lower herbicide efficacy and efficiency under crop residue cover (Chauhan *et al*., 2012)
- Difficulty in soil ameliorant/ incorporation (Costa and Rosolem, 2007)
- Soil nutrient fixation (Kaschuk *et al*., 2010)
- Additional machinery requirement (Hulugalle and Scott, 2008)

Conclusions and suggestions for future perspective

Conservation Agriculture (CA) presents a promising suite of resource-efficient technologies in rainfed areas, yet further research is essential to enhance its widespread adoption. Key areas requiring attention include understanding the synergistic effects of core CA components in rainfed areas—such as zero tillage, permanent residue cover, minimal soil disturbance, crop rotations, and integrated weed management. In dry areas numerous factors influence crop yields under CA compared to conventional tillage, comprehensive site-specific research is crucial. Long-term trials demonstrated a gradual increase in CA crop yields relative to conventional tillage along with environmental benefits. Now a greater emphasis on on-farm research and development is needed. Ultimately, the sustainability of CA systems hinges on balancing global food security, environmental preservation, and farm-level profitability. Therefore, future research endeavors should prioritize these interconnected objectives to ensure the successful and widespread implementation of CA practices.

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Agro-physiological Traits, Nutrient Uptake, Quality and Economics of Oat Cultivation under Saline Water Irrigation and Cutting Management Practices

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Abstract

During *rabi* season of 2022-23 and 2023-24 an experiment was conducted at Research Farm, Agronomy Department, CCS HAU, Hisar to study agro – physiological traits, nutrient uptake, quality and economics of oat cultivation under saline water irrigation and cutting management practices on sandy loam soil. The experiment was laid out in split plot design with irrigation sources (canal and tubewell) and irrigation levels (two irrigation 30 and 60 days after sowing (DAS); three irrigation 30, 60 and 90 DAS) assisted in main plots and cutting management practices {one cut at 50% flowering, two cuts for fodder (60 DAS and at flowering), cut + seed (one cut fodder at 60 DAS and second for seed) and seed (No cut for fodder)} in subplots and was replicated thrice. Irrigation through canal water produced significantly higher grain yield over tube well water irrigation. Similarly, significantly higher yield attributes, yield, nutrient uptake, protein content was recorded under three irrigations over two irrigations. Among cutting management practices, higher monetary benefit was achieved when either the crop was harvested at 50% flowering as fodder crop or harvested as seed crop over rest of the treatment.

Key words: Cutting management, Economics, Irrigation with saline water, Oat, Yield

Introduction

Oat (*Avena sativa* L.) is an important rabi fodder crop used to prepare silage or hay, which is soft, palatable, nutritive and high in protein, fat, vitamin B, and minerals (Pandey *et al.,* 2020). India experiences tremendous shortfall in green fodder production. In recent years, the fodder deficit has further aggravated owing to rapid reduction of pasture and grassland and also due to the poor management of the existing pastures, (Bharti *et al.*, 2021). Increasing fodder and feed demand can be encountered by increasing productivity of fodder to sustain livestock production. Secondly, due to strong antioxidant, anti-inflammatory, anti-proliferative, anti-itching properties and high dietary water-soluble fibre β-glucan level, it is documented as health-beneficial food. Many factors affect oat production, among these irrigation water is of practical significance as irrigation schedule affect productivity and quality aspects of fodder (Jat *et al.,* 2017). Increasing population and declining water resources are posing threat to food and fodder security in arid and semiarid regions and that can be addressed by using poor quality ground water particularly. The crops differ in their tolerance to salinity and application of poor-quality water demonstrating its tolerant nature. (Kumari *et al.,* 2014). In general cutting management follow in fodder crops for higher yields by its influence crop growth, yield and quality.

Material and Methods

Study area

During *rabi* season of 2022-23 and 2023-24 experiment was conducted at Research Farm,

Table 1. Tube well water analysis (pooled)

Source (Tube well)	EC ($dS\ m^{-1}$)	Concentration (meq/l)				
		CO_3	HCO_3	Cl	Ca	Mg
	4.57	0.29	3.5	1.0	1.25	2.95

Agronomy Department, CCS HAU, Hisar, Haryana, India, situated at 29°10′ North latitude and 75°46′ East longitudes at an elevation of 215.2 m above mean sea level.The climate is semi-arid and subtropical, hot and dry summer with mean rainfall of 400 mm.

Experimental details

The texture of the soil was sandy loam and slightly alkaline in reaction (pH: 7.95). The organic carbon, available phosphorus and potassium were 0.49%, 19 kg ha^{-1} and 295 kg ha^{-1} respectively. The experiment was laid out in split plot design with irrigation sources (canal and tubewell) and irrigation levels (two irrigation 30 and 60 DAS; three irrigation 30, 60 and 90 DAS) assisted in main plots and cutting management practices {one cut at 50% flowering, two cuts for fodder (60 DAS and at flowering), cut + seed (one cut fodder at 60DAS and second for seed) and seed (No cut for fodder)}in subplots and was replicated thrice. The seedbed was prepared by applying canal water, and subsequent irrigation was applied as per treatment. The properties of the tube well water sample are given in Table 1.

Single superphosphate and urea were used as the sources of phosphorus and nitrogen, respectively. The oat crop variety HJ 8 was sown on 10th November and 20th November in the growing seasons of 2022-23 and 2023-24, respectively using 75 kg seed/ha.

Agronomical parameters

Agronomical parameters were recorded as per standard described methods. (Kumar *et al.,* 2022)

Nutrient uptake and crude protein

Nutrient uptake was calculated by multiplying the nutrient content (%) with the respective grain yield and expressed in kg ha^{-1} (Kumar *et al.,* 2024). Grain samples were ground after oven drying at 70°C and analyzed for nitrogen, which was estimated by following Micro-Kjeldahl's method (AOAC 1990). Nitrogen percent multiplied by 6.25 and expressed as amount of crude protein in flour.

Physiological parameters

At anthesis stage, normalized difference vegetation index (NDVI) measurements were made using a green seeker, hand held optical sensor unit. SPAD chlorophyll meter reading (SCMR) was taken by chlorophyll meter, which measure the greenness or the relative chlorophyll content of leaves and canopy temperature by infrared thermometry (Goyal *et al.,*2023).

Statistical analyses

The recorded data on growth attributes and yield of oat collected during study years were pooled and analyzed using the online statistical analysis package of OPSTAT and presented at 5% significant level (Sheoran *et al.*, 1998).

Results and Discussion

Agronomical parameters

Sources of irrigation had significant effect on yield attributing character viz., florets/ panicle, panicle length and grain yield. Irrigation through canal water produced significantly higher yield attributing characters and yields (fodder and grain), however, differences were found non-significant in respect of plant height, effective tillers and biological yield. This might be due to the fact saline water restricts the absorption of the nutrients under tubewell irrigation in the root zone by affecting the osmotic potential (Kumari *et al.,* 2014). Among irrigation levels, application of three irrigation produced significantly higher yield attributes and yield except plant height and green fodder yield (Table 2). Satisfactory economic yield associated with tillers per plant and their distribution particularly in forage crops. Increasing levels of irrigation ultimately increased the yield due to increase in growth and yield contributing characters due to photosynthates availability and translocation towards sink organs (Jat *et al.,* 2017). Different cutting management practices had significant effect on yield attributes and yield. Significantly taller plants and yield attributes viz., effective tillers, florets per panicle, panicle length and yield (grain and biological) when crop was grown as seed crop as compared to one cut for fodder and second for seed (Table 2). The taller plants and yield attributing characters may be due to increased uptake of nutrients with increased availability of moisture for plant uptake. This increase in plant height may be attributed to synthesis of food materials, resulting in greater cell division and cell elongation. Significantly higher green fodder yield was registered when crop was harvested as fodder crop at 50% flowering over rest of the treatments (Table 2). It might be due to optimum soil moisture for growth and complementary interaction between vegetative and reproductive growth (Jat *et al.,* 2018).

Nutrient uptake and protein content

Significantly higher protein percent and nutrient uptake in term of N, P and K were found under canal irrigation over tube well irrigation. Nutrient uptake is product of nutrient content and yield, hence superior yield and higher nutrient content in the crop might have resulted in higher nutrient uptake in respective treatments. Correlation coefficients were also calculated, which showed that strong and positive correlation was observed between nutrient uptake and grain yield [Fig. 1(a-c)]. There was a strong and positive correlation between nutrient uptake and grain yield indicating that treatment having higher grain yield absorb more nutrient. Similarly, significantly higher protein percent and nutrient uptake in term of N, P and K were observed under three irrigations over two irrigations (Table 2). Availability of satisfactory volume of moisture to plant not only improves the metabolic process in plant cell but also increase the efficiency of applied mineral nutrients. Biomass production under water stressed condition reduced due reduction in growth of the plants under water deficient condition as compared to well water application.

Table 2. Impact assessment of irrigation and cutting management on growth, yield attributes, yield and economics of oat (pooled two year)

Treatment	Plant height (cm)	Effective tillers/m^2	Florets/ panicle	Panicle length (cm)	Grain yield (kg/ha)	Biological yield (kg/ha)	N uptake (kg/ha)	P uptake (kg/ha)	K uptake (kg/ha)	Crude Protein %	Green Fodder yield (*q/ha)	B:C
Irrigation source												
Tube well	176.45	180.65	69.80	38.00	2212	11404	37.74	7.90	11.64	9.08	339.08	1.13
Canal	180.30	192.30	81.70	40.55	2403	11889	43.02	8.86	13.67	9.66	373.50	1.29
LSD (p=0.05)	NS	NS	3.32	2.52	109	NS	1.88	0.76	0.68	0.17	25.68	-
Irrigation levels												
Two irrigations	177.25	172.3	71.50	37.15	2162	10626	36.95	7.51	11.64	9.12	344.33	1.10
Three irrigations	179.65	200.65	80.00	41.35	2452	12667	43.81	9.21	13.66	9.62	367.92	1.24
LSD (p=0.05)	NS	12.72	3.32	2.52	109	1112	1.88	0.76	0.68	0.17	NS	-
Cutting Management												
One cut at 50% flowering	-	-	-	-	-	-	-	-	-	-	550.39	1.49
Two cuts for fodder	-	-	-	-	-	-	-	-	-	-	364.58	0.90
Cut + Seed	167.45	175.80	72.65	37.80	1890	8553	32.69	6.63	10.21	9.25	153.89	1.21
Seed	189.30	197.15	78.80	40.75	2725	14741	48.07	10.08	15.24	9.49	-	1.44
LSD (p=0.05)	7.27	6.12	3.21	2.35	311	2639	5.63	1.28	1.74	NS	41.24	-

1Q=100 kg, NS= not significant

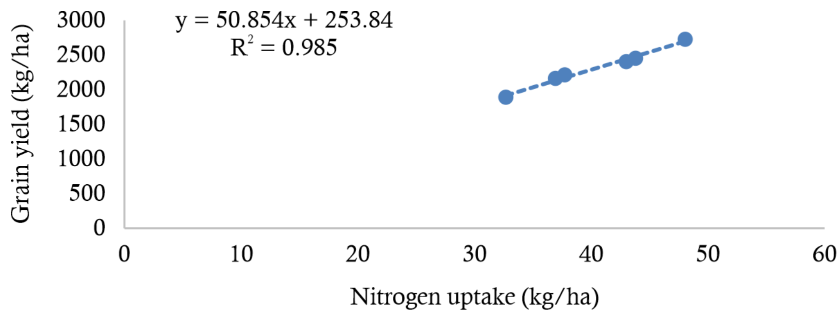

Fig. 1(a) Relationship between nitrogen uptake and grain yield

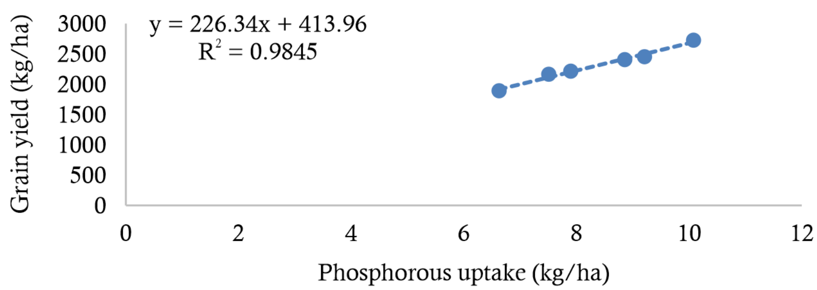

Fig. 1(b) Relationship between phosphorous uptake and grain yield

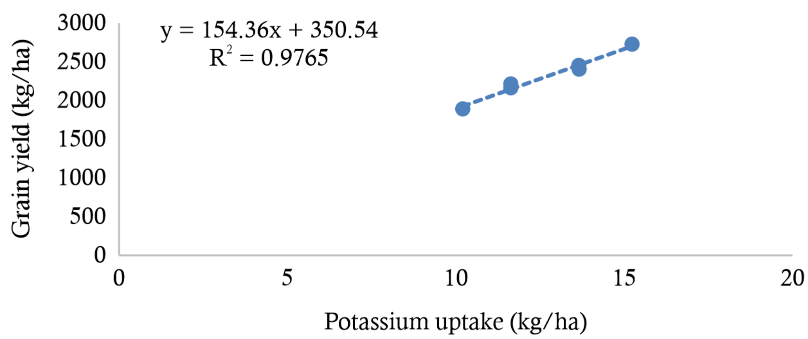

Fig. 1(c) Relationship between potassium uptake and grain yield

Differences were found non-significant in respect of protein percent. Among cutting management practices, significantly higher nutrient uptake was recorded under the treatment when crop was harvested for seed as compared to one cut for fodder and second for seed (cut+ seed). This might be due to additional cut at 60 DAS might have resulted in reduced grain yield in cut + seed treatments which might have resulted in poor nutrient uptake by grains as compared to the treatment when crop was harvested for seed.

Physiological parameters

Irrigation source did not have significant effect on physiological parameters *viz*., NDVI and canopy temperature, however, SPAD value was affected significantly. Significantly higher value of SPAD was recorded with canal irrigation as compared to tube well irrigation [Fig 2(a-c)]. Similarly, Irrigation levels did not have significant effect on physiological parameters viz., NDVI and canopy temperature, however, SPAD value was affected significantly. Significantly higher value of SPAD was recorded with three irrigations as compared to two irrigations [Fig. 2(a-c)]. Cutting management had significant effect on physiological parameters. Correlation coefficients were also calculated, which showed that strong and positive correlation was observed between NDVI, chlorophyll content and grain yield [Fig. 3(a-c)]. This showed that chlorophyll content had direct effect on photosynthesis, leaf water

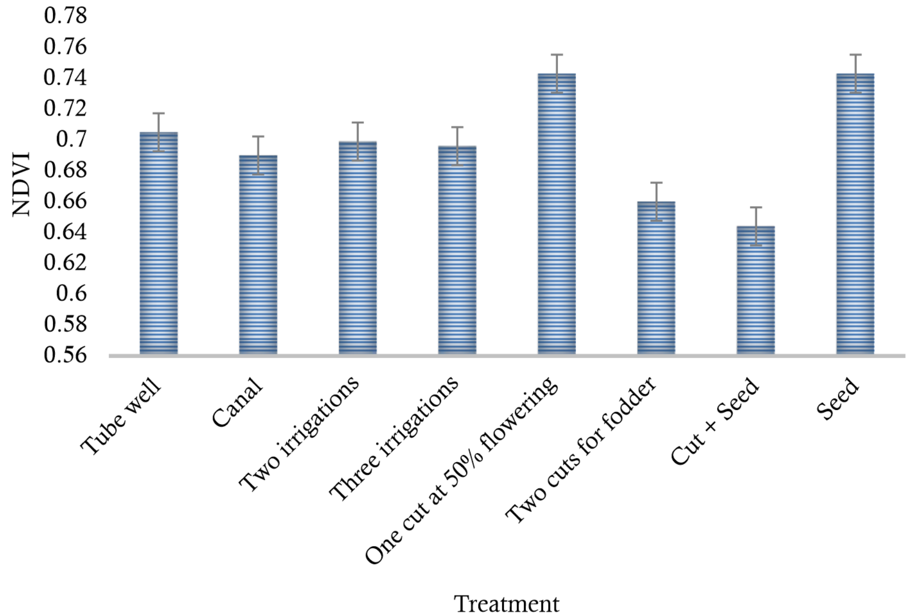

Fig. 2(a) Effect of different treatment on NDVI

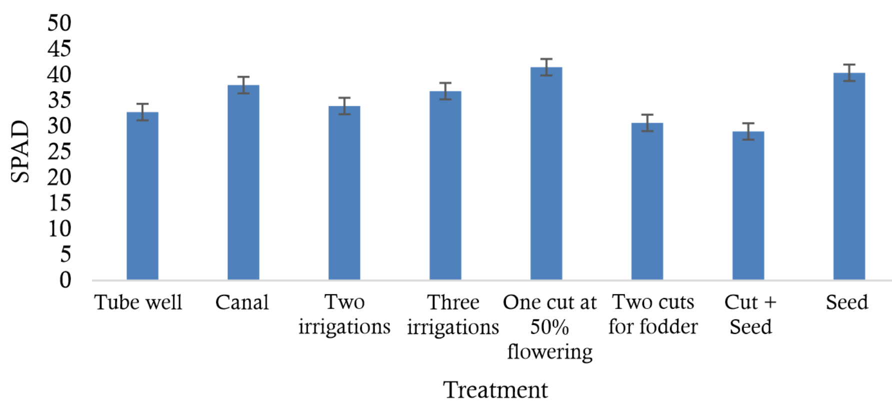

Fig. 2(b) Effect of different treatment on chlorophyll content in oat crop

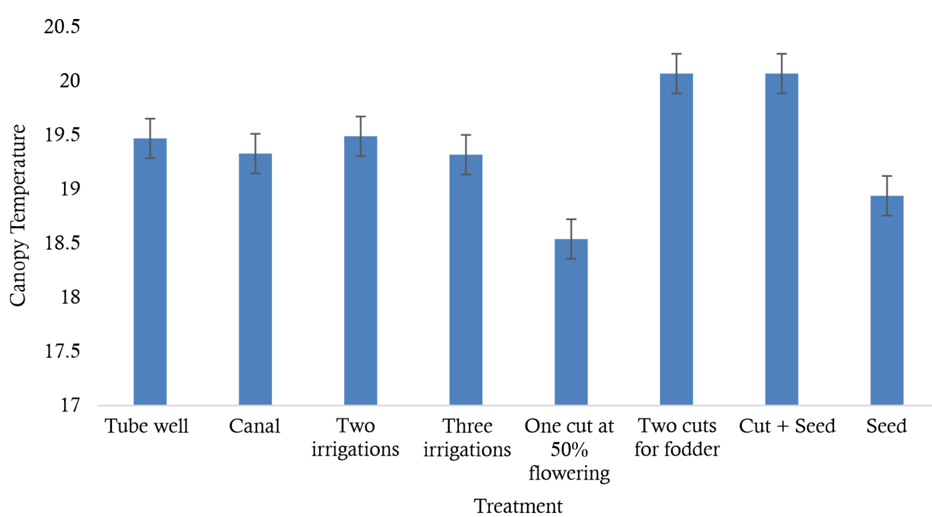

Fig. 2(c) Effect of different treatment on canopy temperature

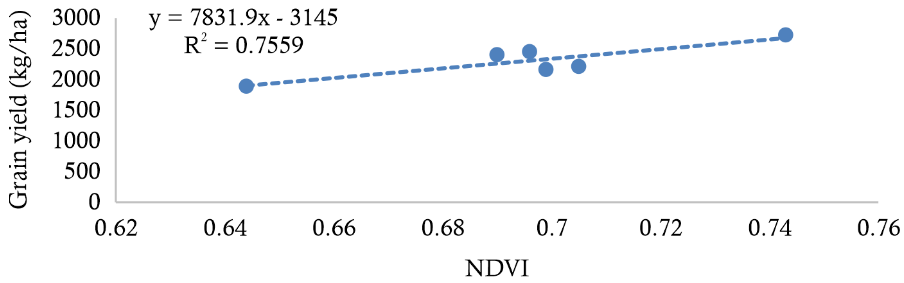

Fig. 3(a) Relationship between NDVI and grain yield

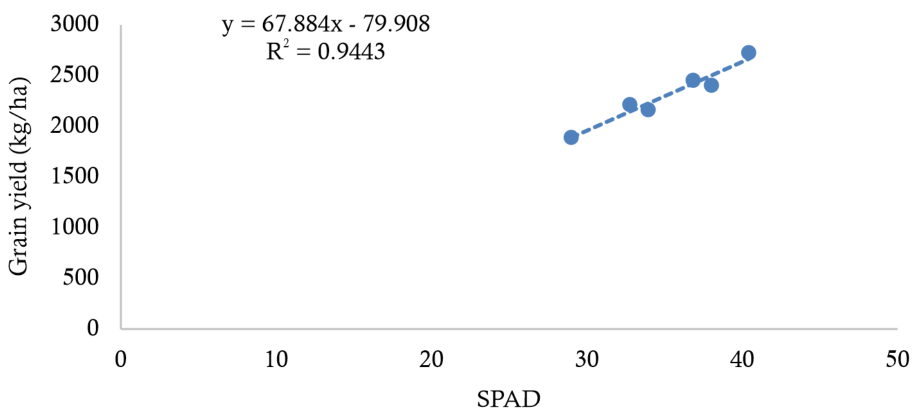

Fig. 3(b) Relationship between Chlorophyll content and grain yield

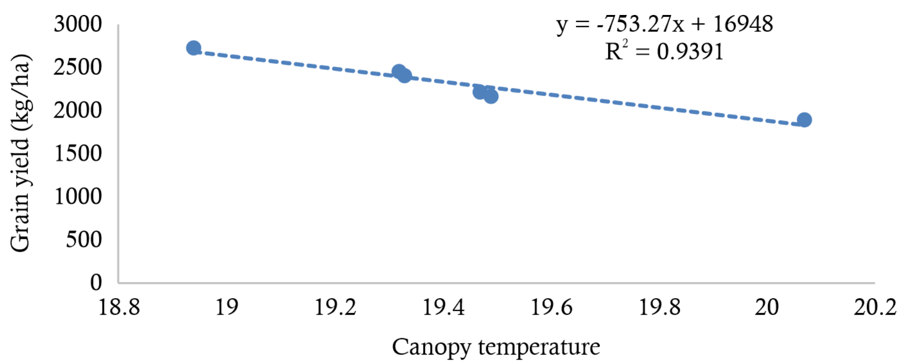

Fig. 3(c) Relationship between canopy temperature and yield

potential and grain yield through formation of yield attributes (Sharma and Kumar, 2014). Higher value of physiological parameters was observed under one cut at 50% flowering and seed as compared to two cuts for fodder and one cut for fodder and second for seed.

Economics

Higher benefit-cost ratio also recorded under canal irrigation as compared to tube well irrigation. Monetary benefits increased with increasing levels of irrigation. Higher benefit-cost ratio recorded with the application of three irrigations over two irrigations. Similarly, higher monetary benefits were achieved when either the crop was harvested at 50% flowering as fodder crop or harvested as seed crop over rest of the treatment.

Conclusions

Significantly higher yield attributes and yield (grain and green fodder) of oat crop was achieved by applying three irrigations with canal water. Among cutting management practices, higher monetary benefit was achieved when either the crop was harvested at 50% flowering as fodder crop or harvested as seed crop over rest of the treatment.

Acknowledgements

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Identification of Suitable Row Spacing, Seeding Rate and Sowing Technique of Quinoa (*Chenopodium quinoa*) under Saline Soil

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Abstract

Agronomic practices are foremost requisite when a new crop is introduced in new agro-ecological regions. Quinoa is newly introduced crop in Indian climate and its agronomic practices are needed to be standardized. We conducted two field experiments to standardize the row spacing, seed rate, and sowing techniques in saline soil during winter season of 2020-21. The first field experiment involved 2 quinoa accessions (EC507740 and CSQ2), 2 row spacing (30 cm and 45 cm) and 3 seeding density (6, 8 and 10 kg ha^{-1}) arranged in Factorial Randomize Block Design. Results showed that both the accessions gave statistically on par grain yield. Row spacing of 45 cm was better in individual plant performance but the grain yield ha^{-1} was obtained significantly higher with sowing in 30 cm row spacing, giving 34.67% yield advantage. Seeding rate of 8 kg ha^{-1} (3.63 Mg ha^{-1}) being on par with 10 kg ha^{-1} (3.74 Mg ha^{-1}) gave significantly highest grain yield of quinoa over 6 kg ha^{-1} seeding rate. The second experiment was comprised of 6 sowing methods viz., T1: broadcasting of seeds in standing water; T2: broadcasting and mixing of seeds in dry soil followed by irrigation; T3: line sowing (1-2 cm depth) in dry soil followed by irrigation; T4: broadcasting of seeds in moist soil followed by irrigation within week; T5: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil followed by light irrigation within week and T6: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil in Randomized Block Design. Results showed that treatments T1, T2, T3 and T4 gave significantly higher % emergence of seedlings compared to that of T5 and T6. As a result of good emergence and stands, these treatments gave higher NDVI values and grain yield over T5 and T6 treatments in saline soil.

Key words: Quinoa, Row spacing, Salinity, Seeding rate, Sowing methods

Introduction

Rising soil salinization has become one of the major environmental threats to food security in arid and semi-arid regions. The salt affected soils presently spreading over approximately 6.74 million ha of agricultural land in India, which are expected to increase further in the future (Sheoran *et al.,* 2021; Kumar *et al.,* 2022). Deteriorating under-ground water quality is another threat in these regions as 32-84% of underground water surveyed as poor quality for irrigation use. Due to scarcity of fresh water availability for irrigation in saline arid and semi-arid areas, farmers compelled to use saline under-ground water. Under such situations, judicious use of poor quality under-ground water with the adoption of efficient drought and salt-tolerant crops coupled with good agronomic practices are the planned strategies for crop production in saline agro-ecosystem (Rai *et al*., 2022).

Introduction of high salt tolerant crops of halophytic and semi-halophytic nature can sustain the productivity of high saline arid and semi-arid areas. Quinoa (*Chenopodium quinoa* Willd.) is one of the such crops recently gained worldwide attention due to its multi-stress tolerability and nutritional quality. It belongs to the Amaranthaceae family originated from stressed areas of Andean region in South America. It is a natural salt tolerant semi-halophyte tolerant to salinity, drought, frost, etc. The Food and Agriculture Organization (FAO) of the United Nations has designated quinoa as a "super crop" due to the crop's resilient ability to grow under all kinds of not-so-favorable conditions (drought, salinity, frost etc.), and for its potential to feed the hungry across the world. Its grains are an excellent source of fiber, protein, minerals, amino acids and vitamins. It has been reported that quinoa can tolerate sea water salinity (40 dS m^{-1}) (Hariadi *et* *al.,* 2011) and could complete life cycle at water salinity levels of 50-75 dS m^{-1} (Eisa *et al.,* 2017). It possesses specific physiological mechanisms and strategic ion compartmentation and accumulation ability, enabling it to grow under various levels of salt stress (Wilson *et al.,* 2002; Prajapat *et al.,* 2023).

Quinoa is a new crop in India and its cultivation is limited to an area of about 8.6 thousand hectares with an average production of 20.6 thousand tonnes (Singh, 2019). It is produced mainly in Andhra Pradesh, Rajasthan, Uttar Pradesh, Maharashtra and Tamil Nadu states, occupying more than 55 percent of total area. Agronomic practices play important role in harnessing the potential yield of crop. However, its potential germplasm and cultivation practices to be followed in saline areas have not been standardized so far in the country. Variable response of quinoa to row spacing and seed rate have been observed in different part of the country. There are very few studies on standardization of agronomic practices in quinoa in India. Ramesh *et al.* (2019) found that sowing on 15th October with crop geometry of 15 cm × 10 cm recorded better yield of quinoa in Telagana. While Bhargava *et al.* (2007) observed that sowing in 25 cm row spacing produced highest foliage yield of quinoa in Uttar Pradesh. Also, the production potential of quinoa in salinity affected areas yet not studied in the country. Quinoa could be a potential crop for diversification in salt affected semi-arid and arid regions and could be source of protein and minerals to combat the nutritional malnutrition in the country. Therefore, the present study was undertaken to standardize the row spacing, seeding rate and sowing methods in saline soils.

Materials and Methods

Site and location

The field experiments were conducted at the Nain experimental farm of ICAR-Central Soil Salinity Research Institute Karnal, Haryana situated at 29°19′7.09″ to 29°19′10.0″ N latitude and 76°47′30.0″ to 76°48′0.0″ E longitude in the Nain village of Sonipat District, Haryana. The soil was sandy loam in texture which classified under mixed Sodic Haplustepts. The site represents semi-arid, subtropical, and monsoonal climate with hot summer months and cooler winter months. The mean annual precipitation of the site is about 680 mm. The initial soil samples taken in the month of October 2020-21 showed 8.13 $pH_{1:2}$, 6-8 dS m^{-1} $EC_{1:2}$, 4.1 g kg^{-1} organic carbon, 121.0 kg ha^{-1} available N, 26.3 kg ha^{-1} available P and 272.3 kg ha^{-1} available K in 0-15 cm soil depth.

Experiment on row spacing and seeding rate

Field study was conducted during winter season of 2020-21 involving two salt tolerant germplasm [EC507740 (AC1) and CSQ2 (AC2)], two spacing [30 cm (G1) and 45 cm (G2)] and three seeding density [6 (S1), 8 (S2) and 10 (S3) kg ha^{-1})]. The experiment was executed in Factorial Randomized Block Design and replicated three times. The salt tolerant accessions screened through previous study (Prajapat *et al.,* 2024) were selected for the study. The field was prepared by passing of two harrows followed by planking. Pre-sowing irrigation was applied and sowing was done in moist soil manually with hand plough at 2 cm depth as per row spacing and seeding rates. High-sodium adsorption ratio (SAR) saline underground water with electrical conductivity of ~3-4 dS m^{-1} and SAR of ~12.4 $mmol^{0.5}$ $L^{-0.5}$ was used for irrigation. One pre-sowing and two post sowing irrigations were applied to crop at 32 DAS and 65 DAS. The crop was fertilized with 30 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} nitrogen. The phosphorus was applied through diammonium phosphate (DAP) fertilizer as basal. After deducting N supplied by DAP as basal, the remaining N was top dressed in two equal parts at 30 days after sowing (DAS) and at 55-60 DAS through urea fertilizer.

The growth, yield and grain yield were recorded at harvest stage of the crop. Plant height was measured from ground level to top of the panicle in cm. No. of branches were counted at 90 DAS. Length of main panicle was measured at harvest stage in cm. Plants from net plot area were harvested manually and threshed after proper sun drying. Grain yield of net plot area was converted in Mg ha^{-1}. Plant samples (excluding grains) were taken at harvest and oven dried at 70 °C. Then 10 ml of di-acid mixture (HNO_3:$HClO_4$

in 10:3 ratio) was added to 0.5 g sample and kept overnight before digestion on electric hot plate. The Na^+ and K^+ concentrations in digested samples were analyzed by using flame photometer (PFP7, Jenway, Bibby Scientifc, UK).

Experiment on sowing techniques

The seed size of quinoa is very small and emergence is very poor if placed deeper or insufficient moisture is available in soil at sowing time. With the objective of standardizing the sowing techniques for getting better emergence and plant stand in saline soil, another field experiment was conducted in the same field during winter season of 2021-22 comprising six sowing methods viz., T1: broadcasting of seeds in standing water; T2: broadcasting and mixing of seeds in dry soil followed by irrigation; T3: line sowing (1-2 cm depth) in dry soil followed by irrigation; T4: broadcasting of seeds in moist soil followed by irrigation within week; T5: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil followed by light irrigation within week and T6: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil. Before sowing, the field was prepared with two passes of harrow followed by planking. Layout was prepared by keeping 4 m × 3 m gross plot sizes. In T1, the plots were irrigated and seeds of quinoa were broadcasted in standing water, while in T2, the seeds were first broadcasted and mixed in dry soil followed by irrigation. In line sowing treatments (T3, T5 and T6), sowing was performed manually with the help of hand plough at 30 cm line spacing as per treatments. In T4, seeds were broadcasted in moist soil and light irrigation was applied within week of sowing. Pre-water soaking of seeds was done for 6 h followed by shade drying in respective treatments. Salt tolerant accession CSQ2 was used in all the treatments with the seed rate of 8 kg ha^{-1}. Fertilization was followed as per previous experiment. Pre-sowing (T4, T5, T6), with sowing (T1, T2, T3) and within week irrigation (T4) was applied with low saline water (~3-4 dS m^{-1}). Subsequent irrigations were applied with high saline water having EC of ~16 dS m^{-1} and SAR of ~26.7 $mmol^{0.5}$ $L^{-0.5}$. Periodical observations on growth parameters, yield attributes and grain yield were recorded.

The emergence per cent in plots was evaluated 10 days after sowing in terms of % ground coverage by the plants visually in seed broadcasted plots. In line sown plots, % emergence in lines was observed as % emergence. Plant height was measured at 45 DAS, 90 DAS and at harvest stage. The number of branches on the main axis of plant were counted at 90 DAS stage. Dry matter accumulation $plant^{-1}$ was recorded at 45 and 90 DAS. The main panicle length (cm) was measured from base of the panicle to top of the panicle. The relative chlorophyll content of top three leaves was measured in terms of SPAD (Soil Plant Analysis Department) values, recorded at 45 DAS and 90 DAS at 09:00–11:00 h with the help of SPAD-502 (DL plus Konica Minolta, Japan). Similarly, Normalized Difference Vegetation Index (NDVI) values were also recorded with the help of Green Seeker hand held sensor (Trimble Inc., USA) by moving the sensor over 30 cm above crop canopy. Plants from the net plot area were harvested manually and threshed. After proper drying, grain yield was recorded and converted in Mg ha^{-1}. Grain samples from each treatment were taken for 1000-grain weight which was measured using seed counter (WAVER IC-VAi, AIDEX Co. Ltd., Japan) and weight recorded in g.

Statistical analysis

The data so obtained from the experiments were statically analyzed following Analysis of Variance (ANOVA) procedure in Factorial Randomized Block Design (FRBD) and one-way ANOVA in RBD for first and second experiments, respectively (Gomez and Gomez 1984). General Linear Model (GLM) procedure in R computer software (R Core Team, 2021) was employed to analysis the data and treatment means were delineated using Least Significant Difference (LSD) test ($p \leq 0.05$).

Results and Discussion

Standardizing row spacing and seeding rate

Results showed that accession CSQ2 recorded taller plants than EC507740 (Table 1). However, both the accessions remained statistically on par in terms of branches $plant^{-1}$ and grain yield ha^{-1} with accession EC507740 recorded numerically higher grain yield. The germplasm EC507740 also

Table 1. Performance of quinoa under different row spacing and seeding rate

Treatments	Plant height at maturity (cm)	No. of branches plant^{-1} (90 DAS)	Length of main panicle (cm)	Test weight (g)	Grain yield (Mg ha^{-1})
Accession					
EC507740	119.7^{A}	16.3^{A}	9.4^{A}	2.97^{A}	3.71^{A}
CSQ2	129.9^{B}	14.7^{A}	9.2^{A}	2.83^{B}	3.33^{A}
Row spacing					
30 cm	123.8^{A}	15.3^{A}	9.1^{B}	2.86^{B}	4.04^{A}
45 cm	125.8^{A}	15.7^{A}	9.4^{A}	2.93^{A}	3.00^{B}
Seeding rate (kg ha^{-1})					
6	121.3^{C}	16.5^{A}	9.8^{A}	2.99^{A}	3.20^{B}
8	123.4^{B}	15.3^{AB}	9.0^{AB}	2.89^{AB}	3.63^{A}
10	129.6^{A}	14.7^{B}	8.9^{B}	2.81^{B}	3.74^{A}

Different capital letters in the same column indicates significant difference at $p<0.05$ using LSD.

recorded significantly the highest test weight (2.97 g) over CSQ 2 (2.83 g). Therefore, both the accession can be used in saline soils of 6-8 dS m^{-1} salinity with saline water irrigation (4 dS m^{-1}).

Among the row spacing, there was non-significant variation in plant height and branches plant^{-1}, while sowing at 30 cm row spacing recorded significantly highest grain yield (4.04 Mg ha^{-1}) than sowing at 45 cm row spacing giving 34.67% yield advantage over broader spacing. Though the yield parameters were numerically higher with 45 cm row spacing with significantly higher test weight, but it could not utilize the ground space efficiently compared to narrow row spacing of 30 cm resulted in lower grain yield on area basis. Ramesh *et al.* (2017) also observed higher grain yield of quinoa with narrower row spacing compared to wider ones.

Increasing seeding density significantly increased the plant height of quinoa being highest with 10 kg ha^{-1} seed rate. There was decrease in no. of branches plant^{-1} with an increase in seeding density and seeding @ 10 kg ha^{-1} recorded significantly lower no. of branches plant^{-1} compared to seeding @ 6 kg ha^{-1}. Grain yield of quinoa significantly increased with increased seeding rate up to 8 kg ha^{-1} (3.62 Mg ha^{-1}) and further increase in seed rate to 10 kg ha^{-1} resulted in non-significant improvement in grain yield of quinoa. The optimum plant stands at 8 kg ha^{-1} seed rate could able to produced higher yield over lower seed rate. Further increase in seed rate to 10 kg ha^{-1} increased the plant stand but at the same time the inter-plant competition might also increase resulting in non-significant increase in grain yield. Gimplinger *et al.* (2008) also opined that higher plant densities above the optimum caused yield reduction in quinoa due increased competition.

The Na content and K/Na ratio in plant did not vary due to any of the treatments (Fig. 1). However, K content was significantly higher in accession EC507740 compared with accession CSQ2. The accession EC507740 shown better tolerance ability, as evidenced from previous study with different salinity levels, through better K uptake to maintain favorable K/Na ratio in plant compared to CSQ2 (Prajapat *et al.*, 2024).

Effect of sowing methods in saline soil

The per cent emergence of quinoa seedlings varied from 53.33 to 91.67% under different treatments significantly (Table 2). Treatments T1 to T3 recorded significantly higher per cent emergence (89.0% to 91.67%) over T4, T5 and T6. Better moisture availability under these treatments by immediate irrigation could result in more germination and emergence. The plant height of quinoa at 45 and 90 DAS was unaffected due to different sowing methods. While plant height of quinoa at harvest stage recorded significantly highest in the treatment T1 (broadcasting of seeds in standing water) which was on par with rest of the treatments except T4.

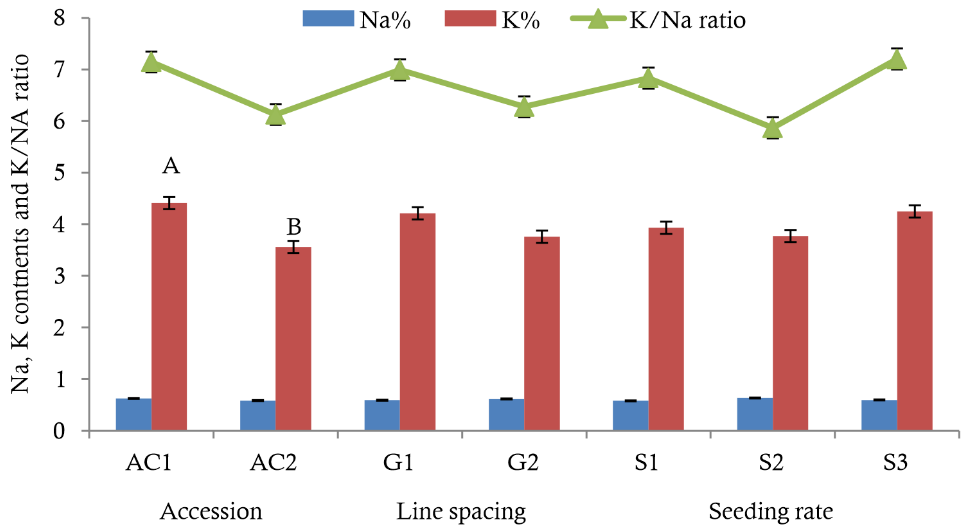

Fig. 1 Effect of different row spacing and seeding rate on Na, K and K/Na ratio of quinoa. AC1: EC507740; AC2: CSQ 2; G1: 30 cm; G2:45 cm; S1: 6 kg ha^{-1}; S2: 8 kg ha^{-1}; S3: 10 kg ha^{-1}. Different capital letters on bars show significant difference at $p<0.05$ using LSD.

Table 2. Effect of sowing techniques on growth attributes of quinoa

Treatment	Emergence (%)	Plant height (cm)			Dry matter accumulation (g $plant^{-1}$)		No. of branches $plant^{-1}$
		45 DAS	90 DAS	Harvest	45 DAS	90 DAS	90 DAS
T1	91.67^{A}	11.89	93.78	95.81^{A}	1.10	9.59^{B}	28.00
T2	91.67^{A}	10.78	94.22	95.56^{A}	0.55	8.59^{BC}	27.00
T3	89.00^{A}	13.00	88.89	90.81^{AB}	0.74	9.05^{BC}	26.22
T4	78.33^{B}	10.22	82.22	85.44^{B}	0.71	15.91^{A}	28.67
T5	76.67^{B}	12.67	90.22	92.37^{A}	0.59	14.35^{A}	27.78
T6	53.33^{C}	12.00	86.67	92.00^{A}	0.80	6.66^{C}	27.67

T1: broadcasting of seeds in standing water; T2: broadcasting and mixing of seeds in dry soil followed by irrigation; T3: line sowing (1-2 cm depth) in dry soil followed by irrigation; T4: broadcasting of seeds in moist soil followed by irrigation within week; T5: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil followed by light irrigation within week and T6: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil Different capital letters in the same column indicates significant difference at $p<0.05$ using LSD.

The dry matter accumulation $plant^{-1}$ was varied non-significantly among the various sowing techniques at 45 DAS but was significantly highest under T4 and T5 treatments over rest of the treatments at 90 DAS stage of the crop. The sparse plant population under these treatments due to poor stand establishment, provided more space to the individual plants might improve individual plant growth and dry matter accumulation.

The no. of branches $plant^{-1}$ at 90 DAS did not vary due to different sowing techniques. The SPAD meter values also remained statistically similar in all the sowing techniques (Table 3). While, the treatments T1-T4 recorded significantly higher NDVI values at 45 and 90 DAS stages over T5 and T6 treatments. The better plant stands under these treatments uniformly covered ground space and attained higher NDVI values compared to T5 and T6 which had poor emergence and overall ground coverage in the plots.

The length of main panicle and test weight was significantly higher under T4 to T6 treatments compared to T1 to T3 treatments (Table 3). Grain yield of quinoa was significantly higher under the treatments T1 (broadcasting of seeds in standing water), T2 (broadcasting and mixing of seeds in dry soil followed by irrigation) T3 (line sowing at 1-2 cm depth in dry soil followed by irrigation) and T4 (broadcasting of seeds in moist soil followed by irrigation within week) treatments

Table 3. Effect of sowing techniques on SPAD, NDVI, yield parameters and yield of quinoa

Treatments	SPAD		NDVI		Length of main panicle (cm)	1000-grain weight (g)	Grain yield (Mg ha^{-1})
	45 DAS	90 DAS	45 DAS	90 DAS			
T1	42.11	53.31	0.37^{AB}	0.76^{A}	7.89^{B}	2.74^{C}	2.60^{AB}
T2	42.11	50.40	0.41^{A}	0.75^{A}	8.17^{B}	2.87^{B}	2.74^{A}
T3	40.11	44.43	0.40^{A}	0.70^{A}	8.39^{B}	2.91^{AB}	2.61^{AB}
T4	45.33	50.29	0.36^{A}	0.69^{AB}	9.11^{A}	2.95^{AB}	2.60^{AB}
T5	43.89	46.73	0.28^{B}	0.67^{B}	9.28^{A}	2.88^{AB}	2.21^{BC}
T6	45.44	50.83	0.27^{BC}	0.66^{B}	9.28^{A}	2.99^{A}	1.95^{C}

T1: broadcasting of seeds in standing water; T2: broadcasting and mixing of seeds in dry soil followed by irrigation; T3: line sowing (1-2 cm depth) in dry soil followed by irrigation; T4: broadcasting of seeds in moist soil followed by irrigation within week; T5: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil followed by light irrigation within week and T6: Line sowing (1-2 cm depth) of pre-soaked seeds in moist soil. Different capital letters in the same column indicates significant difference at $p<0.05$ using LSD.

which were on par with each other but significantly superior over others. In these treatments sufficient moisture was provided by irrigation either immediately or within week of sowing which gave higher emergence % in plots (Table 2). The better emergence ensured the proper plant population and revealed in higher grain yield. These results indicate that good emergence and seed bed is pre-requisite for proper root growth, moisture availability to plants, nutrients absorption, and physical support to the crop (Ali *et al.,* 2020).

Quinoa has very small seeds which limit its deeper placement and seeds to be either broadcasted or placed in shallow depth of 1-2 cm for emergence. When sowing is performed in shallow layers, where moisture evaporates in few days of sowing, a higher but workable moisture level should be ensured at sowing otherwise sowing can be followed by irrigation. Moreover, by selecting appropriate planting technique along with tolerant genotype, good yields could be obtained under saline soil.

Conclusions

We studied the performance of quinoa under row spacing and seeding rate, and different sowing techniques through two separate experiments in saline soils. Both the salt tolerant accessions gave statistically similar yield in saline soils. Narrower row spacing of 30 cm has been found suitable over 45 cm row spacing for better growth and yield of quinoa in saline soil. Seed rate of 8 kg ha^{-1} was found optimum in saline soil of 6-8 dS m^{-1} salinity. However, further experiments involving more combinations of row and plant spacing are required to fine tune the row spacing. To overcome the germination and emergence problem in quinoa it can be sown in relatively higher moisture content or can be broadcasted in dry soil followed by irrigation in light textured saline soil. Alternatively, line sowing in dry soil followed by irrigation can also be adopted in these soils for optimum germination and emergence.

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Impact of Salinity Stress on the Physiological Properties of Fenugreek (*Trigonella foenum graecum L.*): Insights for Sustainable Cultivation Practices

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Abstract

Fenugreek (*Trigonella foenum-graecum*) is widely recognized for its medicinal and pharmaceutical value. However, salinity stress is a major abiotic factor that negatively impacts plant growth and development. This study aimed to examine the effects of different salinity concentrations (50, 100, 150, 200, and 250 mM NaCl) on the physiological and biochemical parameters of fenugreek. Fenugreek is highly regarded for its medicinal and pharmaceutical benefits, yet salinity stress poses a significant challenge to its growth and productivity. This study explored the effects of varying salinity levels on the physiological and biochemical responses of fenugreek. Salinity stress was found to inhibit seed germination, reduce plant biomass, and adversely impact moisture content and chlorophyll levels. While fenugreek demonstrated some tolerance to moderate salinity levels, higher concentrations severely affected its growth and physiological traits. These findings highlight the importance of managing salinity to enhance fenugreek's agricultural performance and productivity.

Keywords: Seed germination percentage, chlorophyll content, plant biomass, salinity stress, *Trigonella foenum graecum*

Introduction

Fenugreek (*Trigonella foenum graecum*) is an annual legume plant that belongs to the *Fabaceae* family. It is cultivated extensively in India and semi-arid regions worldwide due to its recognized medicinal properties (Hasni *et al*., 2009; Aggarwal *et al*., 2013). This plant serves a variety of purposes, including as a spice in cooking, a natural source of dietary fibre, green manure, a vegetable, fodder, and a flavour enhancer, and it is also used as a stabilizer and adhesive in the paper and paint industries (Nathiya *et al*., 2014; Ahmad *et al*., 2016). Furthermore, fenugreek has found its place in the realm of nutraceuticals, proving useful for its physiological benefits. It has been explored as an antioxidant, antibacterial, anticancer, antihelminthic, hypochlolesterolemic, hypoglycemic, and antidiabetic agent (Nathiya *et al*., 2014; Laila and Murtaza, 2015).

India stands as the world's primary fenugreek exporter, a testament to its global significance. The contemporary surge in demand for medicinal plants within the pharmaceutical sector is propelled by a growing inclination toward indigenous medicinal systems. This trend underscores the necessity for the commercial cultivation of medicinal plants, including fenugreek (Qureshi *et al*., 2005). However, an imminent challenge emerges in the form of salinity, a formidable abiotic stressor that significantly impacts fenugreek's agricultural output. This concern is further magnified by the escalating global temperatures, leading to an augmented presence of salinity within agricultural soils (Tuncturk, 2011; Gharshallah *et al*., 2016).

Salinity stress triggers a cascade of effects, manifesting across biochemical, morphological, and physiological dimensions within fenugreek plants. This intricate interplay disrupts osmotic potential, induces extensive oxidative damage, and incites metabolic alterations. The amalgamation of these processes reshapes the plant's response to its surroundings, influencing its growth and productivity. While stress remains a limiting factor throughout a plant's growth stages, juvenile phases are notably more vulnerable to abiotic stresses (Mansour, 2013). Among these, seed germination emerges as a pivotal stage heavily influenced by the characteristics of the growing medium. Salinity can perturb the seeds' absorption potential by altering osmotic potential and metabolic reactions (Attia *et al.*, 2011; Mickky and Aldesuquy, 2017), thereby making seed germination percentage a critical determinant of overall plant productivity. An investigation into the effects of varying salt concentrations on this percentage becomes essential in understanding salinity's impact on fenugreek's agricultural output. Furthermore, fenugreek's yield potential hinges on various factors, including the growth of plant roots, shoots, leaves, and their moisture content.

Consequently, there arises a need to comprehensively explore the effects of salinity stress on fenugreek's physiological parameters. The objectives of this study encompass understanding the effects of salinity stress on: (i) seed germination percentage, (ii) plant root biomass, (iii) plant shoot biomass, (iv) plant moisture content, and (v) photosynthetic pigments - chlorophyll a (Chl a), chlorophyll b (Chl b), and total chlorophyll content (Chl a + Chl b). This study further delves into investigating the salt tolerance limit of fenugreek by scrutinizing all the aforementioned parameters across varying concentrations of NaCl - specifically, 0 (control), 50, 100, 150, 200, and 250 mM. Therefore, the present study seeks to provide a comprehensive insight into how salinity stress influences fenugreek, with the ultimate goal of enhancing our understanding of its resilience and adaptability under adverse conditions. Through a multifaceted analysis encompassing diverse growth aspects, this study aims to contribute valuable knowledge to the realm of fenugreek cultivation and sustainable utilization.

Material and Method

Experimental pot design

A pot culture experiment was conducted to assess the effects of salinity stress on fenugreek. A total of 48 pots, each measuring 26 cm x 32 cm x 19 cm, were prepared. In each pot, 10 kilograms of field soil and organic manure was filled in 4:1 ratio i.e. 25% organic manure was mixed into the soil. Seeds were directly sown in pots, with six seeds in each pot in three replicates. Germination began three days after sowing. Pots were irrigated regularly with tap water. After one month of sowing of seeds, salt stress was induced in plants. This pot test has a formal experimental design, with replication and defined controls and treatments. Plants were grown under natural conditions of temperature, light, and humidity during the growing seasons of fenugreek (February-April).

Salt stress

Six concentrations of NaCl, ranging from 0 mM to 250 mM, were applied weekly to the pots for three months, using 500 mL of saline water for each concentration. Each concentration had three replicates. In the control group (0 mM NaCl), no salt was added, and pure distilled water was used for irrigation. These control pots were irrigated daily with 500 mL of tap water. Salt stress was applied to the plants weekly, using the same concentrations (50 mM to 250 mM) for irrigation with 500 mL of water.

Physiological parameters

Seed germination percentage test

Seeds of fenugreek (*T. foenum-graecum* L.) were kept at 37°C until use. They were sterilized with 15% of sodium hypochlorite for five minutes and rinsed twice with distilled water. The different concentrations of NaCl solution (50, 100, 150, 200 and 250 mM) were prepared in pure distilled water. Pure distilled water was used as control for the study (0mM). All the experiments were done in triplicates. Fifty seeds were placed on filter paper in each petri dish and a 10 ml solution of NaCl was put in each petridish. Fresh solutions were applied every alternate day for the prevention of contaminant and also for the maintenance of concentration. The petri dishes were maintained at 37°C for seven days. The germinating seeds were counted every day. Germination percentage and radical length were determined by the following in each concentration (mean of three replicates) every alternate day during seven days of germination.

$$Germination\ percenage = \frac{Total\ number\ of\ seeds\ germinated\ \times 100}{Total\ number\ of\ seeds\ planted}$$

Estimation of plant biomass

For estimation of plant biomass, the healthy plant parts were collected and the weight of plant root, shoot and leaves was taken and then dried in hot air oven for 30-45 minutes and then measure the weight of dry plant material by the formula i.e.

Plant biomass = Fresh plant weight – Dry plant weight

Estimation of plant moisture content

For estimation of plant moisture content, the healthy plant parts were collected and the weight of plant root, shoot and leaves was taken and then dried in hot air oven for 30-45 minutes and then measure the weight of dry plant material by the formulae i.e.

$$Moisture\ content = \frac{Fresh\ plant\ weight - Dry\ plant\ weight}{Fresh\ weight} \times 100$$

Chlorophyll estimation

0.500 mg of plant extract was mixed with 100 ml acetone and dissolved properly with the help of centrifuge for 15 minutes Chlorophylls a and b were measured with the help of spectro-photometer and calculated according to the formulae of with (Chl a), (Chl b), (Chl a+b) expressed in µg as follows:

$Chl\ a = (12.70)\ A663 - (2.69)\ A645$

$Chl\ b = (22.90)\ A645 - (4.68)\ A663$

$Chl\ a{+}b = (20.21)\ A645 - (8.02)\ A663$

Statistical analysis

Microsoft Excel was utilized for the analysis and interpretation of results. CD values were calculated using HAU-OPSTAT software. SPSS 20.0 was employed for analysis of variance (ANOVA), and Tukey's HSD Post-hoc multiple comparison test was conducted to assess the effect of salinity stress concentration on various physiological properties of fenugreek.

Results and Discussion

Effects of salinity on seed germination percentage of fenugreek

Seed germination is the initial phase of plant growth and considered as the most sensitive stage in its growth cycle. Thus, understanding the effects of salinity stress on seed germination is an important growth parameter in overall production of the particular crop. We investigated the effects of salinity stress on seed germination percentage of fenugreek at different concentrations of NaCl –0, 50, 100, 150, 200 and 250 mM till seven days and the results are shown in Figure 1. The seed germination percentage was 100 percent at day 5 in control samples (0mM NaCl) but it is 90% at 50mM, 80% at 100mM, 50% at 150mM NaCl concentration. However, there is no germination in 200mM and 250mM NaCl concentration at day

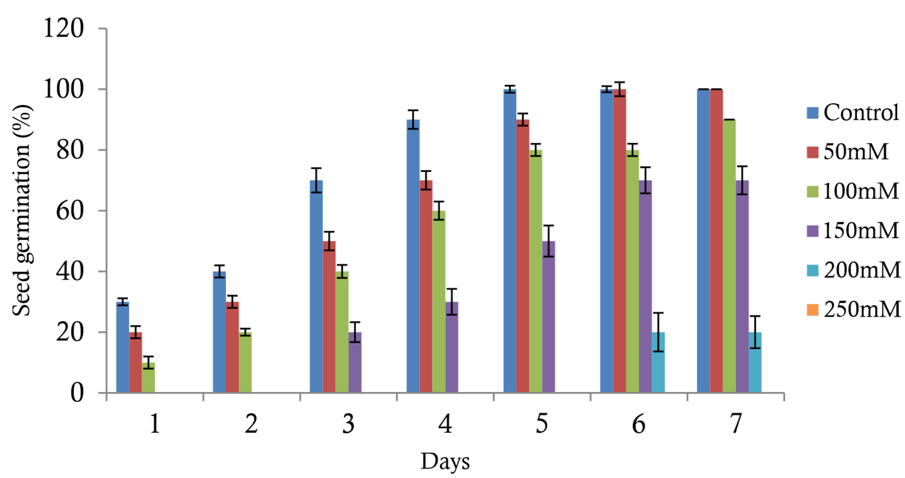

Fig. 1 Seed germination percentage (mean values ± S.E) under different concentrations of salt stress (0, 50, 100, 150, 200 and 250 mM NaCl) were recorded daily up to day 7. No germination was observed at 250mM concentration of NaCl

5 (Fig. 1). Further at day seven, seed germination percentage was 20% at 200mM but zero at 250mM. Thus, salinity stress resulted in significant reduction of seed germination percentage in fenugreek. But with increase in salt concentration above 200mM seed did not germinate and died (Fig. 1). As per the study of seed germination percentage of fenugreek, it was observed that germination percentage was highest in normal distilled water (control).

Our data demonstrated the deleterious effects of salinity on the germination percentage of *Trigonella foenum* seeds. It was observed that the germination process was delayed after salt stress; on day 1, the germination percentage was 30% in the control group, but it was 20% at 50 mM and 10% at 100 mM, with no seeds germinating at 150 mM, 200 mM, and 250 mM salt concentrations. One hundred percent seed germination was observed at 50 mM salt concentration on day 6; however, under other salt stress conditions (100 mM to 250 mM), seed germination did not reach 100%. Furthermore, the effects of salinity concentrations were investigated using analysis of variance (ANOVA), and we found significant effects ($F_5 = 632.2$; ***$P < 0.001$) on the seed germination percentage of fenugreek (Table 4). Thus, our results suggest that salt concentration delayed the germination process, with the delay increasing as salt concentration rose. Salinity disrupts the process of water absorption by seeds and inhibits the hydrolysis of seed reserves, both of which are primary and essential conditions for seed germination (Begum *et al.*, 2010). This understanding of the plant's response to salinity stress has important implications for breeding strategies aimed at improving salt tolerance in fenugreek. Future breeding efforts could focus on selecting fenugreek varieties with enhanced germination performance under saline conditions or on incorporating salt-tolerant traits through traditional breeding or molecular techniques.

Effects of salinity on plant biomass of fenugreek

The yield potential of fenugreek refers to the total biomass produced or the agriculturally significant portion of the crop, which arises from the integration of metabolic reactions within the plant. Hence, any factor that influences the plant's metabolic activity during any growth stage can profoundly impact its overall yield. In our investigation, we carefully assessed fenugreek's plant root and shoot biomass under varying salinity concentrations. Notably, we observed a noticeable decrease in both plant root and shoot biomass as salinity concentrations increased. This finding underscores the complex interplay between salinity stress and the plant's growth dynamics.

Root biomass

The effects of salinity on the fresh and dry root weights of fenugreek were studied at NaCl concentrations of 0, 50, 100, 150, 200, and 250 mM, with results summarized in Table 1 and

Table 1. Data (mean values ± standard error) showing the effects of different concentrations (0, 50, 100, 150, 200 and 250 mM) of NaCl on fresh and dry weight of root, plant root biomass, plant root moisture content of fenugreek.

Salt concentration (mM)	Fresh Root weight (g)	Dry Root weight (g)	Plant root Biomass (g)	Plant root moisture content (%)
Control	0.452 ± 0.006	0.058 ± 0.003	0.394 ± 0.007	72.22 ± 2.16
50	0.381 ± 0.009	0.055 ± 0.003	0.326 ± 0.008	68.24 ± 1.89
100	0.360 ± 0.010	0.053 ± 0.001	0.307 ± 0.006	65.50 ± 2.06
150	0.335 ± 0.013	0.052 ± 0.002	0.283 ± 0.007	62.73 ± 3.14
200	0.244 ± 0.018	0.048 ± 0.004	0.196 ± 0.008	59.28 ± 2.78
250	0.185 ± 0.016	0.045 ± 0.005	0.140 ± 0.009	53.25 ± 2.19
CD	0.022***	0.053***	0.051***	5.023***
Decrease% (Control vs. 250mM)	59.07	22.41	35.53	26.27

****P*-values<0.001

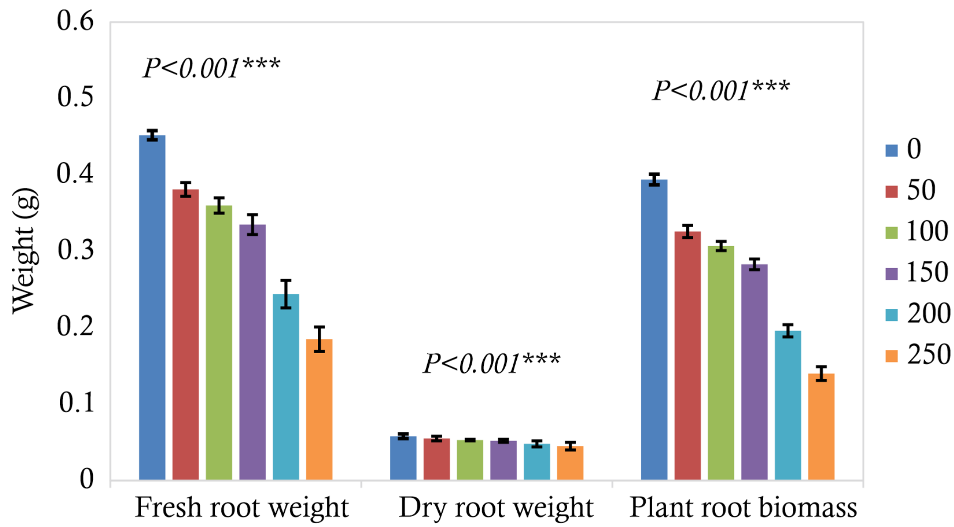

Fig. 2 Effect of different concentrations of NaCl (0, 50, 100, 150, 200 and 250 mM) on fresh root weight (A); dry root weight (B); and plant root biomass (C) of fenugreek. There is significant decrease in fresh root weight; dry root weight and plant root biomass of fenugreek with increase in salt concentrations; P<0.001***= statistically significant

Figure 2. The mean fresh root weight in the control group was 0.452 g, which progressively decreased with increasing NaCl concentrations: 0.381 g at 50 mM, 0.360 g at 100 mM, 0.335 g at 150 mM, 0.244 g at 200 mM, and 0.185 g at 250 mM (Table 1, Fig. 2A). A significant reduction (59.07%; CD = 0.022***) in fresh root weight was observed at 250 mM compared to the control (Table 1). A similar trend was noted for dry root weight, with a 22.41% reduction at 250 mM NaCl (control = 0.058 g, 250 mM = 0.045 g; Table 1, Fig. 2B). Plant root biomass was also lowest at 250 mM NaCl (0.140 g) compared to the control (0.394 g) and other NaCl concentrations (0.326 g at 50 mM, 0.307 g at 100 mM, 0.283 g at 150 mM, and 0.196 g at 200 mM; Table 1, Fig. 2C).

Tukey's HSD multiple comparison test, performed through ANOVA, revealed significant effects of salinity on fresh root weight (F_5 = 303.56; ***P < 0.001), dry root weight (F_5 = 30.24; ***P < 0.001), and root biomass (F_5 = 118.15; ***P < 0.001) (Table 4). These reductions can be attributed to the accumulation of salt in the roots, which led to more pronounced reductions in biomass at higher NaCl concentrations (e.g. 250 mM). The accumulation of salt disrupts water uptake and nutrient absorption, impairing root growth and overall plant development. The significant reduction in root growth under salt stress highlights the urgent need for breeding strategies that focus on enhancing the salt tolerance of fenugreek. The development of salt-tolerant varieties would enable sustainable cultivation in saline soils, which are prevalent in many arid and semi-arid regions. Breeding programs can focus on selecting genotypes with better root architecture, improved salt exclusion mechanisms, or enhanced osmotic adjustment to cope with saline conditions. In addition to traditional breeding, molecular techniques such as marker-assisted selection (MAS) and genetic engineering could accelerate the identification and incorporation of salt-tolerant traits. By targeting genes involved in ion transport, stress signaling, and root growth regulation, breeders can develop fenugreek varieties capable of thriving in high-salinity environments.

Shoot biomass

Data for the fresh and dry shoot weight of fenugreek in control and at different salt concentrations were shown in Table 2 and Figure 3. Significant reduction in fresh (72.95%) and dry weight (95.09%) of shoot were observed with increase in concentration of saline stress (Fig. 3A and 3B). Plant shoot biomass of fenugreek was found lowest (0.094g) at 250 mM concentration of NaCl as compared to control (0.517g) and other concentrations i.e. 0.429, 0.337, 0.255 and 0.155g at 50, 100, 150, 200 mM of salinity stress (Table

Table 2. Data (mean ± standard error) showing the effects of different concentrations (0, 50, 100, 150, 200 and 250 mM) of NaCl on fresh and dry weight of shoot, plant shoot biomass, plant shoot moisture content of fenugreek

Salt conc.	Fresh shoot weight (g)	Dry Shoot weight (g)	Plant Shoot Biomass (g)	Plant shoot moisture content (%)
Control	0.721 ± 0.007	0.204 ± 0.011	0.517 ± 0.008	87.16 ± 1.02
50	0.623 ± 0.009	0.194 ± 0.012	0.429 ± 0.005	86.23 ± 1.09
100	0.512 ± 0.008	0.175 ± 0.010	0.337 ± 0.008	84.52 ± 0.98
150	0.422 ± 0.010	0.167 ± 0.014	0.255 ± 0.012	83.13 ± 1.52
200	0.267 ± 0.017	0.112 ± 0.016	0.155 ± 0.013	80.39 ± 1.37
250	0.195 ± 0.021	0.101 ± 0.015	0.094 ± 0.018	76.39 ± 1.64
CD	0.041***	0.023***	0.035***	4.236***
Decrease% (Control vs.250mM)	72.95	95.09	81.82	12.35

****P*-values<0.001

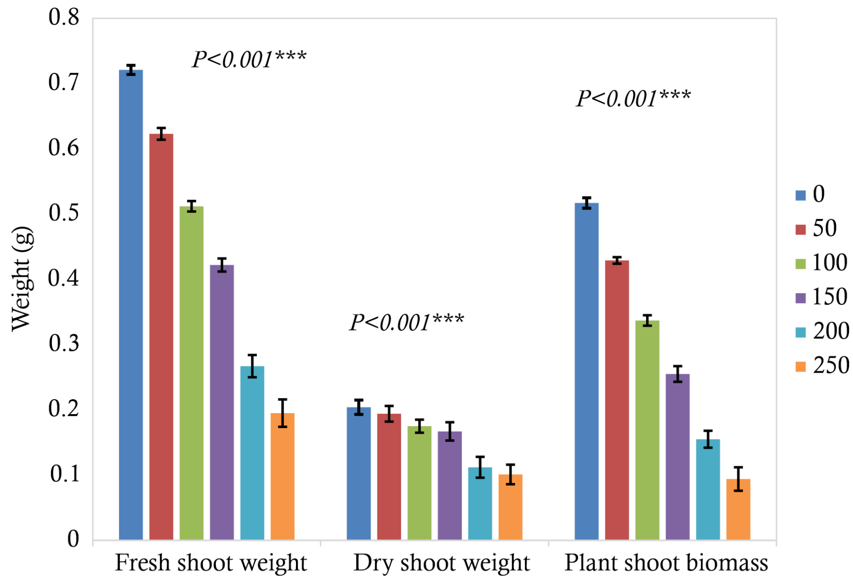

Fig. 3 Effects of varied salinity levels (0, 50, 100, 150, 200 and 250 mM NaCl) on fresh shoot weight (A); dry shoot weight (B); and plant shoot biomass (C) of fenugreek. Significant reduction in these parameters is observed as salt concentrations increase, indicating a decline in fenugreek's growth response to salinity stress. *P*<0.001***= statistically significant

2; Fig. 3C). This may be due to higher accumulation of salt leads to disruption in osmotic potential and oxidative damage in the plant which further resulted into reduction in the plant shoot bio-mass. In the present study, percent reduction of shoot biomass was found highest (81.82%) at 250 mm NaCl concentration as compared to control (Table 2; Fig. 3C). Further, effects of salinity concentration on shoot biomass were statistically analysed by ANOVA and found significant values for fresh shoot weight (F_5= 4.57E3; ****P*<0.001); dry shoot weight (F_5= 48.27; ****P*<0.001) and shoot biomass (F_5= 3.95E3; ****P*<0.001) of fenugreek plant (Table 4).

Plant growth, encompassing root and shoot development, is regulated by intricate physiological and biochemical processes. Salinity stress impacts these processes through various mechanisms. Firstly, elevated salinity levels disrupt the osmotic potential of the growth medium, hampering water uptake by plant roots and nutrient absorption, ultimately retarding growth. Secondly, the accumulation of excess salts in plant tissues triggers oxidative stress, damaging cells and impairing metabolic functions, leading to reduced growth.

The balance between shoot and root growth is pivotal for overall plant performance. Salinity-induced changes in this balance directly influence the plant's ability to extract water and nutrients from the soil, affecting its overall growth rate. The observed decline in both plant root and shoot biomass under increasing salinity concentrations underscores fenugreek's vulnerability to salinity-induced stress. In summary, our study highlights the intricate relationship between salinity stress and fenugreek's growth dynamics. The declining trends in plant root and shoot biomass underscores the adverse impact of salinity on the plant's metabolic processes and physiological functions. Understanding this interplay is vital for developing strategies to enhance fenugreek's resilience and productivity, particularly under challenging environmental conditions.

Effects of salinity on plant moisture content

Plant moisture content plays a very important role in seed germination. Plant moisture content increases the fast seed germination rate for growth. Plant moisture content is an important parameter for plants growth, plant height stem height and plant length. Effect of different concentrations of salinity (0, 50, 100, 150, 200, 250mm NaCl) on plant root moisture content and plant shoot moisture content were illustrated in Figure 4A and 4B respectively.

Our data suggested that salinity stress reduced the moisture content of plant root (26.27%) and shoot (12.35%), thus reducing the plant biomass of fenugreek (Table 1 and 2). This reduction in plant root moisture content with increasing salinity stress might be due to restriction in water absorption by fenugreek in saline conditions. We found highest reduction in plant root moisture content at 250mM concentration of NaCl (53.25%) as compared to control (72.22%) and other concentrations of NaCl i.e. 68.24, 65.50, 62.73, 59.23 at 50, 100, 150 and 200 mM NaCl respectively (Table 1; Fig. 4A). Similar decreasing trends of plant shoot moisture content were found in the present study (Table 3; Figure 4B); which is in concordance with the previous studies in fenugreek (Niknam *et al*., 2006, Talukdar, 2012). Further, statistically significant effects of salinity concentration were suggested by results of ANOVA for plant root moisture content (F_5= 14.87; ***P<0.001) and plant shoot moisture content (F_5= 480.49; ***P<0.001) of fenugreek (Table 4). Thus, this study suggested the deleterious effect of salinity on the moisture content of plant root and shoots which further leads to reduction in plant biomass and agricultural productivity of fenugreek.

Plant moisture content serves a pivotal role in the process of seed germination, profoundly influencing its speed and growth. Additionally, it holds paramount importance as a parameter for various aspects of plant growth, such as plant height, stem height, and overall plant length. The impact of diverse salinity concentrations (ranging from 0 to 250 mM NaCl) on both plant root and shoot moisture content is visually represented in figures 4A and 4B, respectively.

Our findings unmistakably indicate that salinity stress leads to a reduction in the moisture content of both plant roots (by 26.27%) and shoots (by 12.35%), ultimately culminating in a decrease in the overall biomass of fenugreek (Table 1 and 2). This decline in plant root moisture content

Table 3. Data (mean values ± standard error) showing the effects of different concentrations (0, 50, 100, 150, 200 and 250 mM) of NaCl on photosynthetic pigments (chlorophyll a, chlorophyll b, chlorophyll a + b) of fenugreek

Salt concentration (mM)	Chlorophyll a	Chlorophyll b	Total chlorophyll (a + b)
Control	1.438 ± 0.015	3.347 ± 0.039	4.785 ± 0.024
50	1.101 ± 0.057	2.748 ± 0.025	3.849 ± 0.033
100	0.987 ± 0.012	2.134 ± 0.018	3.101 ± 0.020
150	0.962 ± 0.030	1.897 ± 0.016	2.859 ± 0.011
200	0.880 ± 0.025	1.755 ± 0.028	2.635 ± 0.013
250	0.854 ± 0.024	1.710 ± 0.012	2.564 ± 0.014
Decrease (control / 250mM)	0.584	1.639	2.221
Decrease (%)(control / 250mM)	40.61	48.93	46.41

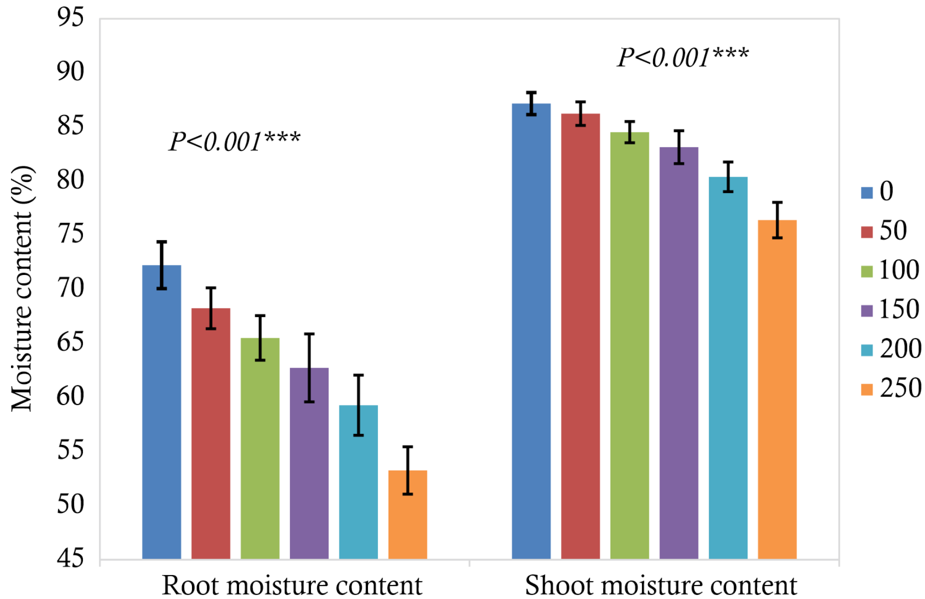

Fig. 4 Effect of different salinity concentrations (0, 50, 100, 150, 200 and 250 mM NaCl) on plant root moisture content (A); and plant shoot moisture content (B). Significant decrease in moisture content after salinity stress were observed for plant root as well as shoot. *P<0.001****= statistically significant

under increasing salinity stress could be attributed to the limited water absorption capacity of fenugreek under saline conditions. Notably, the most pronounced reduction in plant root moisture content was recorded at the highest salinity concentration of 250 mM NaCl, registering a substantial drop of 53.25% compared to the control (72.22%). Similarly, decreasing trends in plant shoot moisture content were also observed, a consistency observed in prior studies on fenugreek (Niknam *et al.*, 2006; Talukdar, 2012).

Furthermore, our statistical analysis through ANOVA underscores the significant impact of salinity concentrations on both plant root moisture content ($F_5 = 14.87$; ***$P < 0.001$) and plant shoot moisture content ($F_5 = 480.49$; ***$P < 0.001$) of fenugreek (Table 4). These results collectively reinforce the notion of salinity's adverse effect on the moisture content of both plant roots and shoots, culminating in diminished plant biomass and a subsequent decrease in fenugreek's agricultural productivity.

Thus, our study underscores the detrimental effects of salinity stress on plant moisture content, a factor that intimately influences growth dynamics and productivity. The reduction in moisture content of plant roots and shoots correlates with the decreased biomass which might be resulted into reduction of agricultural yield in fenugreek under salinity-induced stress. In broader agricultural terms, breeding programs should focus on selecting salt-tolerant varieties of fenugreek that can maintain higher water absorption capacity and moisture retention under saline conditions. By improving the plant's ability to cope with salinity, such breeding efforts could help sustain fenugreek productivity in regions affected by soil salinity. Additionally, integrating sustainable irrigation practices that minimize salt buildup in the soil could further support fenugreek cultivation in saline environments.

Effects of salinity on photosynthetic pigments of fenugreek

To study the effects of salinity on photosynthetic pigments of fenugreek, chlorophyll a, chlorophyll b and total chlorophyll content was estimated at different concentration of salt stress i.e. 0, 50, 100, 150, 200 and 250mM NaCl. Decrease in chlorophyll content was observed at saline conditions as compared to control (Table 3 and Fig. 5). Generally increased salinity causes metabolism disorders those results in inhibition of chlorophyll synthesis (Aggarwal *et al.*, 2013). Reduction in chlorophyll content of fenugreek at saline conditions might be due to degradation of

Table 4. Results of analysis of variance (Tukey's HSD Post-hoc comparison) for the effects of salinity stress (0, 50, 100, 150, 200, 250 mM) on various physiological and biochemical parameters of fenugreek between groups (different NaCl concentrations) and within groups (replicates at each saline concentration). There are six groups for salinity concentrations (0, 50, 100, 150, 200 and 250mM) and three replicates for each group

Sr. No.	Parameters	Salinity	*df*	Mean square	F values	Significance (*P*-values)
1.	Germination (%)	Between Groups	5	5198.267	632.2***	0.000
		Within Groups	12	8.222		
2.	Fresh root weight	Between Groups	5	0.001	303.56***	0.000
		Within Groups	12	0.000		
3.	Dry root weight	Between Groups	5	0.000	30.24***	0.000
		Within Groups	12	0.000		
4.	Plant root biomass	Between Groups	5	0.001	118.15***	0.000
		Within Groups	12	0.000		
5.	Fresh Shoot weight	Between Groups	5	0.028	4.57E3***	0.000
		Within Groups	12	0.000		
6.	Dry shoot weight	Between Groups	5	0.000	48.277***	0.000
		Within Groups	12	0.000		
7.	Plant shoot biomass	Between Groups	5	0.025	3.956E3***	0.000
		Within Groups	12	0.000		
8.	Plant root moisture	Between Groups	5	208.347	14.87***	0.000
	content (%)	Within Groups	12	14.012		
9.	Plant shoot moisture	Between Groups	5	55.037	480.49***	0.000
	content (%)	Within Groups	12	0.115		
10.	Chlorophyll a	Between Groups	5	0.151	21.17***	0.000
		Within Groups	12	0.007		
11.	Chlorophyll b	Between Groups	5	1.301	1.069E3***	0.000
		Within Groups	12	0.001		
12.	Total chlorophyll	Between Groups	5	2.323	253.71***	0.000
	content (a+b)	Within Groups	12	0.009		

df= degree of freedom
****P*-values<0.001

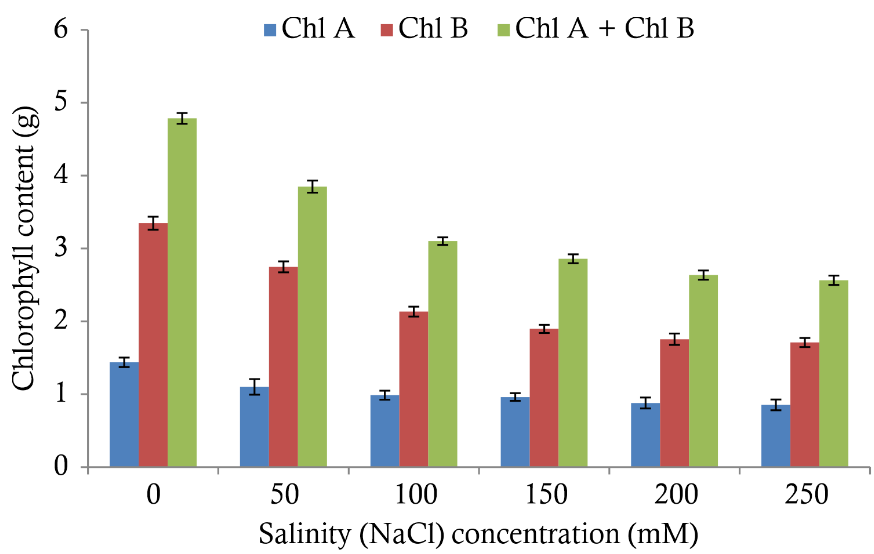

Fig. 5 Amount of chlorophyll A (Chl A), chlorophyll B (Chl B) and chlorophyll A + B (Chl A+ Chl B) in fenugreek leaves at different concentrations (0, 50, 100, 150, 200 and 250 mM) of NaCl. Significant reduction in chlorophyll A, B and A +B was evident after salinity stresses

chlorophyll content and necrosis (Aggarwal *et al*., 2013).

Comparative analysis of effect on chlorophyll content at different saline conditions in the present study showed that maximum reduction of chlorophyll content was observed at 250 mM NaCl condition as compared to control i.e. 40.61% of chlorophyll A, 48.93% of chlorophyll B and 46.43% for total chlorophyll content (Table 4; Fig. 5). Further, analysis of variance showed statistically significant effects of different concentration of salinity stress on chlorophyll a (F_5= 21.17; ***P<0.001), chlorophyll b (F_5= 1.069E3; ***P<0.001) and total chlorophyll content (F_5= 253.71; ***P<0.001) of fenugreek plant (Table 4). Our results showed similar trends observed in the previous studies (Ghorbanpour *et al*., 2011; Al-Saady *et al*., 2012; Talukdar, 2012; Aggarwal *et al*., 2013; Neelesh and Pande, 2015). The significant reduction in photosynthetic pigments under salinity stress directly impacts the photosynthetic efficiency of fenugreek, reducing overall growth, biomass, and yield. This emphasizes the need for strategies to mitigate salinity-induced damage, particularly in saline-prone agricultural regions.

Therefore, one of the practical applications of these findings is the development of salt-tolerant fenugreek varieties through selective breeding. By focusing on traits like higher chlorophyll retention under saline conditions, improved water-use efficiency, and root architecture modifications, breeders could enhance fenugreek's ability to cope with salinity stress. Moreover, optimizing irrigation practices to minimize salt accumulation in the soil and using bio-fertilizers or plant growth-promoting rhizobacteria (PGPR) that enhance plant resilience to salt stress could also be explored. These approaches, combined with breeding for salt-tolerance traits, will help maintain fenugreek productivity in salt-affected soils, ensuring its sustainable cultivation and broader agricultural viability.

Conclusion

This study provides significant insights into the effects of salinity on both the germination and vegetative growth stages of fenugreek (*Trigonella foenum-graecum*). The results demonstrate that increasing salinity levels, particularly above 200 mM NaCl, severely inhibit seed germination, indicating that fenugreek seeds are highly sensitive to salt stress. The identified germination tolerance threshold of 200 mM NaCl suggests that salinity management is critical during the early stages of plant development. During the vegetative growth stage, fenugreek exhibited a higher degree of salt tolerance, with the ability to withstand up to 250 mM NaCl. However, this tolerance came at a significant cost, as high salinity levels led to pronounced reductions in biomass, moisture content, and chlorophyll levels. The decline in root and shoot biomass, along with the compromised moisture retention and photosynthetic efficiency, highlights the negative impact of salinity on plant physiology and growth. In conclusion, while fenugreek can tolerate moderate salinity during its vegetative phase, the adverse effects on plant growth and productivity underscore the importance of managing soil salinity and irrigation practices in fenugreek cultivation. Maintaining optimal soil conditions is essential to prevent yield losses in saline environments, making it crucial for commercial growers to address salinity stress to ensure sustainable production of fenugreek.

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Application of Arjuna (*Terminalia arjuna*) Bark for Adsorptive Removal of Cadmium (II) ions from Simulated Water

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Abstract

The goal of this study was to prepare affordable, easily accessible, and ecologically friendly adsorbent from arjuna (*Terminalia arjuna*) bark and used to remove cadmium ions (Cd^{2+}) from simulated water. To study the influence of various experimental variables such as *p*H (2–8), adsorbent dose (0.01–0.04 g/50mL cadmium solution), contact time (10–100 min), and initial metal concentration (10–100 mg/L); batch experiments were performed. The characterization of the biosorbent was carried out using energy-dispersive X-ray (EDS), field emission scanning electron microscopy (FESEM), and Fourier-transform infrared spectroscopy (FTIR). Utilizing atomic absorption spectroscopy (AAS), the concentration of Cd(II) in an aqueous solution was determined. The arjuna bark biosorbent showed the maximum removal capacity of 72% at optimized *p*H 6. The experimental data revealed that Freundlich isotherm model fitted well as compared to Langmuir model. The positive ÄHp indicates that the adsorption of Cd (II) was endothermic. The current investigation showed that cadmium ion-contaminated water could be successfully remedied using processed powdered arjuna bark adsorbent.

Key words: Cadmium, adsorption, arjuna Bark, isotherm

Introduction

Water is a necessary component of life, civilization, and the earth's environment. The release of heavy metals into water bodies poses a major health risk since elevated levels of these metals in water can harm both the environment and human health (Lakherwal, 2014; Lim and Aris, 2014). Common sources of heavy metal contamination in this environment include the mining industry and its wastes, motor vehicle emissions, lead-acid batteries, paints, fertilisers, soil erosion, leaching of heavy metals, treated timber ageing water supply infrastructure, and microplastics floating in the world's oceans (Azimi *et al*., 2016). Cadmium ions, one of the heavy metals present in wastewater, is regarded as one of the most hazardous pollutants and results in hypertension, emphysema, testicular distortion, and kidney damage (Jalbani and Soylak, 2014). Conventional methods including membrane, separation, evaporation, ion exchange, chemical precipitation, and flocculation that are used to remove heavy metal ions are inefficient and expensive (Rezania *et al*., 2016; Janani *et al*., 2022). The use of biosorbent has grown over the past few decades in comparison to the previously discussed methods because of its great efficiency, convenience of use, cost, and environmental friendliness. (Wang *et al*., 2021). To study the properties of the biomass such as the surface conduct and functional group; scanning electronic microscopy and Fourier transform infrared spectroscopy was used. Arjuna bark is used to assess the effects of operating variables such as initial *p*H, contact time, biosorbent dosage, temperature, and initial metal ion concentration on the cadmium (II) ions removal. Through studies of adsorption isotherms, thermodynamics, and kinetics, the mechanism of metal removal is examined. Studies on the desorption and reusability of arjuna bark are also conducted in order to demonstrate the effective adsorption of cadmium (II) ions in artificial wastewater. This research was conducted in C.C.S.H.A.U. Hisar, Haryana.

Material and Methods

Cadmium nitrate, sodium hydroxide pellets, buffer solutions and nitric acid were purchased from Hi-media chemicals. Arjuna bark was shade-dried for a period of thirty day and was manually ground with a mortar and pestle and sieved. Before being utilized as an adsorbent, the powdered samples of arjuna bark were treated with 400 mL of 1 M HNO_3 (nitric acid) followed by 400 mL of 0.5 M NaOH (sodium hydroxide) for six hours of stirring at 60°C, the biomass was filtered out and given a thorough wash with distilled water (Tomar *et al.,* 2014). Washing proceeded until most of the color disappeared. The adsorbent material was carefully cleaned with deionized water and then dried in an electric oven at 80°C for ten days to make moisture free. The resultant adsorbents were stored in a desiccator for further use in present research work. Appropriate amount of Cd $(NO_3)_2.4H_2O$ were dissolved in deionized water to provide a stock standard solution (1000 mgL^{-1}) of Cd (II) ions and test solutions were prepared from that stock solutions to 20, 30, 40, 50, 60, 70 and 80 mg/L.Cadmium (II) ion concentration in the aqueous solution was measured using an air acetylene burner-equipped atomic absorption spectrometer (AAS) with a slit of 0.7 nm, analytical wavelength of 228.8 nm, the hollow cathode lamp was run at 1.8 L/min of gas flow. FTIR spectrometer was used to record the infrared spectra, which were obtained in the 500–4000 cm^{-1} range. The FTIR spectra of arjuna bark adsorbent was acquired both before and after adsorption. Using FESEM-EDS, the surface morphology of the arjuna bark was studied before and after adsorption. A digital *p*H meter was used for all *p*H measurements. Cadmium (II) ion removal rate and equilibrium data were obtained by batch method analysis of the adsorption process. The cadmium (%) removal and adsorption capacity were calculated using the following equations as recommended by Kayan and Kayan (2007):

$$\%\,removal = \frac{C_o - C_e}{C_o} \times 100 \quad \ldots(1)$$

$$q_e = \frac{(C_o - C_e)V}{m} \quad \ldots(2)$$

Where, C_o (mg/L) & C_e (mg/g) are initial and equilibrium concentrations of the adsorbate, q_e (mg/g) is amount of metal ion adsorbed per unit of the adsorbent at equilibrium, V is the volume of metal ion solution in litre, m(g) is mass of adsorbent.

Results and Discussion

FTIR and FESEM with EDS

The FTIR analysis of arjuna bark provides insight into the interactions between functional groups during the adsorption process. FTIR plots for unloaded biosorbent and Cd(II) loaded biosorbents exhibit a shift in the wavenumbers of the main peaks as clearly shown in Fig 1. The -OH stretching is represented by the broad peak at 3450–3300 cm^{-1}, which is most likely caused by the presence of lignin, carbohydrates, and cellulose groups in the biosorbent. The peak that can be seen at 2950–2800 cm^{-1} is most likely caused by symmetric and asymmetric C–H bond stretching, which is indicative of the presence of lipid content. (Yashni *et al.*, 2021). The C=O stretching peak is located at 1650–1600 cm^{-1}, whereas the highly asymmetric -COO and $-CH_3$ groups (caused by proteins) are responsible for the peaks at 1450–1400 cm^{-1} and 1250 cm^{-1}. Moreover, the high bending vibration of the alkyne, the C=O bond of the carboxylic acid group, and the asymmetric stretching of C–C can

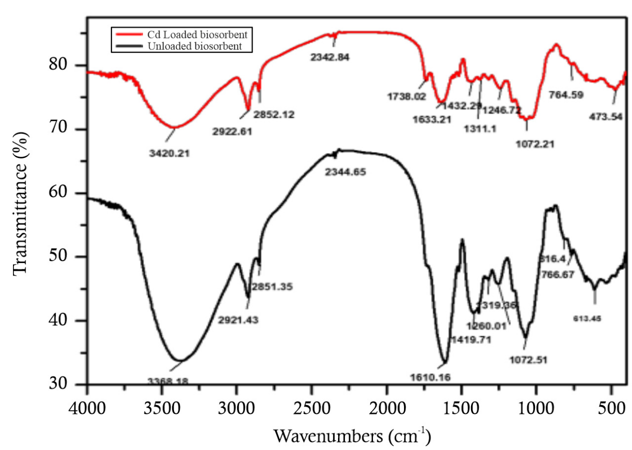

Fig. 1 FTIR spectra of biosorbent before and after metal adsorption

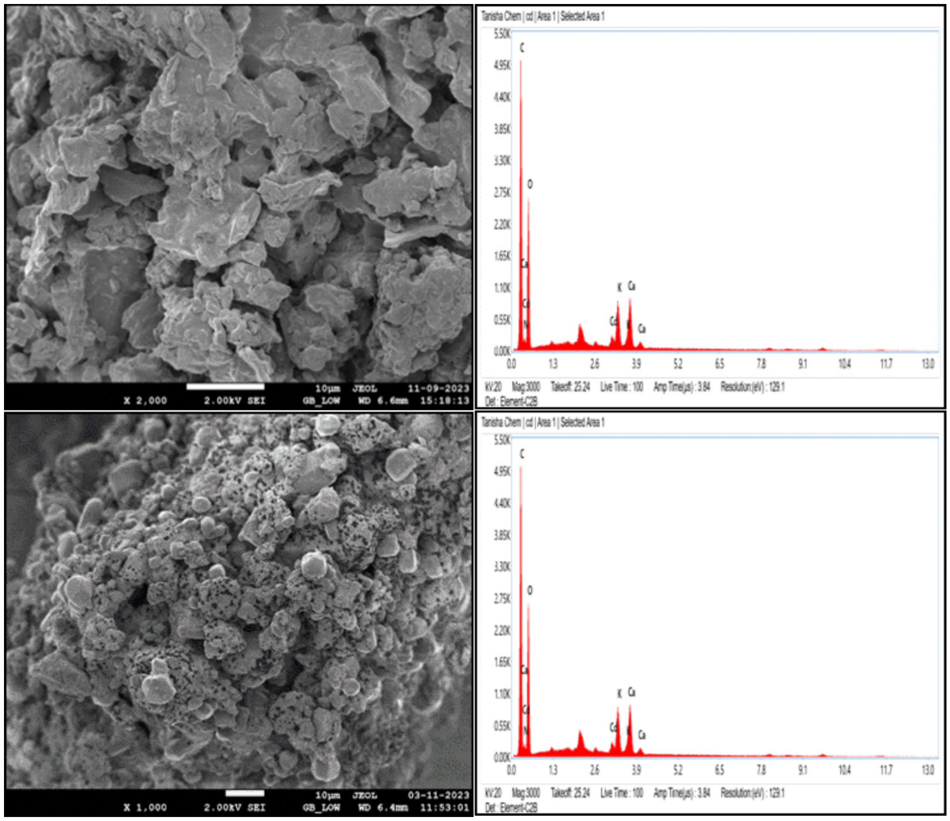

Fig. 2 FE-SEM micrograph of biosorbent- (a) before (b) aftermetal adsorption

be responsible for the peaks at 890.3 cm^{-1}, 1050–1000 cm^{-1}, and 766.63 cm^{-1}. After biosorption, peak was observed at 500-450 cm^{-1} due to metal ions present in biosorbent. The microstructure and surface morphology of the unloaded biosorbent and Cd(II) loaded biosorbents is done using the FESEM equipped with EDS. As shown in fig 2(a) arjuna bark has porous structure and after adsorption of cadmium ions porosity was degraded (fig 2 (b)).

Adsorption Studies

To determine how arjuna bark powder could effectively remove cadmium under different conditions, various batch experiments were investigated at 30° C. The following sections have covered a number of aspects that affect an adsorbent's efficiency in removing cadmium.

Influence of pH

The effect of *p*H was studied by varying the *p*H (2-8) in different sets of 250 mL polypropylene flasks that containing 50 mL of cadmium ion solution of 20mg/L concentrations followed by the addition of 10 g of powdered arjuna bark adsorbent. As shown in fig 3(a) per cent removal of cadmium ion was increased with increase in the pH of the solution. At low *p*H values, adsorbent surface is highly protonated (Joshi *et al.*, 2020; Kataria *et al.*, 2018). At higher pH values, the degree of protonation on the surface of adsorbent is reduced continuously. Thus, for adsorption of cadmium ion; studied *p*H was observed at 6. Eventually at basic region, cadmium adsorption rate dropped due to formation of soluble hydroxylated groups (Das *et al.*, 2022).

Influence of contact time

The impact of contact times on the adsorbent's ability to remove cadmium from powdered samples of arjuna bark was investigated by adjusting the contact time between 10 and 100 minutes at different adsorbent dose of 10 g/50 mL (10-100 mg/L cadmium), *p*H 6, and temperature of 30 °C. It was found that as contact time increased it also increased the percent removal of cadmium ions as shown in fig 3(b). Removal of cadmium ions was increased

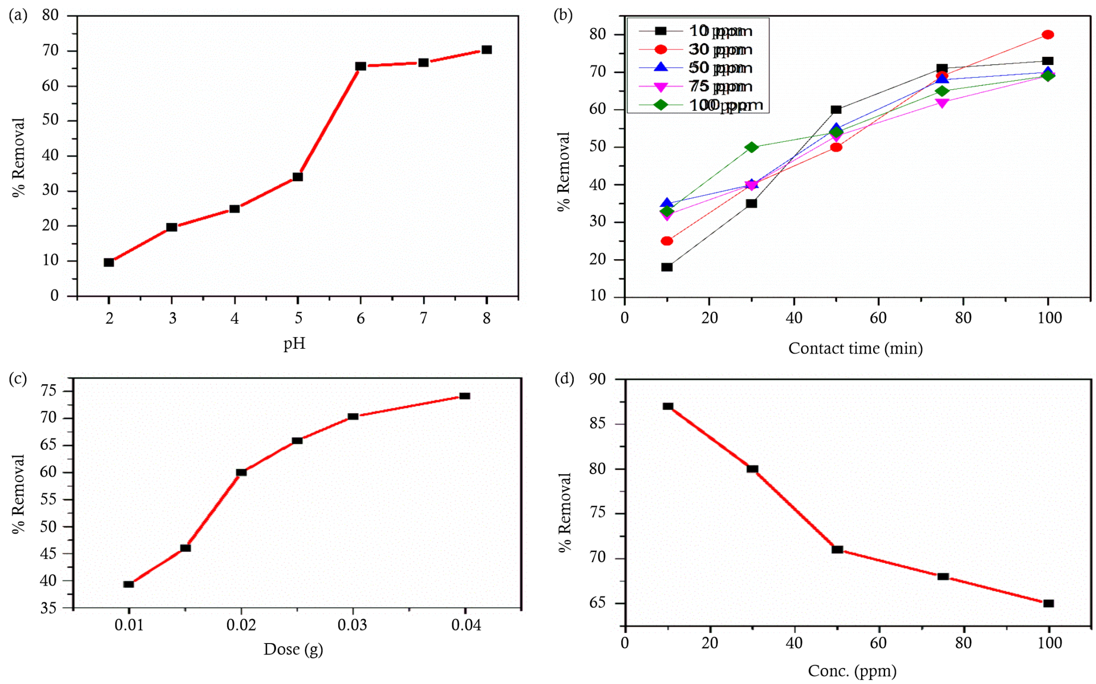

Fig. 3 Effect of (a) *p*H (b) contact time (c)adsorbent dose (d) various concentration

continuously up to initial 70 min. Further there is no significant effect on cadmium removal on increasing time up to 100min. At that time equilibrium is attained and active sites gets saturated (Daniel *et al*., 2022; Fertu *et al*., 2018; Ezeonuegbhu *et al*., 2021).

Effect of adsorbent dose

The amount of adsorbent dose was varied between 0.01 to 0.04 g/50mL to examine the impact of increasing adsorption dosages on the percentage removal of cadmium. The starting cadmium ion concentration was set at 10 mg/L, the contact time was kept at 70 minutes, and the *p*H of the adsorption medium was remained at 6. As the adsorbent dose increased concurrently with the removal effectiveness, as demonstrated in Fig 3(c). The results show that 70% of the cadmium ion was effectively removed at an adsorbent dosage of 0.04 g/50 mL. This could be as a result of the surface area growing with the adsorbent dose, creating more active sites available for the adsorption of the adsorbent. (Nag *et al*., 2018).

Effect of various initial cadmium concentration

The adsorption of Cd (II) metal ions onto adsorbent was assessed at varying concentrations of metal ions (10, 30, 50, 75, and 100 mg/L) while maintaining constant values for the other parameters (pH 6, adsorbent dose of 0.03g, contact time 70 min, temperature 30°C, and stirring speed 200 rpm). The findings demonstrated that as metal ion concentrations increased, the percentage removal of Cd (II) ions decreased significantly, from 88.7 to 69.7%. The results are shown in Fig. 3(d). With an increase in the initial concentration of cadmium ions, the adsorbent materials' capacity is quickly depleted; at high concentrations, the biosorbent site becomes saturated, which lowers the percent removal (Fawzy *et al*., 2016).

Adsorption isotherm models

The models of Freundlich and Langmuir isotherms are helpful in explaining the adsorption process by various adsorbents (Langmuir, 1918; Freundlich, 1906).

Langmuir isotherm Model

Linear form of Langmuir equation is given in equation 3.

$$\frac{C_e}{q_e} = \frac{1}{q_{max} \cdot b} + \frac{C_e}{q_{max}} \quad \ldots(3)$$

Nonlinear form of Langmuir equation is given in equation 4.

$$q_e = \frac{q_{max} b C_e}{1 + bC_e} \qquad ...4)$$

Where, q_{max} (mg/g) is maximum monolayer adsorption capacity, b (L/g) is Langmuir constant.

Freundlich isotherm Model

Equation 5 & 6 provides the generic formula for the Freundlich equation. The adsorbent's adsorption capacity is denoted by k_f, its adsorption intensity is shown by the Freundlich constant 1/ n, and its equilibrium concentration is represented by C_e.

$$q_e = k_f {C_e}^{1/n} \qquad ...(5)$$

One taking logarithm of Eq. (5) shows linear form of Freundlich isotherm model can be written as Eq. (6).

$$\log q_e = \frac{1}{n} logC_e + logk_f \qquad ...(6)$$

where, qe is the total amount of cadmium ion adsorbed/total weight of adsorbents (mg/g). k_f (mg/g) is Freundlich constant, n is heterogeneity factor that relates to intensity of adsorption. As represented in Table 1, increased correlation coefficients (R^2) for the Freundlich model indicated that the adsorption data could be accurately explained by the Freundlich isotherm model. The powdered Arjuna bark adsorbent was heterogeneous in nature. Stated differently, the adsorption approach adheres more closely to the Freundlich isotherm than the Langmuir isotherm (Mukherjee *et al.*, 2020; Oliveira *et al.*, 2021; Madadgar *et al.*, 2023).

Table 1. Adsorption Isotherm parametersfor cadmium ions

Isotherm Models	Parameters	Values
Langmuir	qmax(mg/g)	142.9
	b(L/mg)	0.069
	R^2	0.820
Freundlich	n	1.714
	Kf(mg/g)	13.62
	R^2	0.983

Kinetics Study

In this work, the pseudo-1st-order and pseudo-2nd-order models were attempted in order to comprehend the kinetic behaviour of cadmium ion adsorption onto arjuna bark. The pseudo first order is expressed in linear form in equation 7 (Samimi and Safari, 2022).

$$\log(q_e - q_t) = \log q_e - (\frac{k_1}{2.303})t \qquad ...(7)$$

Here, qe & qt (mg/g) are adsorption capacity at equilibrium time and at time t(min.), respectively, k_1(min^{-1}) pseudo first order rate constant the value of k_1, q_e, R^2 calculated from linear plot between log(q_e-q_t) vs t.

Pseudo second order is in linear form is represented in equation 8 (Staron *et al.*, 2017).

$$\frac{t}{q_t} = \frac{1}{k_2\, q^2 e} + \frac{t}{q_e} \qquad ...(8)$$

Here, k_2(g/mg min^{-1}) is rate constant of pseudo second order. By plotting graph between t/q_t vs t we can calculate k_2, q_e, R^2 values. The q_e (exp) values from the adsorption experiment are compared to the q_e (cal) value calculated using the kinetic models. Table 2 presents the validation findings and the kinetics model parameters. The pseudo-first order regression coefficient is greater than the pseudo-second order regression coefficient, according to experimental data. The results of the kinetic analysis of the arjuna bark-based adsorbent showed that pseudo-first order fits well, indicating the presence of physical adsorption (Joshi *et al.*, 2020; Kumari *et al.,* 2024).

Thermodynamic studies

The thermodynamic parameter, including Gibbs free energy (ΔG^0) and entropy change (ΔS^0) and enthalpy (ΔH^0) for the adsorption of cadmium ions have been evaluated and verified using equations from 9 – 11 (Umeh *et al.*, 2024).

$$\Delta G^O = -RTlnk_d \qquad ...(9)$$

$$k_d = \frac{C_a}{C_e} \qquad ...(10)$$

Table 2. Kinetics model parameters for cadmium ions

Conc. (mg/L)	Pseudo-first order				Pseudo- second order			
	q_e (exp.)	k_1 min-1	q_e (cal.)	R^2 g/mg min	K_2 (mg/g exp.)	q_e (mg/g scal.)	q_e	R^2
10	14.8	0.584	24.5	0.946	0.0001	15.7	51.3	0.644
30	39.9	0.067	72.9	0.945	0.0003	46.7	71.4	0.928
50	59.8	0.072	91.0	0.952	0.0006	78.6	81.3	0.969
75	80.4	0.080	145.7	0.962	0.0003	112.8	117.6	0.945
100	116.3	0.084	237.8	0.931	0.0003	144.9	161.3	0.984

$$\ln k_d = \frac{\Delta H^O}{RT} - \frac{\Delta S^O}{R} \qquad \ldots(11)$$

Here, k_d is equation constant, R gas constant (8.314 J/mol/K), T is temperature in K,C_a is amount of adsorbate on adsorbent surface at equilibrium. ΔH° & ΔS° was determined from linear plot between $\ln k_d$ vs 1/T. The solid-solution interface's increased degree of randomness is confirmed by the positive values of ΔS° for cadmium ions. Additionally, the endothermic nature of the adsorption process is demonstrated by the positive values of ΔH° for cadmium ions *via* biadsorbent (Gurer *et al.*, 2021). Adsorption process feasibility and spontaneity are confirmed by negative "Gp values of cadmium ions at increasing temperatures, indicating physical adsorption as in Table 3 (Iqbal *et al.*, 2009; Wan *et al.*, 2014).

Table 3. Thermodynamic parametersfor cadmium ions

Temperature (K)	ΔG^O (kJ mol^{-1})	ΔH^O (kJ mol^{-1})	ΔS^O (J mol^{-1} k^{-1})
30° C	-1.92	63.74	211.19
40° C	-2.98	-	-
50° CS	-3.27	-	-

Conclusions

The removal of cadmium ions from simulated water using arjuna bark has been investigated under different experimental conditions in batch process. According to SEM images, arjuna bark's surface is rich in pore structures, which facilitates the adsorption of cadmium ions. The process of cadmium ion adsorption on the surface of arjuna bark was found to involve C=O, C-H, and -OH, according to FTIR studies. Hydrogen bond interactions, electrostatic interactions, and van der Waals forces all played a role in this process. Cadmium adsorption was influenced by the ideal *p*H, starting cadmium concentration, adsorbent dosage, and contact time. Based on adsorption studies, it was found that removal of cadmium ions occurs at *p*H 6. The Freundlich isotherm was closely followed during the adsorption process by the adsorbent. Adsorption kinetics followed pseudo first order, suggesting adsorption mechanism is physical phenomenon. The adsorption process's feasibility and spontaneity are confirmed by the cadmium ions' negative "Gp values as temperatures increase, indicating physical adsorption. The results of this study showed that cadmium ion may be successfully removed from an aqueous environment by using powdered arjuna bark as an low cost adsorbent.

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Phytoremediation Efficiency of *Salicornia brachiata* Roxb. - A Salt Marsh Halophyte on Restoration of Shrimp Farm Contaminated Soil

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Abstract

Global climate change and human interference are progressively increasing the level of salt-affected land. Revegetation of saltlands can be possible through successive cultivation of *Salicornia brachiata*, thereby alleviating a significant constraint on crop productivity. Current experiment was conducted on salt-affected agricultural land contaminated by shrimp farm at Thandavarayan Sholangan Pettai, Cuddalore district, Tamil Nadu, utilizing *Salicornia brachiata* a biological tool to assess its efficacy in mitigating salinity. This study was conducted over a period of 4-months to determine the morpho-anatomical variations, biochemical, antioxidant enzymes and soil physico-chemical properties. The results demonstrated that *Salicornia brachiata* exhibits a robust phytoaccumulation capacity of 290 kg NaCl ha^{-1} which also led to a decrease in the soil pH from 8.8 to 6.8, electrical conductivity from 5.7 to 1.96 dS m^{-1} and sodium adsorption ratio from 17.2 to 6.5 mmol L^{-1}. Gradual increase in plant height, biomass, stem thickness, biochemical, and antioxidant enzyme activity was noticed throughout the experimental period when compared to the control.

Keywords: Bioreclamation, Contaminated soil, Phytoremediation, Shrimp aquaculture, Salinization, *Salicornia brachiata*

Introduction

Plants, being sessile organisms facing various environmental challenges that influence their growth and metabolism. Among these, salinity is a key abiotic stressor significantly affecting plant development. Salinity stress arises from salt accumulation in the root zones, leading to physiological drought and compromised productivity (Kundu, 2022). Soil salinization, often induced by irrigation and anthropogenic activities, severely impacts soil health and plant growth, especially in arid and semi-arid regions (Azadi and Raiesi, 2021).

Shrimp farming plays an important but controversial role in the economic development of many countries in Asia, including India because of the high economic returns and often catastrophic environmental impact of production in coastal areas (Islam, 2008). Saline water runoff from shrimp farms has led to the salinization of farmlands, significantly reducing agricultural productivity (Omofunmi *et al.*, 2016). The release of polluted water resulting in eutrophication, elevated toxicity levels and contaminated sediments (Ojewole *et al.*, 2024). Discharge of waste water effluent from shrimp farm directly into ecosystem was reported in Kolleru region, India (Jayanthi *et al.*, 2018) and Gulf of California (Cardoso-Mohedano *et al.*, 2016). Apart from shrimp culture, nearly 952.2 million hectares (Mha), or about 7% of the world's land area, are affected by salinity, with significant portions in India (Kumar and Sharma, 2020). Currently, 6.73 million ha of India's land was damaged by salinity, with highest land area in Gujarat (2.23 million ha) was followed by Uttar Pradesh (1.37 million ha), Maharashtra, West Bengal, Rajasthan and Tamil Nadu (Kundu, 2022).

Saline soils inhibit plant growth by reducing water potential, causing osmotic stress, ion imbalance, and ion toxicity (Bharti *et al.*, 2016). These stresses affect plants at physiological, biochemical, and molecular levels, leading to decreased yield and altered metabolism (Mansour *et al.*, 2021). High salt levels disrupt homeostasis and ion distribution, cause ion toxicity, and reduce nutrient uptake, ultimately leading to oxidative stress induced by reactive oxygen species (Datta *et al.*, 2019). In order to adapt and live in a challenging saline environment, plants have developed into a highly flexible system that can change its morphological, physiological, biochemical, and molecular mechanisms (Wu *et al.*, 2019). Most halophytes and salt-tolerant plants have evolved specific mechanisms of osmoregulation or salt secretion for survival in the salinized soil (Sharma *et al.*, 2024; Dagar *et al.*, 2024).

Traditional soil remediation methods, including physical drainage and chemical amendments (Fernández *et al.*, 2024), are often costly and inefficient (Zamora-Ledezma *et al.*, 2021). In contrast, phytoremediation studied through halophytes, such as *Suaeda maritima, Sesuvium portulacastrum* (Zhang *et al.*, 2024) and *Suaeda nudiflora* (Joshi *et al.*, 2023), are effective in remediating saline-sodic soils due to their salt tolerance and ability to thrive in high-salinity environments.

This study was conducted to find out the phytoremediation potential of *Salicornia brachiata* Roxb., a member of the *Amaranthaceae* family to assess its growth, anatomy, biochemical content, enzymatic activities and physico-chemical properties of salinity affected agricultural soil due to shrimp culture.

Materials and Methods

Description of the experimental site and field set up

The study site was located (Thandavarayan Sholangan Pettai, 11°24' N latitude and 79°44' E longitude) on the east coast of Tamil Nadu, India, near Pichavaram Mangrove Forest on a degraded agricultural field due to shrimp culture at Thandavarayan Sholangan Pettai, Cuddalore district (Fig. 1). Meteorological data, including rainfall patterns and temperature fluctuations, were obtained from the Faculty of Marine Biology, Annamalai University. The study area is a marshy seasonal wetland, with temperature of 34.5 °C during the summer and 23.9 °C in the winter and an average annual rainfall of 1354 mm. Topographically the site was primarily flat with marsh water logged condition and 31 meter above from sea level. The experimental field (shrimp culture waste water affected land) was properly ploughed and levelled, and 5 m × 10 m plots were designated with 30 cm spacing between seedlings to ensure optimal growth and development. *Salicornia brachiata* Roxb. a salt-marsh halophyte belongs to the Amaranthaceae family was selected for this study. It is an annual, succulent, leafless or leaves reduced to small scales, small bushy, highly branched euhalophyte. One month old seedlings were collected from their natural habitat and immediately transplanted into the nursery bed. After one month, acclimatization period,

Fig. 1 Degraded agricultural field due to shrimp culture at Thandavarayan Sholangan Pettai, Cuddalore district, Tamil Nadu

seedlings with similar size were transplanted into experimental field.

The experiment comprised following two set of treatments with five replicates.

1. Control (non-saline soil)
2. Salt-affected agricultural land (saline soil)

The experimental layout followed a randomized block design (RBD). The field study was conducted on post monsoon season over a four-month period from April 2023 to July 2023. Plant samples were harvested for experimental purposes at an interval of 1st, 30th, 60th, 90th and 120th day.

Determination of physico-chemical properties of soil

Soil samples were randomly collected from the top 20 cm around the rhizosphere layer from *Salicornia brachiata* cultivated soil. One soil core (5 cm diameter) in each pit was collected for determining the soil bulk density. Bulk density was measured by core method from undisturbed soil cores dried for 48 hours at 105°C (Meng *et al.*, 2013). Other soil samples were air-dried and passed through a 2 mm mesh to remove any large particles and plant debris. Prior to initiation of study, soil physico-chemical properties were measured and illustrated in Table 1. The salinity (pH) and electrical conductivity (EC) of the soil samples were estimated from 1:5 soil to water suspension, following the methodology by Jackson, (1973), employing as Elico pH and EC meter for sample analysis. Soil potassium and sodium were quantified using the flame photometer instrument, as described by Stanford and English (1949). Calcium and magnesium content were determined through Versanate titration and chloride levels were measured by using Mohr's titration method outlined by Jackson (1973). The sodium absorption ratio was calculated according to the methodology suggested by Richards (1954).

Table 1. Physico-chemical properties of the soil collected from experimental site before and after cultivation of *Salicornia brachiata*. Values are mean ± SE for five replicates. Statistical significance was determined at $p \leq 0.05$.

Physical properties		
Coarse sand (%)		49.83
Clay (%)		26.52
Slit (%)		21.48
Bulk density (g cm^{-3})		1.42
Textural class		Sandy loam
Chemical properties		
	On 1st day	On 120th day
pH (1:2)	8.8 ± 0.57	6.83 ± 0.31
EC (1:2) (dS m^{-1})	5.7 ± 0.16	1.96 ± 0.05
Na (m mol L^{-1})	53.1 ± 0.91	10 ± 0.16
Cl (m mol L^{-1})	67 ± 1.08	23 ± 0.11
Ca (m mol L^{-1})	10.9 ± 0.17	6.1 ± 0.14
Mg (m mol L^{-1})	12.1 ± 0.13	6.8 ± 0.09
K (m mol L^{-1})	8.2 ± 0.22	4.8 ± 0.19
SAR (m mol L^{-1})	16.1 ± 0.38	6.5 ± 0.16

Phenological variations

Plant height and fresh weight were measured immediately after removing the seedlings from the experimental field. The dry weight of the seedlings was determined after they had been dried for 80°C for 24 hours.

Stem anatomy

Stem bits of 2 cm in length were cut from the mature region and five fully expanded stem were sampled from each environment. The cross section of stem was prepared by using a rotary microtome and observed in a calibrated microscope at 40X magnification.

Biochemical analysis

Plant samples were collected for biochemical analysis at periodic time intervals of 1st, 30th, 60th, 90th, and 120th days. Chlorophyll content was determined following the method outlined by Inskeep and Bloom (1985), while protein levels were estimated by using the Lowry method (Lowry *et al.*, 1951). Proline concentration was measured according to Bates *et al.* (1973), phenol content was assessed following the procedure described by Bray and Thorpe (1954), and glycinebetaine levels were quantified as per the methodology outlined by Grieve and Grattan (1983).

Antioxidant activity

Plant samples were collected at an interval of 1st, 30th, 60th, 90th, and 120th days for enzymatic activity analysis. Catalase activity was determined using the method described by Maehly and Chance (1959), while peroxidase activity and polyphenol oxidase were assessed by following the protocol outlined by Kumar and Khan (1982).

Plant pH and EC analysis

Plant samples were collected randomly from salt affected agricultural land were homogenate and passed through a Whatman No 42 filter paper to remove large particles and plant cell debris. The salinity (pH) and electrical conductivity of the plant samples were estimated from 1:2 plant to water suspension, following the methodology proposed by Jackson (1973).

Bioaccumulation of salts

The quantity of salts removed from the soil was based on the formula reported by Ravindran et al. (2007) as follows:

Total accumulation of salt = total biomass × 1 g biomass accumulated salts

Statistical analysis

The experiments were conducted with five replicates, and the results are presented as the mean ± standard error (S.E.). Statistical analysis was performed using Microsoft Office Excel 2021. A one-way analysis of variance (ANOVA), followed by Duncan's Multiple Range Test (DMRT) test at 5% level of significance (P≤0.05), as described by Snedecor and Cochran (1967).

Results

Growth and morphology

The morphological observations, including field view, leaf variations, and growth characteristics, after 120 days cultivation was shown in Figure 2. Plant height was significantly (p≤0.05) influenced by salt in saline soil. *Salicornia brachiata* exhibited its salt tolerance capacity without showing any morphological injuries while cultivated in saline soil. Plant biomass was significantly (p≤0.05) higher in saline soil. Significant increase in plant height (263%), fresh weight (271 %) and dry weight (320 %) was recorded in *Salicornia brachiata* cultivated in saline soil compared to non-saline conditions, as depicted in Fig.3 and 4. This increase is attributed mainly due to accumulation of substantial amounts of NaCl in the plant tissues, which also contributing to greater leaf production and biomass augmentation. In this study it is also noticed that substantial growth was observed between the 60 to 90-day intervals.

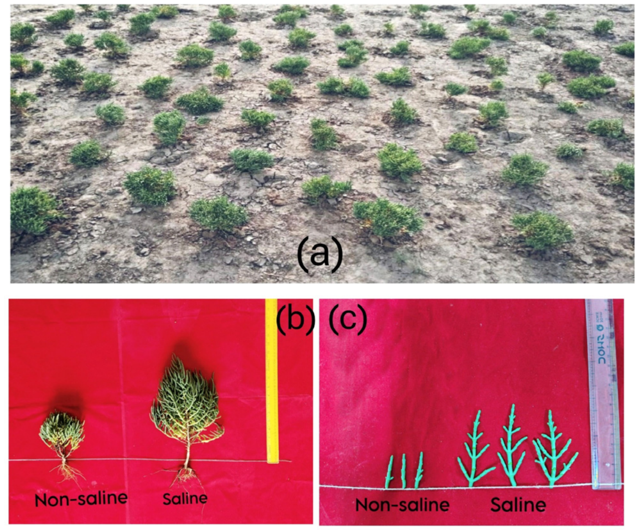


Fig. 2 Field view (a), Growth characteristics (b) and Leaf variations (c) of *Salicornia brachiata* after 120 days of cultivation

Stem (spike) anatomy

Figure 5, represents the anatomical structure of *Salicornia brachiata* grown in non-saline and saline soils over 120 days. The transverse section of the stem (or spike) is a succulent, comprising several distinct layers: the epidermis, cortex, pericycle, and vascular bundles. Stem thickness was measured at 3.4 mm in saline soil and 2.1 mm in non-saline soil grown plants. Similarly, enhanced cell thickness (198 µm) was observed in *Salicornia brachiata* cultivated in saline soil compared to 113 µm in non-saline soil, which aids in maintaining stem water content and turgor pressure, thereby increasing the stem succulence under saline conditions. This study also confirms that *Salicornia brachiata* accumulates significant amounts of salt crystals within its enlarged stem tissues, particularly in the cortical cells and salt glands.

Biochemical studies

Biochemical contents were significantly (p≤0.05) greater in saline soil than non-saline soil. *Salicornia brachiata* cultivated in saline soil exhibits a

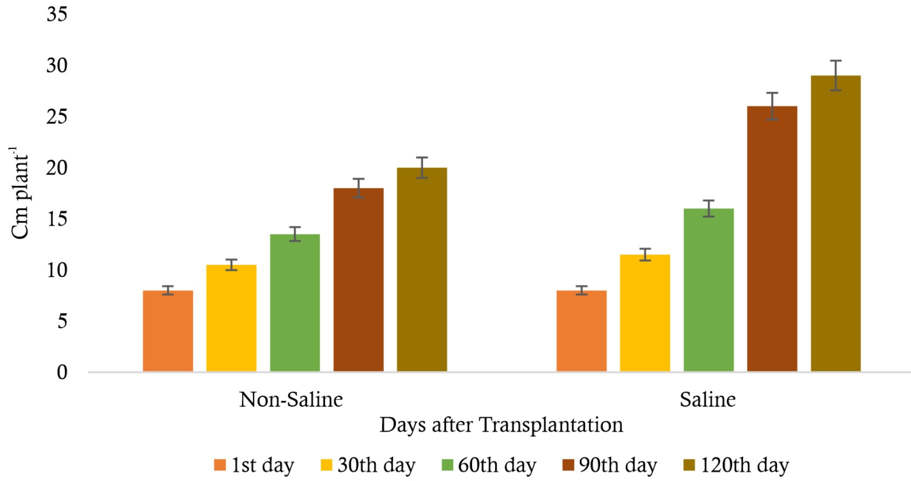


Fig. 3 Plant height of *Salicornia brachiata* cultivated in salt affected agricultural land. Bars are mean ± SE for five replicates

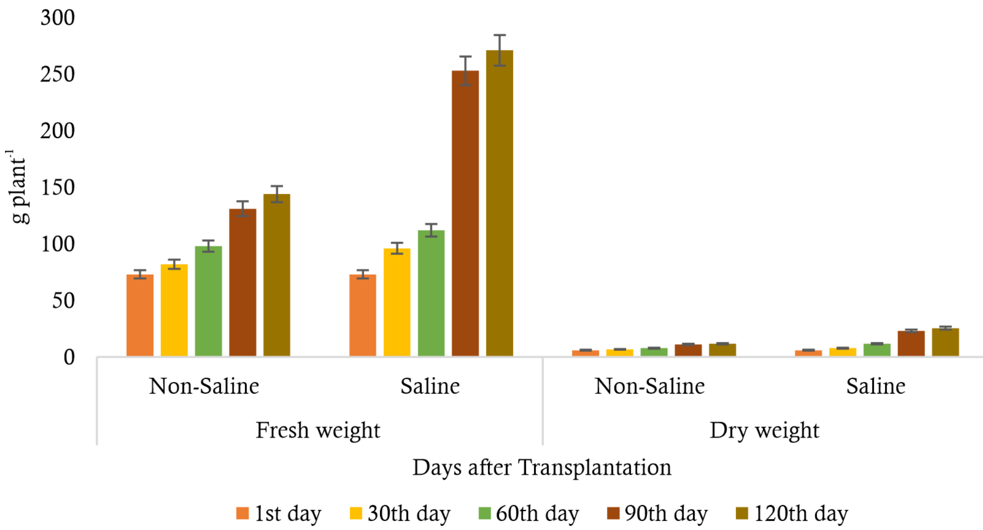
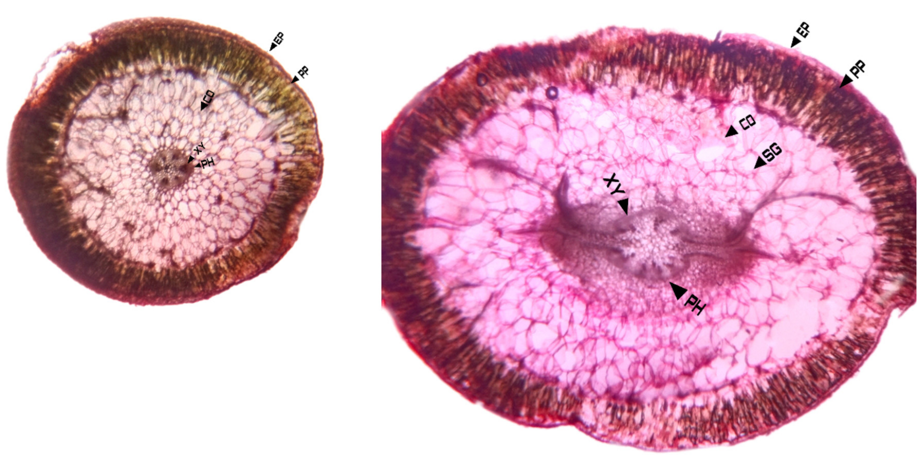


Fig. 4 Plant biomass of *Salicornia brachiata* cultivated in salt affected agricultural land. Bars are mean ± SE for five replicates



(a) Non-saline (b) Saline

EP: Epidermis; MC: Mesophyll cells; PP: Palisade parenchyma;
XY: Xylem, PH: Phloem and SG: Salt glands.

Fig. 5 Stem transverse section of *Salicornia brachiata* grown in control (non-saline soil) and saline (salt affected agricultural land) significant increase in physiological and biochemical constituents after 120 days of growth. Specifically, total chlorophyll, protein, proline, phenol, and glycinebetaine are increased by 358%, 491%, 423%, 91%, and 513%, respectively, compared to plants cultivated in non-saline conditions. These changes underscore the plant's robust adaptive mechanisms to saline environments (Fig. 6).

Antioxidant enzymatic activities

Antioxidant enzymatic activities were significantly ($p \leq 0.05$) influences by salt in saline condition. An increasing trend in catalase, peroxidase, and polyphenol oxidase activity was observed in *Salicornia brachiata* after 120 days of cultivation in saline soil, with an increase of 235%, 496%, and 126%, respectively, compared to plants cultivated in non-saline conditions (Fig. 7). The enzymatic activities progressively increased throughout the study period, peaking between the 60 to 90 days intervals. These antioxidant enzymes play a crucial role in protecting *Salicornia brachiata* tissues from reactive oxygen species and oxidative stress,

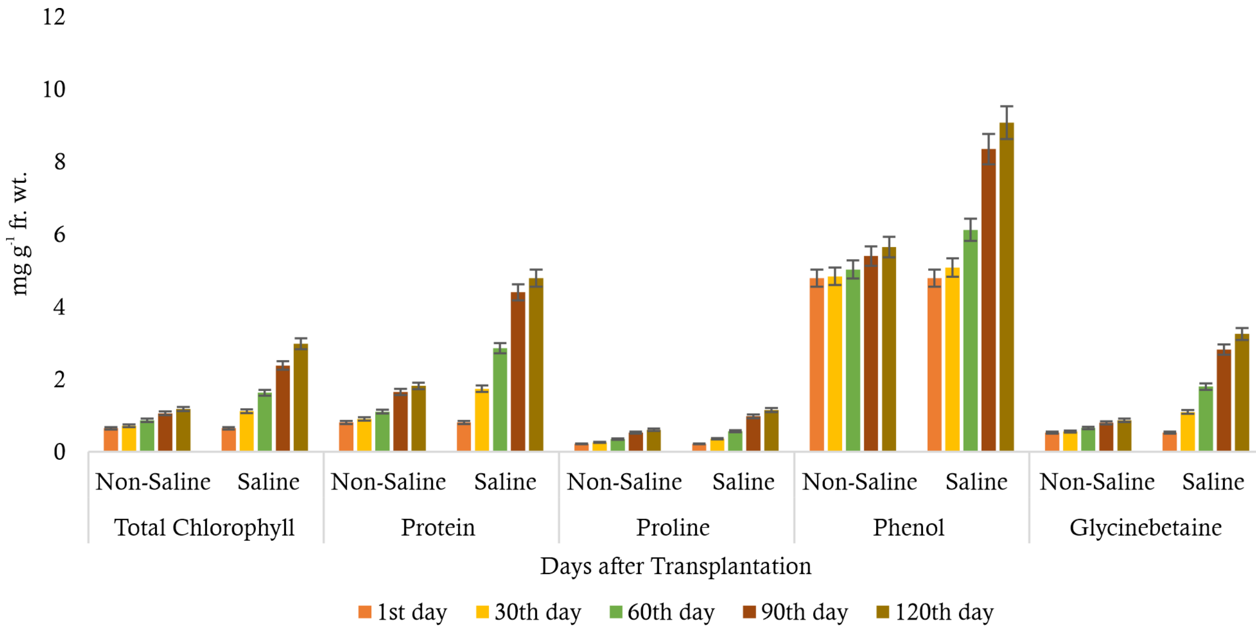


Fig. 6 Biochemical variations of *Salicornia brachiata* cultivated in salt affected agricultural land. Bars are mean ± SE for five replicates

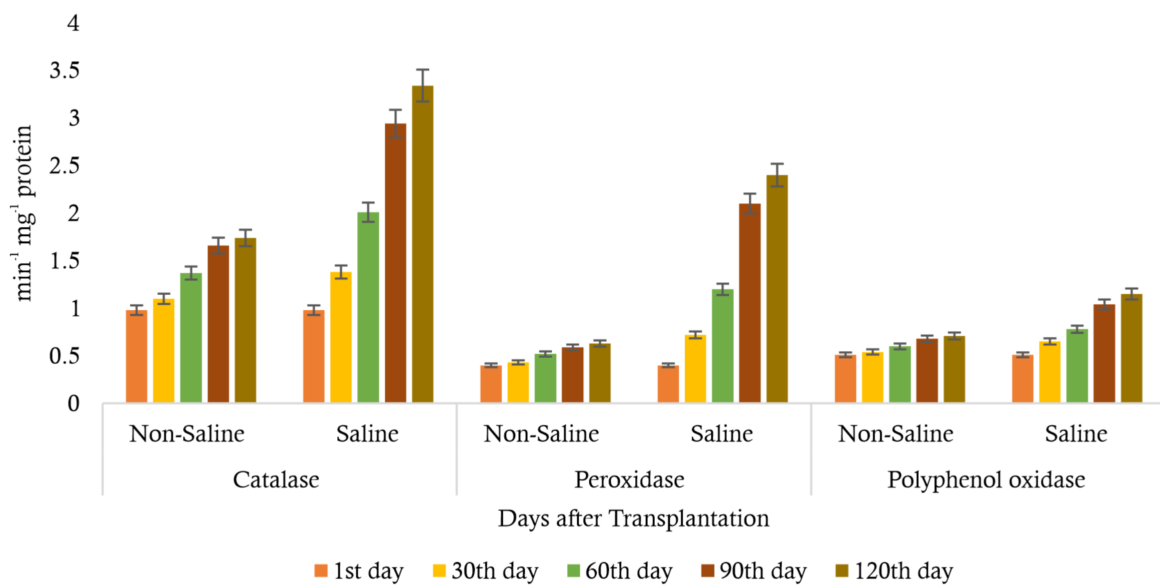


Fig. 7 Antioxidant enzymatic activities of *Salicornia brachiata* cultivated in salt affected agricultural land. Bars are mean ± SE for five replicates

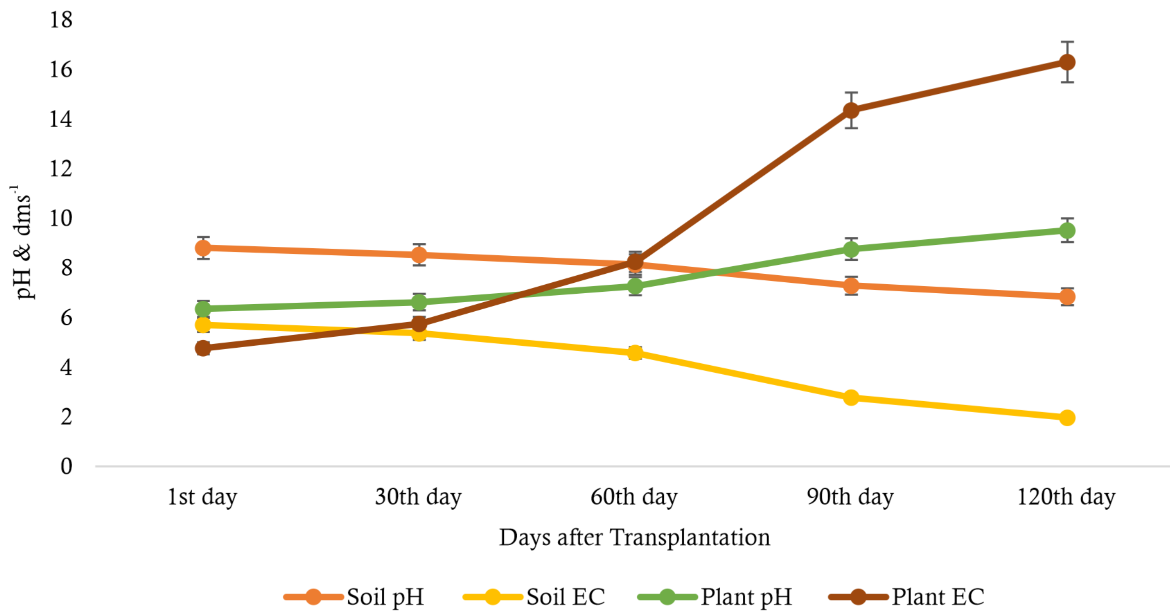


Fig. 8 Soil and plant pH and electrical conductivity of *Salicornia brachiata* cultivated soil. Bars are mean ± SE for five replicates

thereby supporting the plant's growth under saline conditions.

pH and EC of soil samples

In saline soil, the soil pH was significantly decreased from 8.80 to 6.83 after 120 days of cultivation, marking 21% reduction. Concurrently, the electrical conductivity was reduced from 5.7 to 1.96 dS m^{-1} (65% reduction) (Fig. 8).

pH and EC of plant samples

Conversely, the pH of *Salicornia brachiata* plant samples increased from 6.34 to 9.51, and the electrical conductivity from 4.76 to 16.29 dS m^{-1}, representing an increase of 49% and 242%, respectively, after 120 days of cultivation in salt-affected agricultural soil. This rise in pH and electrical conductivity is attributed due to the accumulation of NaCl within the plant tissues (Fig. 8).

Sodium Absorption Ratio

In the current investigation, the Sodium Adsorption Ratio, decreasing from 17.2 to 6.5 mmol L^{-1} (60 % reduction) in soil where *Salicornia brachiata* was cultivated (Fig. 9).

Accumulation of NaCl

Salicornia brachiata significantly reduced the soil salinity by accumulating substantial amounts of

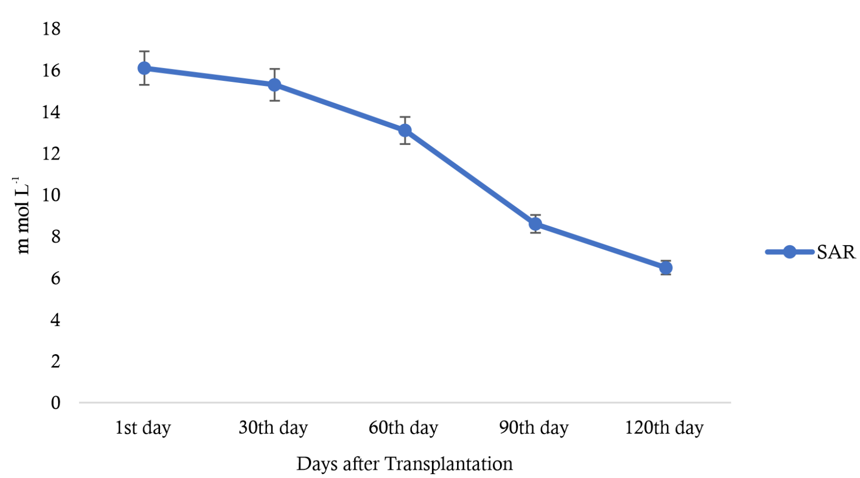


Fig. 9 Sodium absorption ratio (SAR) of *Salicornia brachiata* cultivated soil. Bars are mean ± SE for five replicates

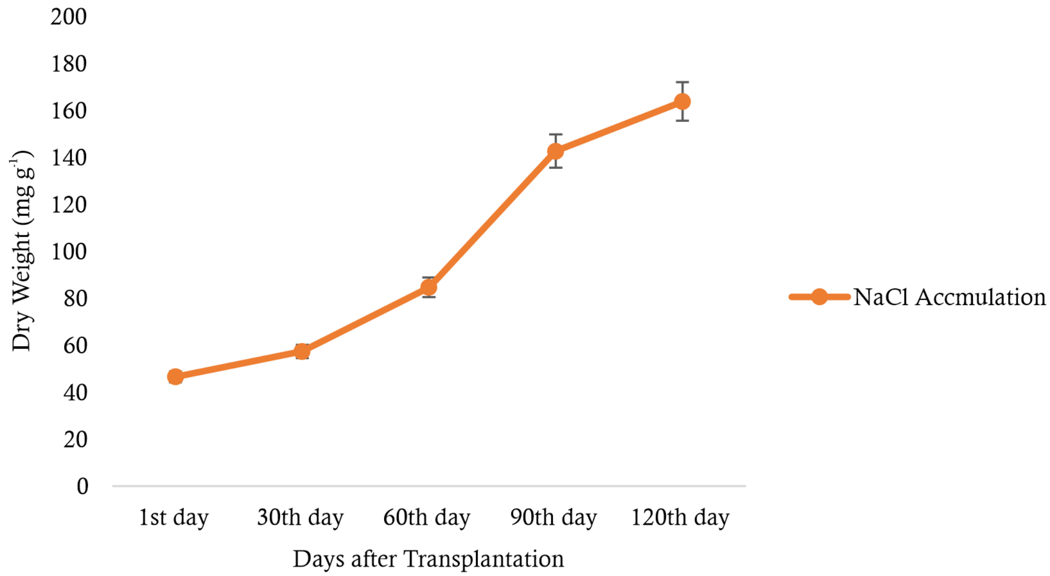


Fig. 10 Bioaccumulation potential of *Salicornia brachiata* cultivated in salt-affected agricultural land. Bars are mean ± SE for five replicates

sodium and chloride. Based on the findings, it was estimated that the *Salicornia brachiata* accumulated 163.8 milligrams of NaCl g^{-1} dry weight (Fig. 10) thereby it has the potential to remove 290 kg NaCl ha^{-1} from saline soil within 120 days.

Discussion

Growth and morphology of *Salicornia brachiata* was notably stimulated under saline conditions, when compared to non-saline soil indicating the presence of salinity in the agricultural field favoured the plant's growth. Similar findings were also observed in *Suaeda prostrata* (Ghanem *et al.*, 2021) and *Suaeda aralocaspica* (Cao *et al.*, 2022). Halophytes, have evolved specific adaptations, including leaf succulence and specialized organs such as salt glands or bladders, which enable them to thrive in high salinity environments (Yuan *et al.*, 2019). However, ionic stress, characterized by the accumulation of Na^+ in leaves, can lead to leaf senescence, nutrient imbalances, and deficiencies (Munns and Tester, 2008). In the present study, *Salicornia brachiata* possess a unique morphological and anatomical adaptations that enable them to thrive in saline environments and also maintains ion homeostasis and equilibrium through ion influx and compartmentalization of sodium chloride. Ion compartmentalization within vacuoles and salt bladders leads to succulence, which helps *Salicornia brachiata* mitigating salt damage and produced higher biomass compared to those in non-saline soil, reflecting its capacity for nutrient absorption and bioaccumulation.

A comprehensive anatomical analysis has revealed that *Salicornia brachiata*, comes under C3 halophyte, exhibiting a range of intricate anatomical adaptations including the presence of salt glands, specialized parenchyma cells, and adaptive vascular arrangements, which collectively enable the plant to thrive in saline environments. Notably, the thickness of stem and mesophyll cells in *Salicornia brachiata* was increased while cultivated under saline conditions contributes to the plant's ability to withstand saline environments by increasing water storage capacity, leading to succulence. A cross-section of the stem reveals a central cylindrical structure formed by the activity of successive cambia, producing xylem vessels and libriform cells, thus playing a significant role (secondary growth) under saline conditions. Furthermore, the results also indicated that accumulated NaCl was stored in specialized spongy parenchyma tissues (salt glands), preventing the apoplastic movement of solutions from the stem exterior into the xylem.

From the current investigation, an increase in chlorophyll content was observed in *Salicornia brachiata* cultivated in saline soil compared to non-saline soil throughout the study period and the maximum synthesis was occurred between 60 to 90 days of cultivation. These results suggest a positive effect of NaCl on chlorophyll synthesis in *Salicornia brachiata* and similar findings were reported form *Arundo donax* (Webster *et al.*, 2016) and *Artemisia santonica* (Rozentsvet *et al.*, 2017). Li *et al.* (2024) highlighted that chlorophyll content is a crucial physiological index directly related to photosynthesis in plants. Under salt stress conditions, cytosolic Na+ toxicity can disrupt the chloroplast ultrastructure, leading to non-stomatal limitations of photosynthesis. Typically, chloroplasts in non-halophytes are significantly damaged by salinity due to weak ion compartmentalization (Wang *et al.*, 2018). In contrast, this study demonstrated that the chloroplasts of *Salicornia brachiata* were protected under salt stress conditions, primarily due to strong ion compartmentalization. This adaptation is also reflected in the synthesis of glycinebetaine, a component of the photosynthesis machinery, which helps to mitigate NaCl toxicity, allowing chloroplasts to tolerate high sodium levels in the cytosol.

Maximum protein content in *Salicornia brachiata* was observed on 120th day when cultivated in saline soil, compared to non-saline soil. Similar increase in protein content under saline conditions has been reported in *Suaeda monoica* (Ayyappan *et al.*, 2013). Protein accumulated in plants under salt stress plays a crucial role in osmoregulation, including osmotin in *Mesembryanthemum crystallinum* and osmatin-like protein in sesame (Wan *et al.*, 2017). Generally, protein content increases with rising salinity levels up to an optimal threshold; beyond this, salinity can lead to a decrease in protein content, as seen in *Phalaris arundinacea* and *Ipomoea pes-caprae* (Wang *et al.*, 2022). Our study also agrees with Wang *et al.* (2015) that plant tissues typically respond to salt stress by degrading existing proteins or producing an abundance of salt stress-related proteins. This study also confirms that salinity induced an increase in protein accumulation throughout the study period, which is crucial for cell survival under salt conditions.

A gradual increase in proline and glycinebetaine was observed in *Salicornia brachiata* cultivated in saline soil compared to non-saline soil. Similar findings have been reported in various species, including *Suaeda eltonica* (Delgado-Gaytan *et al.*, 2020) and *Phaseolus vulgaris* (Borromeo *et al.*, 2024). Research indicates that under salinity, proline enhances water uptake and antioxidant machinery while reducing the accumulation of toxic ions (Zhang and Dai, 2019). Similarly, glycinebetaine aids in osmotic adjustment by regulating the Na+ to K+ ratio and accumulating within cells, thereby diminishing the toxic effects of ions associated with salinity (Tang *et al.*, 2015). Present study confirms that, *Salicornia brachiata* accumulated proline and glycinebetaine as osmoprotectants in their cytosol thereby showed an effective compatible solute for reactive oxygen species scavenging and antioxidant properties and acts as an osmolyte, lowering the plant's water potential and safeguarding membranes under high salinity conditions.

From this study, it was noted that the highest phenol was observed in *Salicornia brachiata* cultivated in saline soil on the 120^{th} day than non-saline soil. Synthesis of phenol was a common response in order to cope up against salinity stress and also play an important role in lignification process. Our results are coincidence with work caried out by Abd El-Maboud and Elsharkawy (2021). Increase in phenol content in *Salicornia brachiata* plays a significant role in ROS scavenging and energy dissipation and its stress mitigation ability against ionic stress.

An increased activity of antioxidative enzymes like catalase, peroxidase and polyphenol oxidase was observed in *Salicornia brachiata* cultivated under saline soil suggests a proactive defence mechanism against oxidative stress induced by salinity. Similar results were also obtained from *Phaseolus vulgaris* (Borromeo *et al.*, 2024), *Suaeda fruticosa* (Gul *et al.*, 2024). Plants exposed to salinity were prone to oxidative stress because of the formation of ROS such as O_2^-, H_2O_2 and OH^- (Parida and Das, 2005). An increased activity of catalase, peroxidase and polyphenol oxidase in *Salicornia brachiata* under saline soil suggests a proactive defence mechanism against oxidative stress induced by salinity. By activating multiple defence mechanisms, these enzymes play a crucial role in safeguarding and promoting growth of *Salicornia brachiata* in saline harsh environments by maintaining cell wall metabolism and structural modifications under salinity and osmotic stress. This enhanced enzymatic activity enables *Salicornia brachiata* to effectively detoxify H_2O_2 even under high salinity conditions throughout the study period.

Plants are detrimentally affected both physically and chemically by excessive soil salinity and high levels of exchangeable sodium. Analyses of rhizosphere soil properties, such as electrical conductivity and pH, indicated the presence of moderate salinity in the *Salicornia brachiata* cultivated soil, attributed to the discharge of shrimp culture wastewater. The soil samples exhibited the reduction in EC and pH; simultaneous increase in plant samples throughout the study period was confirmed that *Salicornia brachiata* effectively reduced the soil EC and pH. Similar studies by Shang *et al*. (2020) found that *Suaeda salsa* decreased soil electrical conductivity from 33 to 22 dSm^{-1} and also a long-term field study conducted by Ding *et al*. (2021) focusing on improving alkali soils through the cultivation of *Atriplex amnicola*, the soil electrical conductivity decreased from 2.20 to 0.42 dSm^{-1}, while pH decreased from 10.6 to 9.5. The present study confirms that the cultivation of *Salicornia brachiata* can effectively mitigate soil salinity in salt affected lands. EC and pH measurements highlight the plant's potential to accumulate substantial amounts of sodium chloride from saline soils.

In the present study, sodium absorption ratio was gradually declined in saline soil cultivated by *Salicornia brachiata* and similar trends in decreasing SAR were observed in other studies, in *Suaeda maratima* (15.61 to 2.79), *Sesuvium portulacastrum* (15.74 to 3.90), *Excoecaria agallocha* (15.52 to 4.39), *Clerodendron inerme* (15.55 to 5.09), *Ipomoea pes-caprae* (15.35 to 6.35), and *Heliotropium curassavicum* (15.30 to 7.65) (Ravindran *et al*., 2007). Bio-reclamation studies on saline sodic soil in Northern Egypt, conducted by Shang *et al*. (2020), highlighted that, compared to ponding and gypsum treatment, *Suaeda salsa* significantly decreased SAR of the soil's surface layer.

The reduction in SAR was observed in this study confirms the efficacy of *Salicornia brachiata* in remediating salt-affected soils. *Salicornia brachiata* reduces soil EC, pH, and SAR through various defense mechanisms, including its ability to bioaccumulation of salts and thereby enhancing soil physical and chemical properties through its root-soil interactions. This process is instrumental in improving saline-alkali lands, as the growth of the root system reduces soil bulk density, increases soil porosity, enhances water infiltration, and ultimately promotes the leaching of salt from the soil matrix.

In the present study, *Salicornia brachiata*, thriving in saline soil exhibited the capability to extract 290 kg ha^{-1} NaCl from the contaminated soil over a period of four-month. As a salt-accumulating succulent halophyte, it selectively secretes Na^+ and Cl^-, consequently reducing the ratio of harmful to nutrient ions (e.g., Na^+/K^+) to levels compatible with plant survival.

Conclusions

Our findings indicate that *Salicornia brachiata*, a salt-marsh halophyte, exhibits robust growth and anatomical adaptations in saline agricultural soils. Throughout its developmental stages, *Salicornia brachiata* accumulates osmoprotectants under saline soil conditions indicates that these compounds play a pivotal role in osmoregulation, aiding in the maintenance of growth potential under saline conditions by mitigating oxidative stress. This study also confirms the role of antioxidant enzymes in alleviating salt toxicity, providing a resilient system for survival in extreme environments. Production of significant biomass and high ash accumulation, making *Salicornia brachiata* an ideal candidate for saline soil restoration for coastal development and the rehabilitation of wasteland or salt-encrusted land.

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Morphometry based Sub-watershed Prioritization Using MCDMs in Non-Fuzzy and Fuzzy Dividends

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Abstract

Prioritization of sub-drainage systems is quintessential in preparing a layout prior to the implementation of any soil and water conservation program. Most of the sub-watershed prioritization approaches find their linkages with the morphometric indices, nevertheless, a frugal and nimble approach for this prioritization exercise using the morphometry is still impending. The conferred study is an attempt towards filling this gap via the use of a statistical cum Mutli-Criteria Decision Making approach for the upper reaches of the Saryu watershed in the Bageshwar district of Uttarakhand Western Himalaya. The study area is a sixth-order drainage system with a geographical extent of 779.05 sq. km and is subdivided into 14 sub-watersheds using SWAT 2012. For the developed watersheds, 14 morphometric parameters, which primarily affect runoff and sediment response are computed and are dispensed as CRITIC inputs towards setting up relative priorities within them. The results from CRITIC were then used to assign ratings for AHP and FAHP, with the latter technique being solved via two methods, namely, geometric mean and extent analysis. A comparison of results suggested that AHP and the geometric mean method for FAHP engendered identical prioritization, while, the extent analysis nullified the effect of seven of the relatively low-rated morphometric parameters, thus producing different results. The study also advocated the use of the deliberated method in the context of managing a larger number of input morphometric parameters, along with their selection for auxiliary prioritization.

Key words: Morphometry, Sub-watershed Prioritization, CRITIC, AHP, FAHP

Introduction

Water and soil system are often considered one of the most imperative assets in maintaining life on the planet. Not only these are indispensable components of any natural ecosystem but provide a multitude of services in the context of food, establishments, and development of mankind. In India, with its fast-growing anthropogenic in order to account its large population, and oblique impacts of Climate Change (CC), soil loss, often leading to land degradation, has become a major challenge (Manivannan *et al.*, 2017; Jat *et al.*, 2020), and in extreme cases often leads to social intimidation. Its assessment, therefore, is a key element of any finely-tuned soil and water conservation policy (Ali and Hagos, 2016). One of the pivotal procedures for the assessment of regions vulnerable to soil erosion is via prioritization of sub-dividends within a drainage system. This makes the prioritization of sub-drainage systems a quintessential work in regards to the discernment of key influencers and preparing the layout of the plan before implementation of any soil and water conservation or flood control program towards combating marring anthropogenic activities and related CC impacts (Nookaratnam *et al.*, 2005; Vittala *et al.*, 2008; Javeed *et al.*, 2009; Ahmed *et al.*, 2018; Prakash *et al.*, 2019). Morphometric indices of any drainage system have always baited a resolute role in the context of the same. Most of the sub-watershed prioritization over Geographical Information System (GIS) finds their linkages with the morphometric indices (Chopra *et al.*, 2005; Mishra and Nagarajan, 2010;

Sridhar *et al.*, 2012; Garde and Kothari, 2016; Mishra *et al.*, 2017; Sukritiyanti *et al.,* 2018), though sometimes are also coupled with land use and soil statistics of the area under consideration (Samal *et al*., 2015; Mundetia *et al*., 2018; Bhattacharya *et al*., 2019; Gunjan *et al*., 2019; Das *et al*., 2021).

With the advent of integrating Multi-Criteria Decision Making (MCDM) techniques in GIS, the process of prioritizing sub-drainage systems within a spatial extent has become much smooth and cultured (Meshram *et al*., 2019; Sangma and Guru, 2019; Sarkar *et al*., 2022). Though a critical issue of input parameter selection always remains among the scientific community possible due to the (i) Availability of a large number of morphometric parameters, therefore, raising questions like which one to opt for, and (ii) Diverse characteristics exhibited by the area under study. This brings the research team into a dilemma of subjectiveness in parameter selection. Even when if someone manages to select some criteria parameters for an MCDM it remains quite capricious over how to weigh the same with respect to the other parameters.

The presented study attempts to simplify this quandary, first via the use of a statistical yet quick MCDM technique called Criteria Importance for Intercriteria Correlation (CRITIC), which shall not only aid in deciding the influence of one input over the other but also in the selection of a few critical indices when a large number of inputs are available. The area selected for the deliberated study is the upper reaches of a Western Himalayan drainage system, namely, the Upper Saryu watershed in Uttarakhand, India. Irrefutably, the conferred study is a direct contribution towards apt management of soil and water resources and finds linkages with the mandates of several Sustainable Development Goals of the United Nations (UN), namely, Goal 6, 13, and 15.

Study Area

The area tabbed for the deliberated study is the upper Saryu watershed which nests in the Bageshwar district of Uttarakhand from latitude 29°49′16″ N to 30°9′25″ N and longitude 79°35′45″ E to 80°2′59″ E. The watershed is bounded by the drainage areas of the Pindar, Gomti, and Ramganga East rivers in the north, west, and east, respectively. The Saryu River, the largest spring-fed stream of the Kumaun division of Uttarakhand (Negi, 1993), commences from Sarmul, a place situated southeast of Nandakot. The climate of the Area of Interest (AOI) is temperate and sub-tropical. Based on Sentinel-2A data, the land use can be broadly classified into eight categories, namely, forest, pasture, cropland, shrubland, built-up, bare ground, waterbody, and snow/ ice packs. Two soil types were observed for the region, namely SNUM 3661 and 3717, with the texture class of clay loam and loam as per the Soil Map of Food and Agriculture Organization (FAO), UN. Fig. 1 illustrates the index map of the study area.

Methodology

The conferred study employed Environmental System Research Institute (ESRI) ArcGIS version 10.4.1 with Soil and Water Assessment Tool (SWAT) 2012 integration for delineating watershed boundary, development of sub-watersheds as shown in Fig. 1, and contemplating morphometric parameters. For this purpose, Cartosat-1 DEM of spatial resolution ~32 m was used as an input. In regards to the development of drainage network, the 'Hydrology' tool from the 'Spatial Analyst Toolbox' is extensively used. Further Survey of India (SOI) toposheet with Open Series Map (OSM) no. 44H/12, 44H/16, 44I/4, 44N/9, 44N/10, 44N/13, 44O/1, and 44O/2, of scale 1:50000, were also georeferenced and digitized to account for first-order streams which are often either under or overlooked using the conventional 'flow accumulation' thresholds of ArcMap. In the context of the development of sub-watersheds, the sub-outlets were manually defined based on the local drainage pattern as per the SOI toposheet which was followed by the calculation of 'sub-basin parameters' using the SWAT 2012 interface in an automated way. These SWAT-derived sub-basin parameters were then used to compute eighteen (18) morphometric indices, fourteen (14) of which that primarily affect the generation of runoff and sediment response were used as input for CRITIC MCDM for assessment of relative priorities. Details of the

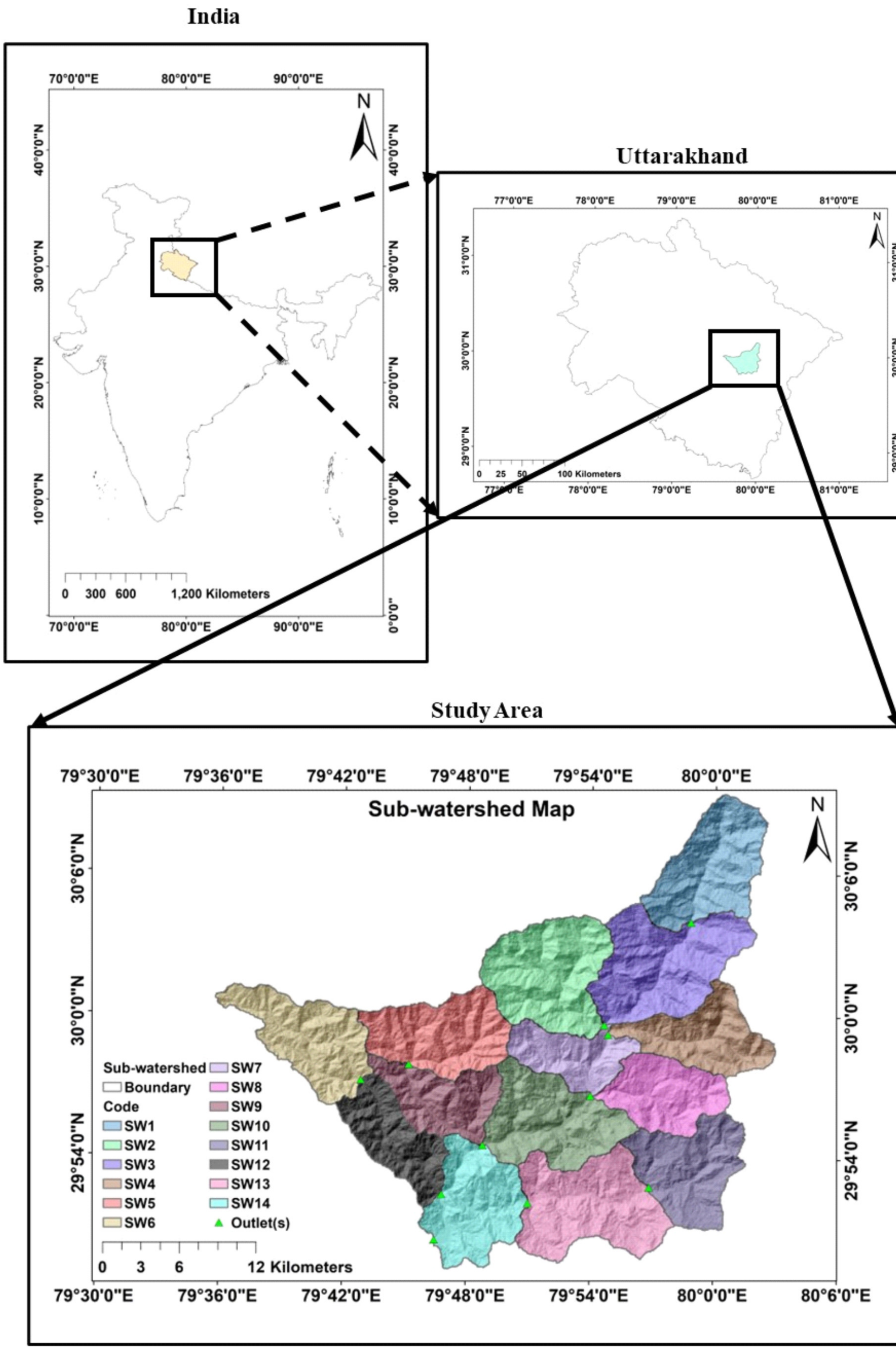

Fig. 1 Index map of Upper Saryu watershed

estimated morphometric parameters are provided in Table 1.

Criteria Importance for Intercriteria Correlation

CRITIC, an MCDM developed by Diakoulaki *et al*. (1995), was utilized to obtain the relative importance of the input morphometric indices among each other along with deciding their Analytical Hierarchical Process (AHP) rating using the computed CRITIC weights or measure of conflict created (W_{cj}). The first step involves the computation of the most ($X_{j\ most}$) and least

Table 1. Morphometric parameters along with their description

S.N.	Parameter	Description	Reference, if any
Linear aspects			
1	Basin length (L_b)	Largest displacement from the outlet along the main channel to its source projected to the periphery of the boundary	Singh (1994)
2	Stream order (u)	Hierarchical ranking of streams from headwaters	Strahler (1952)
3	Stream number (N_u)	Defines number of streams under each order	Pareta and Pareta (2011)
4	Stream length (L_u)	Total length of stream of each order and is given by $L_u=\sum_{i=1}^{Nu} L_i$, where L_i is the length of stream of each order	Horton (1945)
5	Avg. stream length ($\bar{L}_u$)	Avg. length of stream under each order and is given by $\bar{L}_u=\frac{L_u}{N_u}$	Horton (1945)
6	Bifurcation ratio (R_b)	Ratio of total number of streams of given order 'u' to total number of streams in next higher order 'u+1'. For a drainage system it is computed using Horton's law of stream numbers which states $N_u=R_b^{k-u}$, where 'k' is the trunk order	Horton (1932)
7	Stream-length ratio (R_l)	Ratio of avg. length of streams of order 'u' ($\bar{L}_u$) to the avg. length of streams of next lower order ($\bar{L}_{u-1}$). For a drainage system it is computed using Horton's law of stream lengths which states $\bar{L}_u=\bar{L}_1 R_l^{u-1}$, where '$\bar{L}_1$' is the avg. stream length of first order	Horton (1945)
Areal aspects			
8	Circulatory ratio (R_c)	Ratio of area of watershed to area of circle whose circumference equals perimeter of the watershed $R_c=\frac{4\pi A}{P^2}$	Strahler (1964)
9	Shape factor (S_f)	Ratio of square of basin length to the drainage area $S_f=\frac{L_b^2}{A}$	Smart and Surkan (1967)
10	Stream frequency (F_s)	Total number of streams of all order per unit area of watershed $F_s=\frac{\sum_{i=1}^{K} N_{ui}}{A}$	Horton (1945)
11	Drainage density (D_d)	Ratio of total length of streams of all order to the drainage area $D_d=\frac{\sum_{i=1}^{K} L_{ui}}{A}$	Horton (1945)
12	Infiltration number (I_n)	Product of drainage density and stream frequency $I_n = D_d * F_s$	Faniran (1968)
13	Length of overland flow (L_g)	Represents the approximate length of water over the ground surface before the flow gets condensed into definite channels and is numerically equal to half of the reciprocal of the drainage density $L_g=\frac{1}{2D_d}$	Horton (1945)
Relief aspects			
14	Basin relief (R)	Difference between maximum (H) and minimum (h) elevation when measured along the longest dimension of a watershed parallel to the primary channel $R = H - h$	Schumm (1956)

Contd...

S.N.	Parameter	Description	Reference, if any
15	Relief ratio (R_r)	Ratio of basin relief to basin length $R_r=\frac{R}{L_b}$	Schumm (1956)
16	Slope (S)	Avg. weighted gradient of a drainage area	-
17	Hypsometric Integral (HI)	Ratio of the difference of mean and minimum elevation to the difference of maximum and minimum elevation $HI=\frac{\text{Mean Elevation-Min. Elevation}}{R}$	Strahler (1956)
18	Ruggedness number (R_n)	Product of basin relief to drainage density $R_n = R * D_d$	Melton (1958)

($X_{j\ least}$) effective values for each of the input morphometric parameters. If larger values of a morphometric index have the potential to generate more runoff and sediment response, then it is classified as $X_{j\ most}$ and vice-versa. This was followed by the development of a Normalized Decision Matrix (NDM) from the Input Decision Matrix (IDM) using Eq. (1) and Standard Deviation (SD) was computed for each of the normalized indices.

$$n_j=\frac{(X_j-X_{j_{least}})}{(X_{j_{most}}-X_{j_{least}})} \quad (1)$$

Where X_j is the parameter value in the individual cell of IDM

Subsequently, a Correlation Matrix (CM) is developed for the NDM using the corrplot package in RStudio version 2023.03.0. Afterward, a Symmetric Matrix (SM) and SM Values (SMV) are computed using Eq. (2) and (3), respectively.

$$SM_i=(1-r_{jk}) \quad (2)$$

$$SMV=\sum_{i=1}^{m} SM_i \quad (3)$$

Then a product of SMV and SD is obtained for each of the morphometric parameters to obtain the Criterion Information (C_j). The W_{cj}, in %, is obtained by normalizing the individual C_j values with the summation of C_j for all the input parameters and then multiplying the same with 100. Finally, the parameters are arranged in descending order of W_{jc} and ranked accordingly. The values of W_{jc} provide a cornerstone for the ensuing AHP rating following the Saaty scale (Saaty, 1990). The lowest W_{jc} was treated as unity and other values are normalized using the lowest value. Subsequently, the first (Q_{1c}), second (Q_{2c}), and third (Q_{3c}) quartiles are computed for this new data series. Values below Q_{1c} are rated from equally to between equally and slightly important (1 or 2), between Q_{1c} and Q_{2c} as slightly important (3), between Q_{2c} and Q_{3c} as between slightly and quite important (4), and greater than Q_{3c} are rated from quite important to between extremely to absolutely important (5, 7, and 8) over the Saaty's scale.

Analytical Hierarchal Process and Fuzzy Analytical Hierarchal Process

The Saaty' AHP (Saaty, 1980), one of the most preferred MCDM among the scientific community when it comes to solving spatial problems and translating subjectiveness or linguistic meanings to numerical values (Mustafa *et al.*, 2011; Samanta *et al.*, 2011; Zolekar and Bhagat, 2015), is employed for the assignment of final weights or priority vectors (W_j) to the input morphometric indices using a 14×14 Pairwise Comparison Matrix (PCM). Further, to account for uncertainty in relation to crisp ratings of AHP another MCDM, i.e., the Fuzzy AHP is also utilized. Finally, the W_j of each morphometric parameter were used to compute a priority score value (S_i) for each sub-watershed, which is the summation of the product of W_j and normalized value of the respective parameter. The S_i were then subjected to quartile-based classification for setting up classes of relative importance to sub-watersheds in regards to prompt implementation of catchment conservation services. S_i values below or equal to first quartile (Q_1) classified under low, greater than Q_1 but less than or equal to second quartile (Q_2) as moderate, greater than Q_2

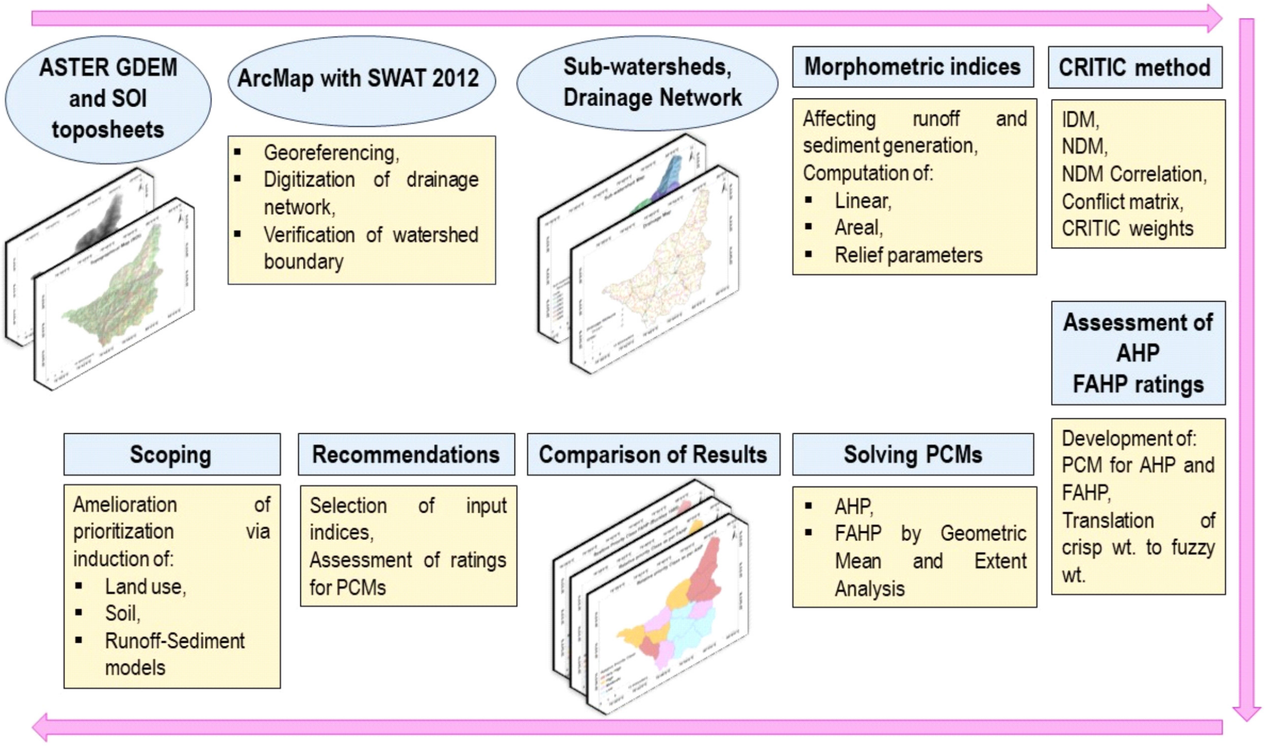

Fig. 2 Adapted methodology

but less than or equal to third (Q_3) as high, and greater than Q_3 in very high classes of relative priorities. Fig. 2 summarizes the adapted methodology for the presented study.

Results and Discussion

Morphometric Analysis

The AOI, i.e., Upper Saryu watershed, appears to be a sixth-order drainage system with a geographical area of 779.05 sq. km, a perimeter of 213.73 km, and a total stream length of 2210.11 km. It comprises 3489 streams of which 2552 are of 1st, 733 of 2nd, 153 of 3rd, 36 of 4th, 07 of 5th, and 01 streams is of 6th-order, respectively, as per the Strahler classification (Strahler, 1952). The arrangement of drainage channels in the AOI follows more or less a sub-dendritic and dendritic type of pattern. The average length of streams of all orders for the watershed is 0.63 km. Fig. 3 depicts the drainage network of the AOI.

The minimum and maximum elevation of the AOI is 827 m and 4227 m, respectively, with a weighted average elevation of 1747.1 m AMSL. Further, using SWAT 2012, the study area was divided into 14 sub-watersheds (coded from SW1 to SW14) with geographical extents ranging from 35.09 sq. km for SW7 to 76.99 sq. km for SW3, respectively. Fig. 3 illustrates the drainage map of the Upper Saryu watershed. Some key morphometric indices of the Upper Saryu watershed are discussed below:

Basin length (L_b)

The L_b value for the AOI was estimated to be 43.50 km with the sub-watersheds L_b ranging from 11.27 km for SW7 to 18.47 km for SW3, respectively. It influences the time of concentration (Kirpich, 1940). The larger basin length usually corresponds to larger runoff volumes and consequently greater sediment responses.

Bifurcation ratio (R_b)

The R_b value for the Upper Saryu watershed appears to be 4.762, which is relatively large. Rai *et al.* (2017) suggested that large R_b typically corresponds to ineffectual control of geologic structures over drainage characteristics. Further, Bogale (2021) associated highly dissected topography with greater R_b values leading to a low time of concentration and high potential towards flash floods. For the sub-watersheds, R_b ranges

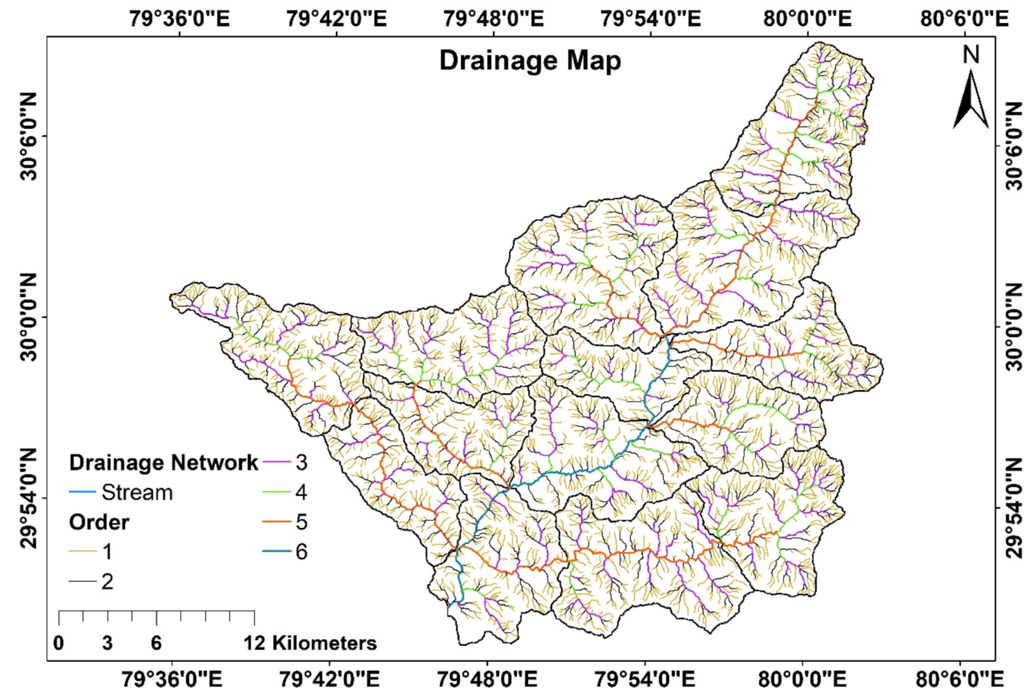

Fig. 3 Drainage network of Upper Saryu watershed

from 2.653 (SW7) to 4.451 (SW13), respectively.

Stream-length ratio (R_l)

In regards to estimating the stream-length ratio Horton's law of stream lengths was used followed by linear regression post conversion of Horton's equation into a linear form. The R_l for the AOI was estimated at 2.35, while for the sub-watersheds the range appears to be from 1.16 (SW5) to 2.38 (SW12). As one moves from lower to higher order streams numerical value of R_l seems to increase suggesting a mature geomorphic stage as per the recommendations of Tamma Rao *et al*. (2012).

Circulatory ratio (R_c)

Often referred to as a compactness ratio, R_c is a non-dimensional number with a range from 0, indicating ideally elongated, to 1, suggesting a perfect circular watershed. For the AOI the value of R_c was estimated at 0.214 with the range for sub-watersheds from 0.260 (SW7) to 0.381 (SW2). The higher the value of R_c, the lower shall be the time of concentration, consequently larger shall be the peak runoff rate typically transporting more sediment from a drainage system. Further, R_c is also a function of slope, lithology, and land use (Miller, 1953).

Shape factor (S_f)

Being an areal parameter shape factor is another morphometric index defining the shape aspect of a drainage system. For the sub-watersheds of the Upper Saryu, S_f varies from 2.702 (SW5) to 6.209 (SW12), while for the entire AOI, its value is estimated at 2.429. Typically, larger values of S_f indicate an elongated watershed, while a lower value suggests a circular one.

Stream frequency (F_s)

Primarily a function of lithology, F_s represents the average number of streams per unit area of a drainage system. For the Upper Saryu watershed, its numerical value was estimated at 4.48 per sq. km, while for the sub-watersheds its amplitudes were between 3.64 per sq. km (SW3) to 6.22 per sq. km (SW1).

Drainage density (D_d)

D_d is often linked with the extent of the closeness of the stream within a drainage system. It affects the infiltration volume and runoff at the outlet of any drainage area. D_d for the AOI is estimated at 2.84 km/sq. km, while for the sub-watersheds it reciprocates from 2.56 km/sq. km (SW7) to 3.23 km/sq. km (SW1). These D_d values pin the AOI under the class of coarse drainage texture as per Smith (1950) classification.

Infiltration number (I_n)

Infiltration number is more or less linked to the measure of infiltration volume that may be accommodated by a drainage system. A higher number typically dovetails with lower infiltration and subsequently larger runoff and vice-versa (Simth, 1950). For the AOI the value of I_n was estimated at 12.71 per cu. km, while for the sub-watersheds, it extends from 9.68 per cu. km (SW3) to 20.11 per cu. km (SW1).

Length of overland flow (L_g)

This quantity is inversely proportional to D_d and defines the length at which overland flow shall traverse before it gets concentrated in well-defined channels, thus is the epitome of sheet flow. Higher values of L_g reflect lower runoff and vice-versa. For the study area its value is estimated at 0.176 km, while in the case of sub-watersheds, the same harmonizes between 0.155 km (SW1) and 0.196 km (SW7).

Basin relief (R)

Being one of the relief parameters, basin relief is an important criterion towards understanding the denudational attributes of a drainage system (Sharma *et al.*, 2013) and is the difference between the highest and the lowest elevation of a drainage area. For the developed sub-watershed, it ranges from 955 m (SW14) to 2591 m (SW1), while for the entire AOI, its value was estimated at 3400 m.

Relief ratio (R_r)

This morphometric index is a measure of overall steepness, thus, gauges the overall erosional processes of a drainage area (Vittala *et al.*, 2004). For the sub-watersheds, it assorts from 0.06 (SW13) to 0.19 (SW1), at the same time it concentrates on the numerical value of 0.078.

Slope (S)

For the presented work, sub-watershed slopes are computed via SWAT 2012 in an automated way with values extending from 38.30% (SW13) to 59.93% (SW4). For the AOI the average slope was computed using the weighted average approach from the mean slopes of sub-watersheds and their respective drainage area and was estimated at 54.91%, thus cataloging the same under the class of very steep slopes as per the recommendations of Kumar and Kushwaha (2013).

Hypsometric Integral (HI)

HI is a critical non-dimensional index while defining the geomorphic development stage of a drainage area. Further, it also reflects the extent of activity in the geologic structures of a drainage system. For the sub-watersheds, the HI ranges from 0.352 (SW10), representing the transition from mature to the old stage, to 0.479 (SW12), illustrating the mature stage of watershed development. For the entire AOI, it diminishes to 0.271 placing the same under the old or monadnock stage of development as per Strahler (1956) recommendations.

Ruggedness number (R_n)

R_n communicates cumulative reaction of slope and stream-length attributes (Aher *et al.*, 2013), with low value illustrating lower erosion potentiality and vice-versa. For the AOI the value of R_n was estimated at 9.464, while for the sub-watersheds the same varies from 2.534 (SW14) to 8.337 (SW1).

CRITIC Results

From the 14 input morphometric indices for the developed sub-watersheds, a 14×14 IDM was prepared along with the determination of the most and least effective parameter values. For all the indices except L_g, higher values are assigned as most effective ($X_{j\ most}$), whereas lower values were identified as the least effective ($X_{j\ least}$) in regards to the generation of surface runoff and corresponding sediment response, while the converse convention is used for the L_g. The IDM is then normalized using Eq. (1) to produce an NDM and subsequently SD values for the NDM were estimated. Later a CM of r_{jk} was developed from the NDM with r_{jk} computed between normalized input indices and is represented in

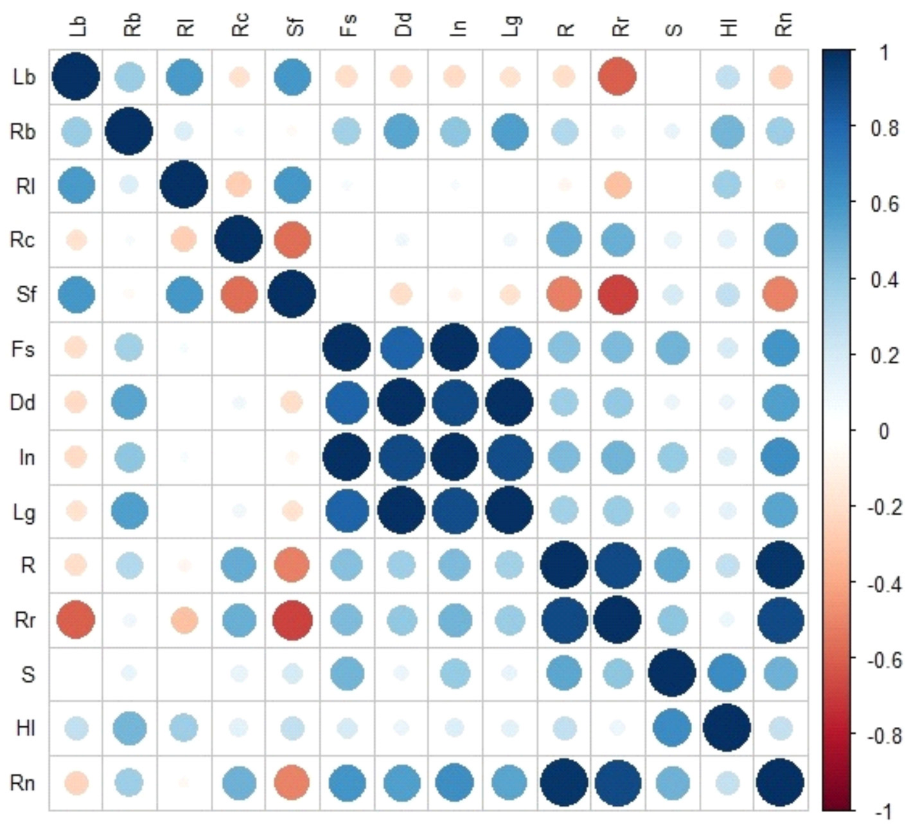

Fig. 4 Correlation plot for the NDM

Fig. 4. This was followed by computation of SM along with SM values, summation of which along with the SD of NDM was used to assign CRITIC weights (W_{jc}). It was observed that two shape parameters, i.e., S_f and R_c, were assigned the highest priorities in the CRITIC approach with the percentage wt. of 10.79% and 9.90%, while, I_n and R_n received the lowest priority with the W_{jc} values of 5.78% and 5.04%, respectively. The lowest W_{jc}, i.e., 5.04%, is then assigned the index of unity and all other W_{jc} are then normalized using the same. For this newly developed series Q_{1c}, Q_{2c}, and Q_{3c} are computed which are 1.204, 1.293, and 1.507, respectively. Subsequently, AHP ratings are assigned to each morphometric parameter following the discussed methodology from section 3.1. Table 2 depicts the IDM and NDM for the sub-watersheds, while Table 3 represents the SV, W_{jc} values, and AHP/ FAHP ratings for the input morphometric parameters.

Outputs of AHP and FAHP

A 14×14 PCM was developed with all the computed morphometric parameters and their respective Saaty ratings as identified following the CRITIC approach as shown in Table 3. Consequently, priority vector (W_j), eigenvalues (λ_{max}), Consistency Index (CI), and Consistency Score (CS), were computed for the developed PCM. The average value of λ_{max} was estimated at 14, with a CI count of 0. The Random Index (RI) value of 1.57, as adapted from Saaty (1980) recommendation, was used for the estimation of CS which appeared to be less than 10 % suggesting that the comparison is mathematically coherent and adapted AHP W_j is apposite. For the FAHP part, crisp AHP ratings were rendered to their triangular fuzzy counterparts and the resultant matrix was solved using two approaches, namely, the Geometric Mean Method (GMM) and the Extent Analysis Method (EAM). The W_j values following each of the approaches were then used to compute the score values (S_i) for each sub-watershed using a sum normalized matrix of morphometric parameters. Table 4 illustrates the AHP and FAHP ratings with their respective W_j.

Finally, a quartile-based approach was exercised over the computed S_i values towards the

Table 2. Input and normalized morphometric parameters in IDM and NDM for the developed sub-watersheds

Sub-watershed/ Parameters	L_b	R_b	R_l	R_c	S_f	F_s	D_d	I_n	L_g	R	R_r	S	HI	R_n
IDM														
SW1	13.36	3.945	2.107	0.358	2.904	6.22	3.23	20.11	0.155	2591	0.194	57.72	0.417	8.377
SW2	14.10	3.842	1.967	0.381	2.803	4.15	2.75	11.41	0.182	2071	0.147	58.74	0.464	5.702
SW3	18.47	4.076	2.097	0.316	4.432	3.64	2.66	9.68	0.188	2121	0.115	56.34	0.440	5.643
SW4	15.69	3.892	2.174	0.270	5.277	5.88	3.01	17.68	0.166	1692	0.108	59.93	0.420	5.090
SW5	12.41	3.875	1.165	0.344	2.702	4.88	2.88	14.05	0.174	1808	0.146	59.31	0.417	5.209
SW6	16.82	3.997	1.958	0.265	4.985	4.70	3.01	14.17	0.166	1308	0.078	51.50	0.400	3.942
SW7	11.27	2.653	1.798	0.260	3.620	3.82	2.56	9.77	0.196	1515	0.134	49.33	0.371	3.874
SW8	13.62	3.411	1.846	0.353	4.175	4.03	2.80	11.27	0.179	1629	0.120	46.92	0.373	4.554
SW9	14.11	3.676	1.900	0.265	4.846	4.97	2.91	14.43	0.172	1376	0.098	57.15	0.416	3.997
SW10	15.23	2.879	1.871	0.304	3.657	4.04	2.61	10.53	0.192	1433	0.094	47.69	0.352	3.740
SW11	12.13	3.748	1.773	0.315	2.712	4.53	3.15	14.27	0.159	1461	0.120	39.35	0.389	4.599
SW12	15.92	3.440	2.379	0.286	6.209	4.34	2.72	11.81	0.184	1054	0.066	56.81	0.479	2.869
SW13	16.78	4.451	2.158	0.279	3.811	4.02	2.78	11.17	0.180	1120	0.067	38.30	0.397	3.109
SW14	16.17	3.058	1.899	0.344	4.639	3.92	2.66	10.44	0.188	955	0.059	45.98	0.380	2.543
$X_{j\ least}$	11.27	2.653	1.165	0.260	2.702	3.64	2.56	9.68	0.196	955	0.059	38.30	0.352	2.543
$X_{j\ most}$	18.47	4.451	2.379	0.381	6.209	6.22	3.23	20.11	0.155	2591	0.194	59.93	0.479	8.377
$(X_{j\ most} - X_{j\ least})$	7.20	1.798	1.214	0.121	3.508	2.58	0.68	10.43	-0.041	1636	0.135	21.63	0.127	5.833
Sub-watershed/ Parameters	L_b	R_b	R_l	R_c	S_f	F_s	D_d	I_n	L_g	R	R_r	S	HI	R_n
NDM														
SW1	0.290	0.718	0.776	0.809	0.058	1.000	1.000	1.000	1.000	1.000	1.000	0.898	0.512	1.000
SW2	0.393	0.661	0.661	1.000	0.029	0.197	0.290	0.167	0.341	0.682	0.651	0.945	0.884	0.541
SW3	1.000	0.791	0.768	0.464	0.493	0.000	0.153	0.000	0.186	0.713	0.413	0.834	0.691	0.531
SW4	0.613	0.689	0.831	0.082	0.734	0.868	0.668	0.768	0.718	0.450	0.362	1.000	0.534	0.437
SW5	0.158	0.680	0.000	0.696	0.000	0.480	0.479	0.419	0.538	0.521	0.642	0.971	0.515	0.457
SW6	0.771	0.747	0.653	0.043	0.651	0.412	0.676	0.431	0.725	0.216	0.139	0.610	0.376	0.240
SW7	0.000	0.000	0.521	0.000	0.262	0.071	0.000	0.009	0.000	0.342	0.559	0.510	0.150	0.228
SW8	0.326	0.421	0.561	0.770	0.420	0.152	0.353	0.153	0.408	0.412	0.449	0.398	0.170	0.345
SW9	0.394	0.569	0.605	0.046	0.611	0.515	0.515	0.456	0.573	0.257	0.285	0.872	0.501	0.249
SW10	0.550	0.126	0.582	0.366	0.272	0.154	0.078	0.082	0.097	0.292	0.260	0.434	0.000	0.205
SW11	0.120	0.609	0.501	0.459	0.003	0.347	0.874	0.440	0.898	0.309	0.455	0.048	0.296	0.352
SW12	0.645	0.438	1.000	0.221	1.000	0.271	0.244	0.204	0.290	0.061	0.053	0.856	1.000	0.056
SW13	0.764	1.000	0.818	0.156	0.316	0.149	0.324	0.143	0.377	0.101	0.057	0.000	0.357	0.097
SW14	0.681	0.225	0.605	0.694	0.552	0.109	0.157	0.073	0.191	0.000	0.000	0.355	0.222	0.000
SD	0.286	0.277	0.230	0.334	0.307	0.296	0.301	0.295	0.301	0.276	0.278	0.339	0.281	0.254

IDM: Input Decision Matrix, NDM: Normalized Decision Matrix, SD: Standard Deviation

Table 3. Conflict NDM with the CRITIC weights and AHP & FAHP ratings

Conflict NDM	L_b	R_b	R_l	R_c	S_f	F_s	D_d	I_n	L_g	R	R_r	S	HI	R_n
L_b	0.000	0.619	0.421	1.190	0.407	1.207	1.216	1.217	1.195	1.214	1.605	0.974	0.742	1.248
R_b	0.619	0.000	0.826	0.939	1.071	0.653	0.459	0.591	0.429	0.703	0.913	0.877	0.529	0.630
R_l	0.421	0.826	0.000	1.271	0.405	0.938	1.009	0.944	1.015	1.091	1.323	0.984	0.626	1.067
R_c	1.190	0.939	1.271	0.000	1.557	1.012	0.911	0.972	0.913	0.486	0.496	0.875	0.850	0.513
S_f	0.407	1.071	0.405	1.557	0.000	1.030	1.208	1.094	1.185	1.520	1.689	0.810	0.740	1.508
F_s	1.207	0.653	0.938	1.012	1.030	0.000	0.181	0.014	0.186	0.569	0.547	0.523	0.813	0.403
D_d	1.216	0.459	1.009	0.911	1.208	0.181	0.000	0.100	0.002	0.632	0.596	0.886	0.885	0.434
I_n	1.217	0.591	0.944	0.972	1.094	0.014	0.100	0.000	0.107	0.548	0.525	0.612	0.835	0.368
L_g	1.195	0.429	1.015	0.913	1.185	0.186	0.002	0.107	0.000	0.653	0.624	0.875	0.862	0.455
R	1.214	0.703	1.091	0.486	1.520	0.569	0.632	0.548	0.653	0.000	0.096	0.474	0.741	0.028
R_r	1.605	0.913	1.323	0.496	1.689	0.547	0.596	0.525	0.624	0.096	0.000	0.593	0.903	0.098
S	0.974	0.877	0.984	0.875	0.810	0.523	0.886	0.612	0.875	0.474	0.593	0.000	0.359	0.510
HI	0.742	0.529	0.626	0.850	0.740	0.813	0.885	0.835	0.862	0.741	0.903	0.359	0.000	0.755
R_n	1.248	0.630	1.067	0.513	1.508	0.403	0.434	0.368	0.455	0.028	0.098	0.510	0.755	0.000
Sum	13.254	9.240	11.920	11.985	14.226	8.076	8.520	7.927	8.501	8.755	10.008	9.350	9.641	8.018
SD	0.286	0.277	0.230	0.334	0.307	0.296	0.301	0.295	0.301	0.276	0.278	0.339	0.281	0.254
C_j	3.794	2.559	2.742	4.002	4.365	2.394	2.563	2.337	2.563	2.419	2.786	3.168	2.710	2.038
W_{jc} (%)	9.38	6.33	6.78	9.90	10.79	5.92	6.34	5.78	6.34	5.98	6.89	7.83	6.70	5.04
Rank	3	10	6	2	1	12	8	13	9	11	5	4	7	14
Norm. W_{jc}	1.861	1.255	1.345	1.963	2.141	1.174	1.257	1.146	1.257	1.187	1.367	1.554	1.329	1.000
AHP rate	7	3	4	8	8	2	3	2	3	2	4	5	4	1
FHAP rate	(6, 7, 8)	(2, 3, 4)	(3, 4, 5)	(7, 8, 9)	(7, 8, 9)	(1, 2, 3)	(2, 3, 4)	(1, 2, 3)	(2, 3, 4)	(1, 2, 3)	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)	(1, 1, 1)

Table 4. PCM of AHP and FAHP along with their respective weights

Para	S_f	R_c	L_b	S	R_r	R_l	HI	D_d	L_g	R_b	R	F_s	I_n	R_n	AHP Wt. (%)
PCM AHP															
S_f	1	1	1 1/7	1 3/5	2	2	2	2 2/3	2 2/3	2 2/3	4	4	4	8	14.29
R_c	1	1	1 1/7	1 3/5	2	2	2	2 2/3	2 2/3	2 2/3	4	4	4	8	14.29
L_b	7/8	7/8	1	1 2/5	1 3/4	1 3/4	1 3/4	2 1/3	2 1/3	2 1/3	3 1/2	3 1/2	3 1/2	7	12.50
S	5/8	5/8	5/7	1	1 1/4	1 1/4	1 1/4	1 2/3	1 2/3	1 2/3	2 1/2	2 1/2	2 1/2	5	8.93
R_r	1/2	1/2	4/7	4/5	1	1	1	1 1/3	1 1/3	1 1/3	2	2	2	4	7.14
R_l	1/2	1/2	4/7	4/5	1	1	1	1 1/3	1 1/3	1 1/3	2	2	2	4	7.14
HI	1/2	1/2	4/7	4/5	1	1	1	1 1/3	1 1/3	1 1/3	2	2	2	4	7.14
D_d	3/8	3/8	3/7	3/5	3/4	3/4	3/4	1	1	1	1 1/2	1 1/2	1 1/2	3	5.36
L_g	3/8	3/8	3/7	3/5	3/4	3/4	3/4	1	1	1	1 1/2	1 1/2	1 1/2	3	5.36
R_b	3/8	3/8	3/7	3/5	3/4	3/4	3/4	1	1	1	1 1/2	1 1/2	1 1/2	3	5.36
R	1/4	1/4	2/7	2/5	1/2	1/2	1/2	2/3	2/3	2/3	1	1	1	2	3.57
F_s	1/4	1/4	2/7	2/5	1/2	1/2	1/2	2/3	2/3	2/3	1	1	1	2	3.57
I_n	1/4	1/4	2/7	2/5	1/2	1/2	1/2	2/3	2/3	2/3	1	1	1	2	3.57
R_n	1/8	1/8	1/7	1/5	1/4	1/4	1/4	1/3	1/3	1/3	1/2	1/2	1/2	1	1.78

Contd...

PCM FAHP

Para	S_f	R_c	L_b	S	R_r	R_l	HI	D_d	L_g	R_b	R	F_s	I_n	R_n	GMM Wt.	EAM Wt.
S_f	(1, 1, 1)	(1, 1, 1)	(1, 8/7, 9/7)	(7/5, 8/5, 9/5)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(7/3, 8/3, 3)	(7/3, 8/3, 3)	(7/3, 8/3, 3)	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)	(7, 8, 9)	14.03	23.68
R_c	(1, 1, 1)	(1, 1, 1)	(1, 8/7, 9/7)	(7/5, 8/5, 9/5)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(7/3, 8/3, 3)	(7/3, 8/3, 3)	(7/3, 8/3, 3)	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)	(7, 8, 9)	14.03	23.68
L_b	(7/9, 7/8, 1)	(7/9, 7/8, 1)	(1, 1, 1)	(6/5, 7/5, 8/5)	(3/2, 7/4, 2)	(3/2, 7/4, 2)	(3/2, 7/4, 2)	(2, 7/3, 8/3)	(2, 7/3, 8/3)	(2, 7/3, 8/3)	(3, 7/2, 4)	(3, 7/2, 4)	(3, 7/2, 4)	(6, 7, 8)	12.26	19.86
S	(5/9, 5/8, 5/7)	(5/9, 5/8, 5/7)	(5/8, 5/7, 5/6)	(1, 1, 1)	(1, 5/4, 3/2)	(1, 5/4, 3/2)	(1, 5/4, 3/2)	(4/3, 5/3, 2)	(4/3, 5/3, 2)	(4/3, 5/3, 2)	(2, 5/2, 3)	(2, 5/2, 3)	(2, 5/2, 3)	(4, 5, 6)	8.81	10.97
R_r	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/2, 4/7, 2/3)	(2/3, 4/5, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 4/3, 5/3)	(1, 4/3, 5/3)	(1, 4/3, 5/3)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	7.28	7.27
R_l	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/2, 4/7, 2/3)	(2/3, 4/5, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 4/3, 5/3)	(1, 4/3, 5/3)	(1, 4/3, 5/3)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	7.28	7.27
HI	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/2, 4/7, 2/3)	(2/3, 4/5, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 4/3, 5/3)	(1, 4/3, 5/3)	(1, 4/3, 5/3)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	7.28	7.27
D_d	(1/3, 3/8, 3/7)	(1/3, 3/8, 3/7)	(3/8, 3/7, 1/2)	(1/2, 3/5, 3/5)	(3/5, 3/4, 1)	(3/5, 3/4, 1)	(3/5, 3/4, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 3/2, 2)	(1, 3/2, 2)	(1, 3/2, 2)	(2, 3, 4)	5.30	0.00
L_g	(1/3, 3/8, 3/7)	(1/3, 3/8, 3/7)	(3/8, 3/7, 1/2)	(1/2, 3/5, 3/5)	(3/5, 3/4, 1)	(3/5, 3/4, 1)	(3/5, 3/4, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 3/2, 2)	(1, 3/2, 2)	(1, 3/2, 2)	(2, 3, 4)	5.30	0.00
R_b	(1/3, 3/8, 3/7)	(1/3, 3/8, 3/7)	(3/8, 3/7, 1/2)	(1/2, 3/5, 3/5)	(3/5, 3/4, 1)	(3/5, 3/4, 1)	(3/5, 3/4, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 3/2, 2)	(1, 3/2, 2)	(1, 3/2, 2)	(2, 3, 4)	5.30	0.00
R	(2/9, 1/4, 2/7)	(2/9,1/4, 2/7)	(1/4, 2/7, 1/3)	(1/3, 2/5, 1/2)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 2, 3)	3.75	0.00
F_s	(2/9, 1/4, 2/7)	(2/9,1/4, 2/7)	(1/4, 2/7, 1/3)	(1/3, 2/5, 1/2)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 2, 3)	3.75	0.00
I_n	(2/9,1/4, 2/7)	(2/9,1/4, 2/7)	(1/4,2/7, 1/3)	(1/3,2/5, 1/2)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1/2, 2/3, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 2, 3)	3.75	0.00
R_n	(1/7,1/8, 1/9)	(1/7,1/8, 1/9)	(1/8,1/7, 1/6)	(1/4, 1/5, 1/6)	(1/5, 1/4, 1/3)	(1/5, 1/4, 1/3)	(1/5, 1/4, 1/3)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1/3, 1/2, 1)	(1, 1, 1)	1.87	0.00

Para: Parameter, GMM: Geometric Mean Method or Buckley (1985), EAM: Extent Analysis Method or Chang (1996) identification of four (04) classes of relative priorities for the developed sub-watersheds. It was observed that the Saaty's AHP and GMM engendered identical results of prioritization at the sub-watershed level, yielding 226.64 sq. km area in low, 157.81 sq. km under moderate, 168.76 sq. km covered in high, and 225.84 sq. km of the area is very high classes of relative priorities, respectively. But the results from the EAM were relatively different with the effect of D_d, L_g, R_b, R, F_s, I_n, and R_n being nullified during the setting of priority vectors. The technique resulted in 220.20 sq. km, 148.92 sq. km, 189.12 sq. km, and 220.81 sq. km of the geographical area under low, moderate, high, and very high classes of relative priorities, respectively. Details of Q_1, Q_2, and Q_3 quartiles following each MCDM methodology along with sub-watersheds under various relative priority classes are depicted in Table 5 and illustrated in Fig. 5.

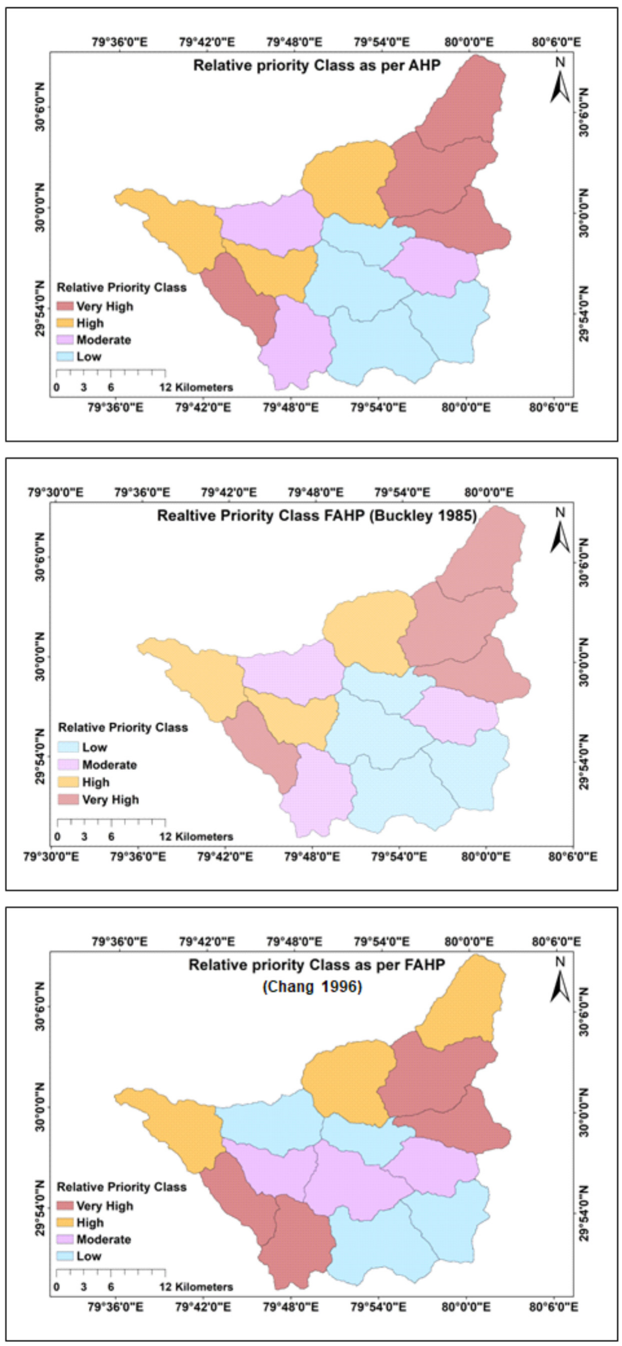

Fig. 5 Relative priority maps of Upper Saryu watershed for different MCDMs

Table 5. Relative priority from AHP and FAHP (Buckley (1985) and Chang (1996))

Description	Saaty AHP	FAHP Buckley (1985)	FAHP Chang (1996)
Quartiles for S_i			
Q1	6.725	6.711	6.720
Q2	7.132	7.127	7.265
Q3	7.529	7.516	7.329
Sub-watershed Priority Class			
Low	SW7, SW10, SW11, SW13	SW7, SW10, SW11, SW13	SW5, SW7, SW11, SW13
Moderate	SW5, SW8, SW14	SW5, SW8, SW14	SW8, SW9, SW10
High	SW2, SW6, SW9	SW2, SW6, SW9	SW1, SW2, SW6
Very High	SW1, SW3, SW4, SW12	SW1, SW3, SW4, SW12	SW3, SW4, SW12, SW14
Sub-watershed Priority Class (Area-wise, in sq. km)			
Low	226.64	226.64	220.20
Moderate	157.81	157.81	148.92
High	168.76	168.76	189.12
Very High	225.84	225.84	220.81

Conclusion

The study presents a streamlined and efficient approach for sub-watershed prioritization in the upper reaches of the Saryu watershed, Uttarakhand, using morphometric indices. While existing methods for morphometry-based prioritization often involve complex computations and lack standardized procedures, the presented work simplifies this process through a combination of the CRITIC method and MCDM models, specifically AHP and FAHP. The results showed that AHP and FAHP (when solved using GMM) produced similar prioritization outcomes, while FAHP with EAM generated different results by omitting indices with relatively low ratings. The flexibility of the CRITIC approach allows users to prioritize sub-watersheds using either all or selected morphometric indices based on Wjc values, offering a customizable solution. Future enhancements could incorporate land use and soil data to further refine prioritization. For high-priority areas, models like SWAT, etc., could be used to identify sites requiring conservation efforts. This study provides a practical contribution to soil and water conservation, particularly in addressing the challenges posed by climate change.

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Simulation of Rice Performance under Alkaline Soil Pedon Using CERES-Rice Model

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Abstract

A multi-location field experiment was conducted on crop establishment methods of rice under different soil texture. Field experiments in Indian Punjab were conducted on three soil textures including sandy loam, sandy clay loam, and clay loam soils. The experiment was conducted in randomized block design with nine treatment combinations of direct-seeded rice (DSR) and transplanted flooded rice (TFR), along with different irrigation strategies. The results of multi locations field study were used for CERES-Rice model calibration and validation. Simulation study was performed in a soil pedon near Ferozpur, Punjab to evaluate the performance of rice establishment methods under alkaline soil enlivenment. The CERES-Rice model showed satisfactory accuracy in simulating grain yield, biomass, and evapotranspiration (ET), with low RMSE values, indicating minimal residual variation. Other evaluation indices such as Nash-Sutcliffe Modelling Efficiency (ME), R^2 values demonstrated strong correlation between observed and simulated data. The index of agreement (d) values, ranging from 0.71 to 0.76, indicated good reliability of the model. These results confirmed the model's predictive capability and effectiveness under varying climatic conditions, supporting improved crop management. The simulated grain yield of TFR in neutral soil (Pedon 1) was 5.7 t ha^{-1} and reduced to 5.0 t ha^{-1} for direct seeded rice. In contrast, alkaline soil (Pedon 2) had lower yields (4.9 t ha^{-1} for TFR) and crop failure for DSR, reflecting poor nutrient dynamics and water retention. The water use efficiency for TFR in alkaline soil was slightly reduced, highlighting challenges in such soils.

Keywords: Calibration, Evapotranspiration, Pedon, Soil texture, Water use efficiency

Introduction

Rice (*Oryza sativa* L.) is a cornerstone of global agriculture, serving as the primary staple food for more than half of the world's population (Asma *et al.*, 2023). It plays a crucial role in food security, especially in Asia, where it is grown extensively. However, rice productivity faces significant challenges due to various factors, including soil salinity and alkalinity (Fahad *et al.*, 2019). The global extent of saline and alkaline soils is substantial, affecting over 800 million hectares, with significant portions located in major rice-growing areas such as South Asia, China, and parts of Southeast Asia (Roy *et al.*, 2021). In these regions, addressing soil alkalinity is essential to maintaining and improving rice productivity. Soil salinity or alkalinity is a widespread issue that affects the physical and chemical properties of soil, ultimately leading to reduced crop yields. Understanding the effects of salt affected soil on rice production and finding effective management practices is vital for sustaining and improving agricultural productivity in regions. Soils which are characterized by high pH (greater than 8.5), results in adverse effects on plant growth due to poor soil structure, low availability of essential nutrients, and excessive sodium ions (Hailu and Mehari, 2021). These soils often exhibit a sodic nature, where sodium replaces calcium and magnesium in the soil colloid, leading to poor soil permeability, waterlogging, and aeration issues.

Additionally, alkaline soils tend to have low organic matter content, which further limits their fertility. Such conditions make it difficult for plants to absorb essential nutrients like nitrogen, phosphorus, potassium, and micronutrients (e.g., zinc and iron), leading to stunted growth, poor root development, and reduced crop yields (Shrivastav *et al*., 2020). These problems are particularly acute in arid and semi-arid regions where high rates of evaporation lead to the accumulation of soluble salts, further aggravating soil salinity/alkalinity.

As global food demand continues to grow, managing rice cultivation under adverse soil conditions has become a priority in agronomic research and sustainable agriculture initiatives. Simulation models have emerged as effective tools for understanding and predicting crop performance under various environmental and management conditions. They help simulate complex interactions between soil, water, and crop processes, offering insights into the effects of different management strategies on crop growth and yield. The CERES-Rice (Crop Environment Resource Synthesis-Rice) model is one such process-based crop growth model that has been widely used to study rice production under diverse environmental conditions. This model simulates the phenology, growth, and yield of rice based on inputs related to soil, weather, and management practices (Timsina and Humphreys, 2003). By incorporating data on soil physical and chemical properties, weather conditions, and agronomic practices, CERES-Rice can predict how rice plants respond to different environments, making it a useful tool for evaluating the performance of rice in alkaline soils. The CERES-Rice model captures the physiological processes of rice plants, including photosynthesis, respiration, nutrient uptake, and grain filling. It also accounts for soil-water-plant interactions, making it possible to assess the impact of various soil conditions on rice performance. By simulating different scenarios, researchers and agronomists can explore potential management strategies, such as soil amendments, irrigation practices, and cultivar selection, to mitigate the adverse effects of soil alkalinity. The use of such models helps in reducing the need for extensive field trials, saving time, resources, and costs, while still providing valuable insights into crop performance (Reynolds *et al*., 2018).

Despite extensive research on the physiological, biochemical, and molecular responses of plants to soil salinity and alkalinity, there is still a gap in practical solutions that can be readily adopted by farmers. Simulation models like CERES-Rice bridge this gap by allowing researchers to test various agronomic practices under controlled conditions and recommend the best management strategies for farmers dealing with soil alkalinity (Kundathil *et al*., 2023). Rice crop simulation models have been extensively evaluated in Punjab and Haryana, India. ORYZA2000 outperformed WOFOST in simulating rice growth parameters and yield in Punjab (Mukherjee *et al.,* 2011). Integration of Weather Research Forecasting and DSSAT models revealed significant correlations between water stress and rice yield anomalies in both states (Rajasivaranjan *et al.,* 2022). CERES-Rice and InfoCrop-Rice models accurately simulated phenology and yield for different rice cultivars and transplanting dates in Punjab (Kaur and Kaur, 2022). The DNDC model effectively simulated nitrogen dynamics in rice-wheat systems across the Indo-Gangetic Plains, including Punjab and Haryana (Pathak *et al.,* 2006). These studies highlighted regional variations in crop yields, nitrogen uptake, and loss mechanisms. Punjab and Haryana generally showed higher yields and nitrogen uptake due to favorable climatic conditions and increased nitrogen use. However, simulations indicated negative nitrogen balances across all states, suggesting the need for improved nitrogen management practices. The integration of simulation models into agronomic research offers a holistic approach to understanding and managing the challenges associated with alkaline soils, providing a pathway to sustainable and resilient agricultural practices. The present study carried out with objective to simulate the performance of rice under different pedons. The significance of this research lies in its ability to offer practical solutions for improving rice productivity in regions affected by soil alkalinity. By using the CERES-Rice model, the study provides a scientific basis for developing and recommending agronomic practices that can enhance the resilience and productivity of rice crops under alkaline soil conditions. Furthermore, the insights gained from this research can be extended to other crops and regions facing similar challenges, contributing to broader efforts to improve food security and promote sustainable agricultural practices worldwide.

Material and Methods

Field experiment

Field experiments were conducted across three soil textures in Indian Punjab, sandy loam and sandy clay loam at Punjab Agricultural University (PAU), Ludhiana, and clay loam at Regional Research Station (RRS), PAU-Gurdaspur. Ludhiana's semi-arid climate features hot summers and cold winters, while Gurdaspur's sub-mountainous region has a slightly different environment. The study, involving 9 treatments combinations in a randomized block design with three replications, tested various crop establishment methods (direct seeded rice and transplanted flooded rice) and irrigation strategies. Soil of the experimental site (Pedon 1) was neutral in reaction, low in organic carbon at all locations, the details of soil properties given in Yadav (2024). The Results from these experiments were utilized for model calibration and validation.

Simulation study

Simulation of CERES-Rice model was done based on the previously calibrated and validated genetic coefficient set. The basic framework of the model is depicted in Fig. 1. A different weather station in the same year run for an alkaline soil (Pedon 2) (1.5 km from Dangarkhera-Roheranwali road, between Fazilka-Abohar, Ferozpur, Punjab- 30º 12′52 N, 74º 10′54 E) for simulation of DSR and TFR establishment methods of rice. The soils in south-western Punjab's Ferozpur district are deep, well-drained, and coarse loamy with a calcareous profile, displaying an A-Bw-C horizon sequence. They exhibit an aridic moisture regime due to prolonged dryness with carbonate content increases with depth and a hyperthermic temperature regime, as their mean annual soil temperature exceeds 22°C. The CERES-Rice model in DSSAT requires detailed soil and weather data to simulate rice growth accurately. Soil inputs include texture, structure, hydraulic properties, wilting point, hydraulic conductivity, and chemical attributes like pH, organic matter, and nutrient levels. Weather data involves daily maximum and minimum temperatures, solar radiation, and precipitation, with optional inputs like relative humidity. These parameters enable precise modelling of water use and crop growth under varying environmental conditions. The

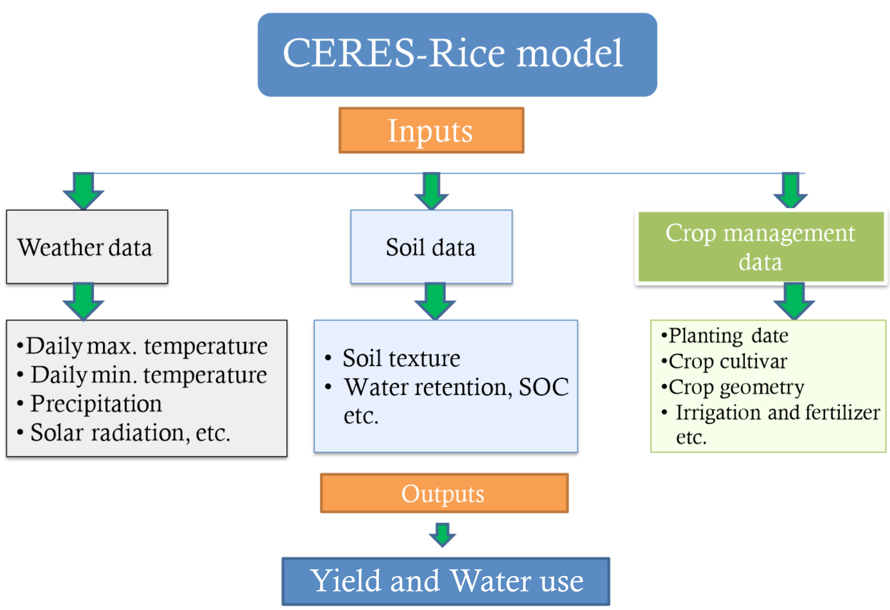

Fig. 1 Framework of CERES-Rice model

weather data of Fazilka for the same years (2022 for calibration and 2023 for validation) was used for simulation study (Fig. 2). The detailed characteristics of alkaline pedon given in the Table 1. Crop management file in model was prepared as per package of practices, PAU.

Performance of the model or model accuracy metrics

Root Mean Square Error (RMSE), normalized RMSE (nRMSE), determination coefficient (R^2), index of agreement (d), and Nash-Sutcliffe Modelling Efficiency (ME) were used as evaluation metrics to assess the agreement between the observed and simulated data of the CERES-Rice model. Table 2 presents the details and estimation of the model accuracy metrics.

Results and Discussions

Calibration and validation of CERES-Rice model

The generated cultivar genetic coefficients were used in the current study, and the calibrated and validated DSSAT CERES-Rice model was

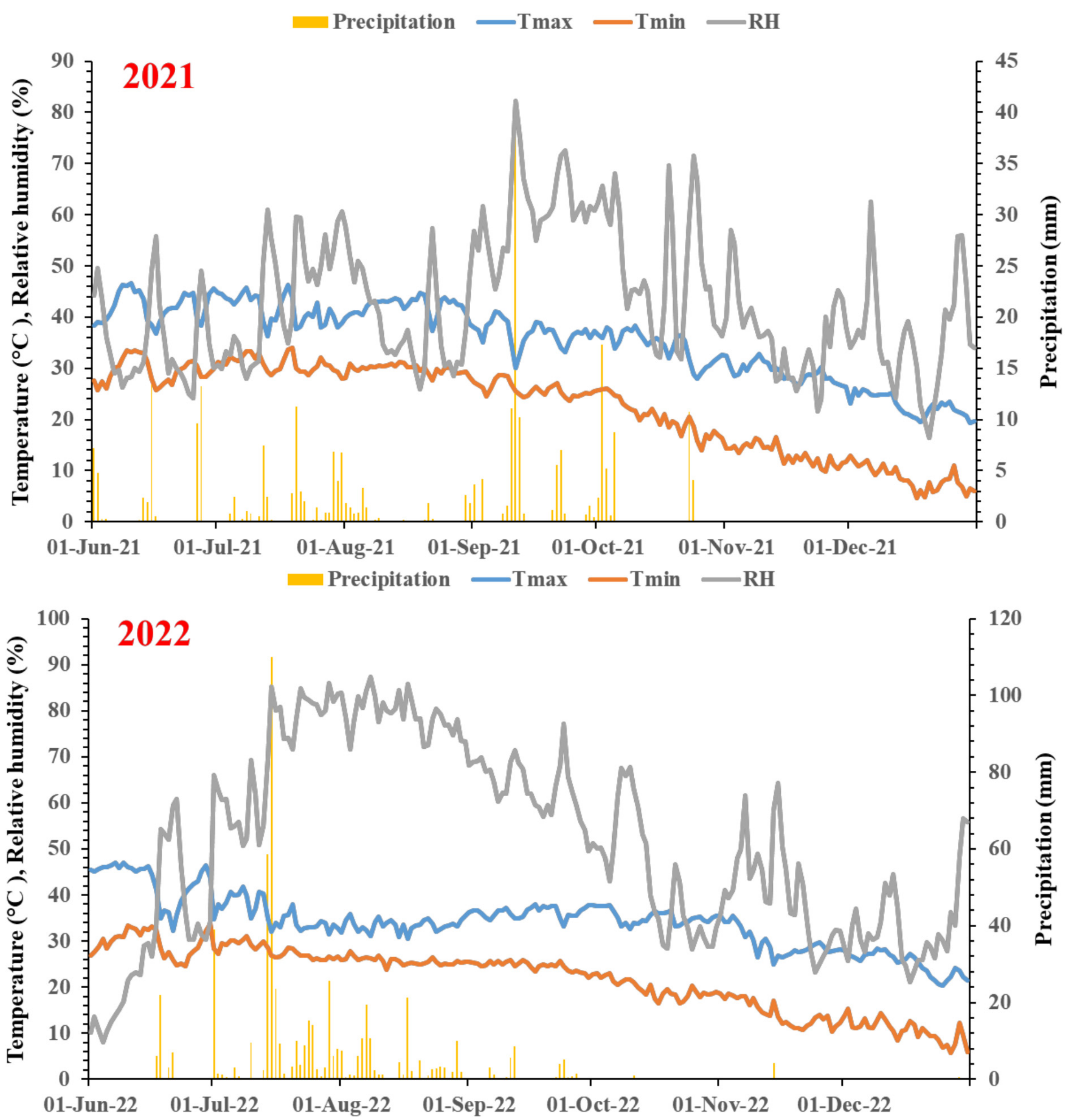

Fig. 2 Weather data during crop growth seasons; calibration (2021) and validation (2022)

Table 1. Soil properties of alkaline pedon used in simulation study

Soil depth	Horizon	Sand (%)	Silt (%)	Clay (%)	pH	$CaCO_3$ (%)	Extractable bases (cmol kg^{-1})			CEC (cmol kg^{-1})
							Ca+Mg	Na	K	
0-18	Ap	46.6	39.6	13.8	8.63	4.3	6.8	0.27	0.05	7.12
18-39	Bw1	47.0	37.6	15.4	8.79	5.5	6.8	0.26	0.07	7.13
39-74	Bw2	44.7	37.3	18.0	9.52	4.0	7.2	0.24	0.04	7.48
74-123	Bw3	45.9	38.3	15.8	8.96	9.8	6.4	0.51	0.25	7.16
123-148	Bw4	40.7	41.7	17.6	9.32	10.3	6.8	0.43	0.35	7.58
148-160	C1	43.4	43.8	12.8	9.49	10.8	6.0	0.80	0.32	7.12
160+	C2	61.4	28.4	10.2	9.62	11.5	6.3	0.24	0.09	6.63

Table 2. Details of model accuracy metrics

S.N.	Mertics	Formula	References
1	Root mean square error (RMSE)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$	Jyolsna *et al.,* 2024
2	Normalized Root mean square error (nRMSE)	$nRMSE = \left[\frac{RMSE}{\bar{O}i}\right] \times 100$	Singh *et al.*, 2018
3	Coefficient of determination (R^2)	$R^2 = \left\{\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right\}^2$	Jyolsna *et al.,* 2024
4	Nash sutcliffe Modelling Efficiency (ME)	$ME = 1 - \left\{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(P_i - \bar{O}_i)^2}\right\}$	Nash and Sutcliffe, 1970
5	Index of agreement (d)	$d = 1 - \left\{\frac{(P_i - O_i)}{\sum_{i=1}^{n}(P_i' + O_i')^2}\right\}$	Willmott, 1981
		where, o2 i = oi – o and p2 i = pi – p.	

Where Pi: simulated, Oi: observed values, $\bar{O}$i and $\bar{P}$i: Means and n: number of results

evaluated using the 2022-23 datasets (Yadav, 2024). The model demonstrated a strong fit for both years, with robust R^2 and RMSE values indicating accurate calibration and validation (Fig. 3). The simulated yields closely matched observed yields across various treatments in sandy loam soil, sandy clay loam and in clay loam. The calibrated coefficients for the rice cultivar PR 126 are detailed in Table 3. The description of the genetic coefficients is described in Hoogenboom *et al. (*2024).

The model performance statistics for grain yield, biomass, and ET using the CERES-Rice model demonstrated satisfactory accuracy and predictive capability (Table 4). The RMSE values for yield, biomass, and ET are 0.21, 0.20, and 0.20, respectively, indicating low residual error. The Nash-Sutcliffe Modelling Efficiency (ME) values of 0.62 for yield, 0.53 for biomass, and 0.64 for ET reflect moderate model performance, where values closer to 1 indicate better agreement. The index of agreement (d) values, ranging from 0.71

Table 3. Cultivar coefficients calibrated for the rice cultivar "PR126"

Genetic coefficient	Units	PR126
P1	GDD (°C)	454
P20	h	12.1
P2R	GDD (°C)	141
P5	GDD (°C)	351
G1	-	71
G2	mg	0.027
G3	-	1.01
THOT	-	33

variations between observed and simulated values.

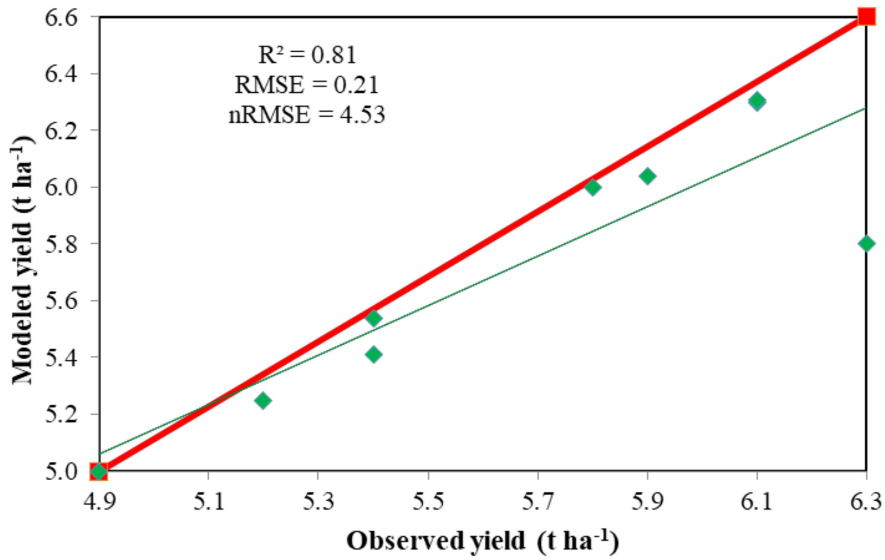

Fig. 3 Validation of CERES-Rice for grain yield of rice

Table 4. Model performance statistics for grain yield, biomass and ET

Indices	Yield	Biomass	ET
Root mean square error (RMSE)	0.21	0.20	0.20
Nash sutcliffe modeling efficiency (ME)	0.62	0.53	0.64
Index of agreement (d)	0.72	0.76	0.71
Coefficient of determination (R^2)	0.81	0.86	0.80

to 0.76, suggest good model reliability in replicating the observed trends. Additionally, the R^2 values of 0.81 for yield, 0.86 for biomass, and 0.80 for ET reveal a strong correlation between observed and simulated data, indicating the model's effectiveness in estimating crop performance and water use. Similar findings, reflected by low RMSE values highlight minimal variation between observed and simulated data, indicating a high degree of accuracy (Rathod *et al.*, 2021). Additionally, moderate Nash-Sutcliffe efficiency values and high coefficients of determination (R^2) reflect the model's strong predictive capability and reliability under diverse climatic conditions (Hoogenboom *et al.*, 2019). The model's high index of agreement further validates its effectiveness in reproducing observed trends, making it a valuable tool for enhancing crop management strategies and supporting food security efforts (Singh *et al.*, 1990; Ahmad *et al.*, 2013a, Paschapur *et al.*, 2022). The results indicate that the generated genetic coefficients of CERES-Rice model can adequately simulate grain yield, biomass, and ET under the given conditions.

The CERES-Rice model has been widely used to simulate rice growth and yield under various conditions. Studies have evaluated its performance for different rice varieties in many countries including India (Swain and Yadav, 2009). The model generally showed reasonable accuracy in predicting phenology, biomass, and grain yield, with some variations depending on the variety and environmental conditions. It has been used to assess the effects of nitrogen fertilization, irrigation regimes and climate change factors such as increased CO_2 and temperature. While the model performed well in many cases, some studies noted limitations, such as overestimation of yields at higher nitrogen rates and the need for recalibration under specific conditions (Mirakhori *et al.,* 2017). The CERES-Rice model proves to be a valuable tool for simulating rice production under various management and environmental scenarios.

The simulated grain yield (t ha^{-1}) and WUE, kg m^{-3} in neutral and alkaline soils explained the contrasting performance of the CERES-Rice model under different soil conditions and crop establishment methods (Table 5). For Pedon 1 (neutral soil), the model predicted yields of 5.7 t ha^{-1} for TFR and 5.0 t ha^{-1} for DSR, with WUE of 0.20 kg m^{-3} and 0.41 kg m^{-3}, respectively. These results indicated that neutral soils provide a conducive environment for both crop

Table 5. Simulated grain yield (t ha^{-1}) and water use efficiency (kg m^{-3})

Particulars	Pedon 1 (Neutral soil)		Pedon 2 (Alkaline soil)	
	TFR	DSR	TFR	DSR
Yield (t ha^{-1})	5.7	5.0	4.9	Crop failure*
WUE (kg m^{-3})	0.20	0.41	0.40	-

P: Precipitation; I: Irrigation; ET: Evapotranspiration; T: Transpiration; D: Drainage; WUE: Water use efficiency, *Model indicated that crop failure due to water and nitrogen stress.

establishment methods, allowing for optimal growth conditions and efficient water use (Ahmad *et al*., 2013a). These results also align with findings from studies that demonstrate how well-managed neutral soils can optimize crop growth, providing favourable conditions for both water retention and nutrient availability (Ritchie *et al*., 1998; Hoogenboom *et al*., 2019). In contrast, for Pedon 2 (alkaline soil), the yield for TFR was lower (4.9 t ha^{-1}) as compared to neutral Pedon while DSR resulted in crop failure due to water and nitrogen stress. The WUE for TFR in Pedon 2 was slightly lower at 0.41 kg m^{-3} than the Pedon 1. The inability of DSR to establish successfully under alkaline conditions is consistent with research showed that such soils often exhibit poor nutrient dynamics and water retention capabilities, which are crucial for rice cultivation (Singh *et al*., 2021; Ahmad *et al*., 2013b). Studies in Kerala, India, and Iran found the model accurately simulated phenology and grain yield, with RMSE ranging from 0.89 to 1.92 for physiological maturity (Vysakh *et al.,* 2016). The model showed reasonable accuracy in simulating grain yield, biological yield, and LAI under different irrigation and nitrogen treatments (Mirakhori *et al.,* 2017). In north-western Himalayas, the model effectively predicted phenology, grains m^{-2}, single grain weight, and grain yield for multiple rice varieties and planting dates (Jha *et al.,* 2020). However, some limitations were noted, including overestimation of grain yield in Kerala (Vysakh *et al.,* 2016) and failure to accurately simulate panicles m^{-2} and biomass yield at maturity in the Himalayas (Jha *et al.,* 2020). Furthermore, the slight reduction in WUE for TFR in alkaline soils compared to neutral soils further emphasizes the challenges posed by soil chemistry on water use efficiency (Goswami and Dutta, 2020). This difference suggests that while neutral soils can support effective management strategies, alkaline soils require specific interventions, such as soil amendments or improved irrigation practices, to enhance productivity and WUE (Chandran *et al*., 2021). This comparison indicates that neutral soil is more conducive for both crop establishment methods, while alkaline soil poses significant challenges, particularly for DSR.

Conclusions

Soil reaction is the major limiting factor for rice production. Model evaluation indices such as RMSE, Nash-Sutcliffe Modelling Efficiency, R^2 and index of agreement (d) were indicated good reliability of simulated yield using CERES-Rice. The simulated grain yield suggested that direct seeded rice failed to establish under alkaline soils. The failure of direct seeded rice mainly due to water and nitrogen stress as indicated in model output. The simulated yield and water use of transplanted flooded rice slightly reduced under Pedon 2 reflecting poor water retention and nutrient dynamics under alkaline soil environment. This is recommended that transplanted flooded rice is the suitable under alkaline soil environment by sustaining yield under salt stress while direct seeded rice is the water saving option under neutral soils. Further, it is recommended to apply and study the impact of the suitable set of management practices for alkaline pedons *viz.* salt tolerant variety, application of gypsum and organics for buffer the pH of soil under alkaline environment**.**

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Cultivation of Onion Under Fertigation Using Saline Water in the Semi-Arid Region of Haryana in India

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Abstract

The growing shortage of good quality water has compelled farmers to rely on marginal water for food grain production to meet rising food demands. This situation is expected to worsen in the future. With background of emerging water quality issue, the present study was designed to examine the response of onion to fertigation under saline water irrigation with electrical conductivity levels of 0.3, 2.5, and 5.0 dS m^{-1}. The experiment was carried out in micro-plots having surface drip system, located at Research Farm, Department of Soil Science, CCSHAU Hisar. A Split plot experimental design was used to conduct the research, with three levels of irrigation water (ECiw: 0.3, 2.5, and 5.0 dS m^{-1}) as a main factor and three nitrogen levels (75% RDN, 100% RDN, and 125% RDN) as a sub-factor. The data revealed that onion yield decreased significantly with increase in ECiw from 0.3 to 5.0 dS m^{-1}. The highest crop yield (30. 932 Mg ha^{-1}) was achieved with canal irrigation at 125% RDN, which was statistically similar to 100% RDN (29.854 Mg ha^{-1}) under canal water irrigation. At salinity level of 2.5 dS m^{-1}, onion yield was comparable for 100% and 125% RDN, indicating that farmers should apply only recommended dose of nitrogen under these conditions. However, at 5.0 dS m^{-1}, a significant improvement in onion yield was observed when nitrogen dose were raised from 75% to 125% RDN, suggesting that farmers should use 125% recommended dose of nitrogen under saline water (5.0 dS m^{-1}) in surface drip system.

Keywords: Water quality, Fertigation, Nitrogen, Crop yield, Onion

Introduction

Onion (*Allium cepa* L.) is an important bulb crop and provides a significant source of income for the farmers. It is second most important vegetable crop after tomato in world. Onion bulb is highly nutritive as it contains 86.80 g water, 11.0 g carbohydrates, 0.6 g of fiber, 1.2 g protein and various vitamins and minerals (*Rahman et al*., 2013). Worldwide, 88.48 million tons of onions are produced annually from 5.30 Mha areas, with a productivity of 16.70 Mg ha^{-1}. India is a leading producer of onion at global level (Anonymous, 2020), recorded an annual production of 30.21 million Mg from approximately 1.74 million hectare and a productivity rate of 17.40 Mg per hectare (Anonymous, 2023). In Haryana, the area under onion crop is 29.93 thousand hectares producing 701.50 thousand tons with an average productivity of 23.03 Mg per hectare.

Most important but less prioritized threat to the existence of human life is the continuous depletion of groundwater resources. Now, water scarcity is no longer a concern of future as it has already hit many parts of country. Agriculture is the primary sector that consumes the major portion of India's good quality water. Studies indicated that 32-84% of ground water used for irrigation contains poor quality water, particularly in areas receiving low annual rainfall *i.e.* arid and semi-arid regions of the country (Kumar and Sharma, 2020). With further depleting fresh water resources and unpredictable rainfall, farmers are left up with only option to irrigate the crops with poor-quality water. This situation is expected to become more critical in future (Rani *et al.,* 2020). To confront the rising challenge of salinity and depleting water resources, it is essential to develop strategies for efficient utilization of poor-quality water for crop production. In these prospects, fertigation provides an effective solution to both, water scarcities and efficient use of poor quality water. Fertigation, simply implies the application of fertilizers through irrigation system. It allows precise, consistent and targeted application of nutrient to the crops root zone that will create an ambient environment and improve the overall yield of the crop. It also enhances the fertilizer and water use efficiency as reported by Dingre and Pawar in 2020. Applying water to crop via drip method may save 56.4% of water and produced 22% more yield in tomatoes compared to furrow irrigation (Tagar *et al.,* 2012).

Nitrogen plays a critical role in onion production under both good as well as poor irrigation water conditions due to its higher demand compared to other essential nutrients. Its importance further enhanced under the salt stress conditions because it plays significant role in mitigating the adverse effect of salt accumulation. It has been reported in studies that N improves the plants ability to withstand osmotic stress by maintaining osmotic balance, promoting root growth, and enhancing photosynthetic efficiency, which collectively enhance the plant tolerance against salt stress.

Currently, population is rising exponentially and natural resources are dwindling, in such scenario, meeting the rising demand of vegetables, is a significant challenge to the scientific community. Expanding the area under cultivation to increase production is not a feasible option. Instead, enhancing productivity through the judicious use of available resource is a more viable strategy (Daszkiewicz, 2022). This can be attained by implementing recent technologies like drip irrigation and fertigation. Through the targeted and direct supply of nutrients in a controlled manner, fertigation helps maintain optimal nutrient levels under saline conditions. This method improves nutrient uptake efficiency, reduces salt accumulation, and improves the use efficiency of water. Several findings have been published regarding the benefits of drip irrigation in enhancing onion production under good water quality. There is need to study the response of onion to fertigation under saline water irrigation. Considering the significance of the preceding discussion, this study was conducted to examine the response of onion in terms of growth and yield to fertigation under saline water conditions in semi-arid conditions of Haryana state.

Materials and Methods

The present study was conducted at the Research Farm of the Department of Soil Science, CCSHAU Hisar, Haryana. The meteorological data recorded during the growing season was obtained from the observatory and is represented in Fig. 1. The experiment was executed in protected micro-plots, each measuring 2 × 2 m with a soil depth of 1.2 m. The experimental layout is illustrated in Fig. 2.

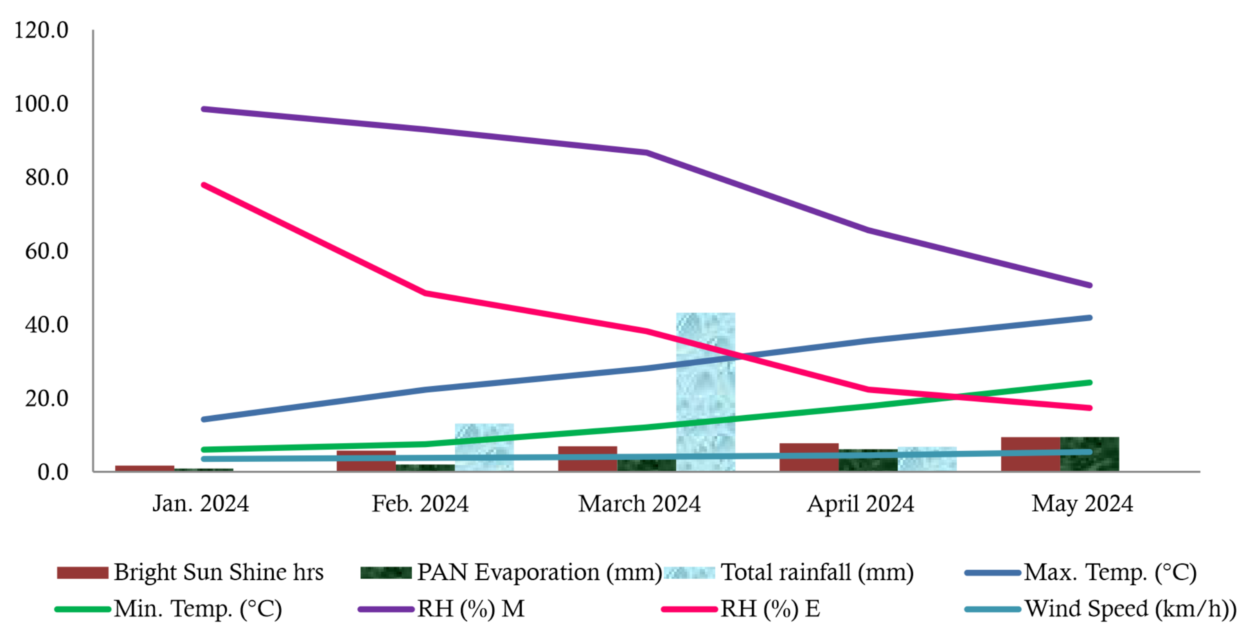

Fig. 1 Seasonal meteorological data during of the crop growth period

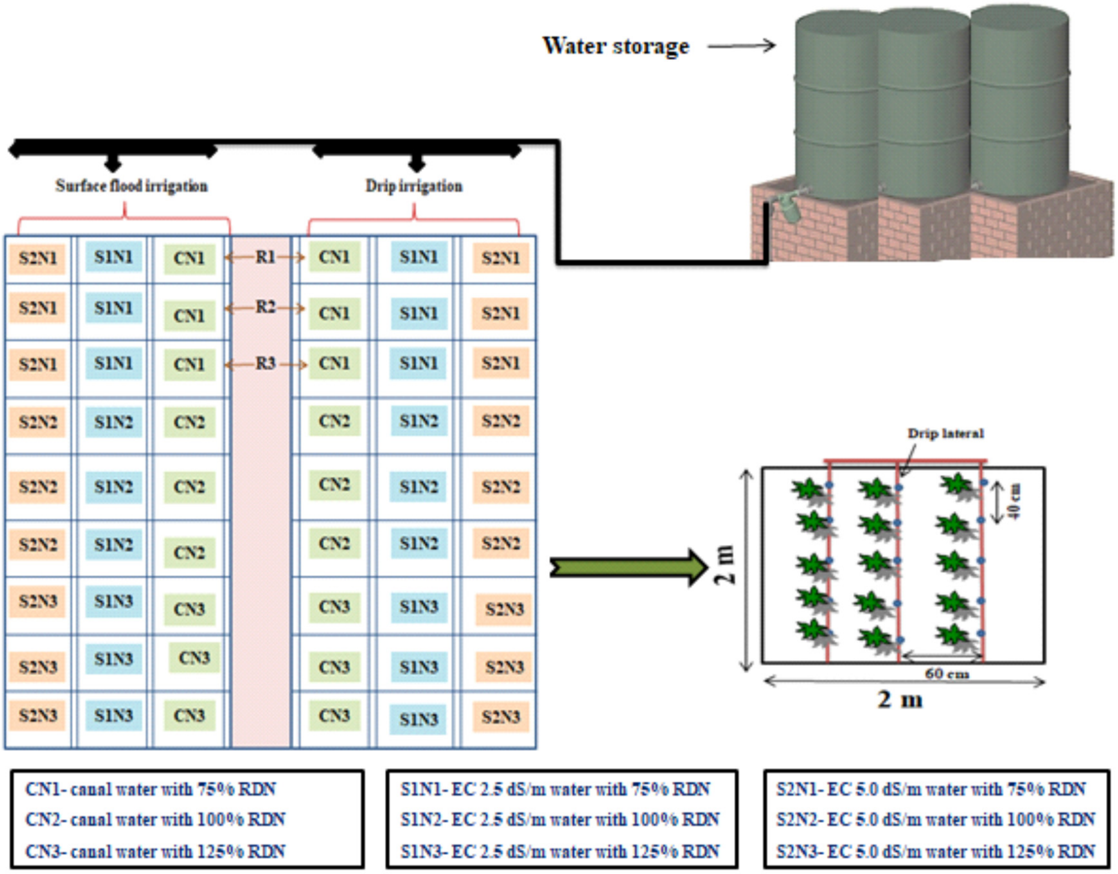

Fig. 2 Layout of experimental set up

The experiment was laid out in the split plot design with three replications. Plots were irrigated with three level of water quality under drip system *i.e*. ECiw: 0.5 dS m^{-1}, ECiw: 2.5 dS m^{-1} and ECiw: 5.0 dS m^{-1}. These three water quality treatments were subcategorized into three more treatments containing different level of N fertigation *i.e*. 75%, 100% and 125% of the recommended nitrogen dose (RDN) in split plot design. The seedlings of onion variety Hisar Onion-4 were prepared in a nursery at the Vegetable Farm of CCSHAU by adopting all the package and practices recommended for onion. The micro-plots were ploughed before the transplanting so as to loosen the soil profile and remove the weeds. One-third of N dose (41.67 kg ha^{-1}), along with full doses of the phosphorus (50 kg ha^{-1}) and potassium (25 kg ha^{-1}), were applied at the time of seedling transplanting. The remaining N dose was supplied according to the specified treatments. The seedlings were transplanted on 4th January 2024 at spacing of 10 × 15cm in micro-plots of 2 × 2 m area. Nitrogen (N) was applied eight times through fertigation in these microplots, consisting of one basal application and seven splits application. The basal application of nitrogen is amounted to 12.36 g, 16.48 g, and 20.60 g $plot^{-1}$, corresponding to 75%, 100%, and 125% of the recommended nitrogen dose (RDN).. The remaining N was delivered in seven splits at rates of 3.53 g $plot^{-1}$, 4.71 g $plot^{-1}$, and 5.89 g $plot^{-1}$ for respective RDN levels. The schedule and dose of N-fertigation is presented in the Table 1.

Harvesting was done on 27 May 2024, when 70% crop fall down. The growth parameters were observed at periodical intervals and yield attributes and yield recorded at harvesting. The soil samples were analyzed before transplanting of seedlings and after harvesting of onion, by adopting the standard methodologies. The data collected from split-plot experiment with three replications were statistically analyzed using the OPSTAT software (Sheoran *et al.,* 1998), developed by Chaudhary Charan Singh Haryana Agricultural University. All significance tests were conducted at the 5% level.

Table 1. Nitrogen-fertigation schedule of onion crop

Application time	75% RDN	RDN	125%RDN
Basal dose (g plot^{-1})	12.36	16.48	20.60
Fertigation dose (g) week^{-1}plot^{-1}	3.53	4.71	5.89
Total	37.08	49.45	61.83

RDN depict recommended dose of nitrogen

Results and Discussion

Effect on growth metrics and yield

Plant height (cm)

The average height of onion at maturity varied from 41.03 cm to 60.03 cm. The results presented in table 2 revealed that salinity concentration and nitrogen doses significantly affect the onion height. An increasing trend of plant height was observed with increase in the application of N dose from 75 to 125% RDN under good as well as saline water treatment. A negative correlation was observed between plant height and the salinity levels, as onion height decreases with the increase in salinity level from ECiw 0.3 to 5.0 dS m^{-1}. The results obtained were in the line of work with Nawaz, *et al.* (2017) and Fagodiya *et al*. (2020). The decline correlation can be ascribed to salt deposition in the onion rhizosphere due to saline water application, which negatively affects N availability in the soil. Also due to high pH N, may be loss as volatilization. High chloride concentration under saline conditions also restricts the nitrate uptake by onion which may be responsible for the decrease in onion height. The maximum plant height (60.03 cm) was obtained in the treatment receiving 125% RDN with canal water irrigation (0.3 dS m^{-1}) whereas; the shortest height (41.03 cm) was recorded in the treatment irrigated with 5.0 dS m^{-1} saline water and receiving 75% RDN, respectively.

The data further revealed that, with drip irrigation and use of 75% dose of recommended nitrogen (RDN), the reduction in plant height was 8.67% and 25.53%, respectively. While, the reductions were 6.82% and 20.54% under 100% RDN, and 5.68% and 17.47% under 125% RDN, at an EC_{iw} 2.5 and 5.0 dS m^{-1}, in comparison with canal water irrigation. These results indicates that reduction in plant height due to salinity was less in the treatment receiving the higher nitrogen dose (125% RDN) compared to the lower doses describing the sensitivity of onion towards N application under saline conditions.

Equatorial diameter of bulb

The influence of water quality and N levels on equatorial diameter of onion is shown in the Table 3 and Fig. 3. It was observed from the data that increasing N level from 75 to 125% dose of recommended nitrogen, there is increase in the equatorial diameter under good as well as saline water. This shows a positive relation between the N dose and the equatorial diameter which was in support of results of Nasreen *et al.* (2007), Bhasker *et al.* (2018) and Tripathi *et al.* (2010). The maximum diameter was found in the treatment receiving good quality water (canal, 0.3 dS m^{-1})

Table 2. Influence of nitrogen fertigation and different saline water irrigation on plant height (cm) of onion

Nitrogen Level	Electrical conductivity (dS m^{-1}) of irrigation water			
	Canal (0.3 dS m^{-1})	2.5 dS m^{-1}	5.0 dS m^{-1}	Mean
75% RDN	55.10	50.32	41.03	48.82
RDN	58.21	54.24	46.25	52.90
125% RDN	60.03	56.62	49.54	55.40
Mean	57.78	53.73	45.61	
LSD (p=0.05)	Nitrogen (N) = 1.34, Salinity level (S) =1.56, N × S = NS			

Table 3. Average equatorial diameter of onion bulb (cm) under different treatments

Nitrogen Level	Electrical conductivity (dSm^{-1}) of irrigation water			
	Canal (0.3 dS m^{-1})	2.5 dS m^{-1}	5.0 dS m^{-1}	Mean
75% RDN	5.57	5.33	4.88	5.26
RDN	6.09	5.81	5.39	5.76
125% RDN	6.55	6.46	6.02	6.34
Mean	6.07	5.87	5.43	
LSD (p=0.05)	Nitrogen (N) = 0.15, Salinity level (S) =0.18, N × S = NS			

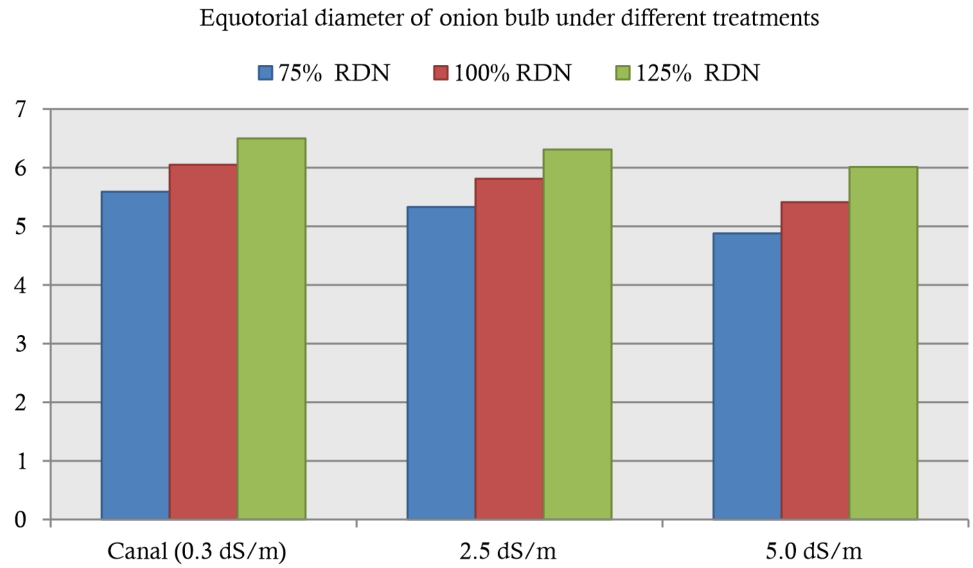

Fig. 3 Equatorial diameter of onion at maturity

with125% RDN (6.55 cm) whereas; minimum was seen under saline water irrigation of EC 5.0 dS $m^{-1}$and 75% RDN (4.88 cm). Drip irrigation with frequent application of N under fertigation enables better plant growth due to higher accumulation of photosynthates and carbohydrates in the sink region.

Polar diameter of bulb

The average polar diameter of onion bulbs (Table 4 and Fig.4) ranged from 4.35 to 5.04 cm, 4.01 to 4.44 cm, and 3.29 to 3.58 cm, with means of 3.88, 4.17, and 4.35 cm at nitrogen levels of 75%, 100%, and 125%, respectively, under salinity levels of ECiw 0.3, 2.5, and 5.0 dS m^{-1}. Water quality and N levels significantly affect bulb size, with higher salinity leading to reduced polar diameter, consequently smaller bulbs. This reduction may be due to limited nutrient mobility under salt stress. The maximum polar diameter (5.04 cm) was obtained with 125% RDN and canal water irrigation (0.3 dS m^{-1}) whereas; the shortest

Table 4. Average polar diameter of onion bulb (cm) for different treatments

Nitrogen Level	Electrical conductivity (dS m^{-1}) of irrigation water			
	Canal (0.3 dS m^{-1})	2.5 dS m^{-1}	5.0 dS m^{-1}	Mean
75% RDN	4.35	4.01	3.29	3.88
RDN	4.77	4.32	3.41	4.17
125% RDN	5.04	4.44	3.58	4.35
Mean	4.72	4.26	3.43	
LSD (p=0.05)Nitrogen (N) = 0.12, Salinity level (S) =0.12, N × S = NS				

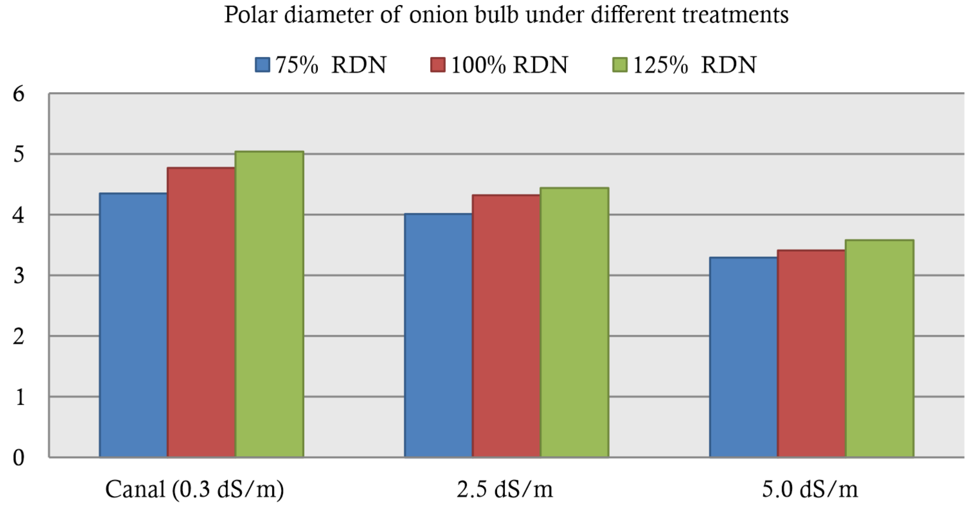

Fig. 4 Polar diameter of onion at maturity

diameter (3.29 cm) was recorded with ECiw 5.0 dS m^{-1} EC and 75% RDN. The data further indicates that increasing N dose from 75 to 125% RDN enhances the polar diameter, demonstrating the role of nitrogen in onion bulb development.

Onion bulb yield

Onion performance significantly varied with water quality and N levels (Table 5). The data revealed that yield reduction due to saline water at EC levels of 2.5 and 5.0 dS m^{-1}, were as follows: 5.48% and 27.26% with 75% RDN, 5.13 % and 22.63% with 100% RDN, 4.59% and 20.68% with 125% RDN, respectively, compared to canal water. A favorable relationship was noted between N dose and average weight on onion bulb. The application of N has enhanced both growth and yield of onion both under good as well as saline water conditions; however, the improvement under salt stress was more pronounced than under stress-free conditions. This suggests that onions exposed to saline conditions are more sensitive to nitrogen application and require more N to cope up the salt stress. A similar cause-and-effect relationship was reported by Wang *et al.,* 2013, indicating importance of nitrogen management in optimizing vegetable production in saline environments. The data further indicated a significant reduction in mean yield of onion at levels of 2.5 and 5.0 dS m^{-1} compared to the canal water irrigation, demonstrating a negative relationship between the yield and salinity level (Fagodiya *et al.*, 2020). The maximum average bulb weight was recorded with 125%RDN under good quality of water, whereas the minimum bulb weight was found in treatment receiving irrigation water of 5.0 EC with 75% nitrogen dose. At salinity level of 2.5 dS m^{-1}, onion yield remained at par for 100% and 125% RDN, indicating that farmers should apply only recommended nitrogen dose in such conditions. However, at 5.0 dS m^{-1}, a significant improvement in onion yield was observed with increase in nitrogen dose from 75% to 125% RDN, suggesting that farmers should use

Table 5. Influence of nitrogen fertigation and different saline water irrigation on yield (Mg ha^{-1}) of onion

Nitrogen Level	Electrical conductivity (dSm^{-1}) of irrigation water			
	Canal (0.3 dSm^{-1})	2.5 dSm^{-1}	5.0 dSm^{-1}	Mean
75% RDN	26.851	25.378	19.531	23.920
RDN	29.854	28.322	23.100	27.092
125% RDN	30.932	29.510	24.533	28.325
Mean	29.212	27.737	22.388	
LSD (p=0.05)	Nitrogen (N) = 1.202, Salinity level (S) =1.378, N × S = NS			

Table 6. Effect of nitrogen fertigation and different saline water irrigation on soil ECe (0-15 cm) under onion crop

Nitrogen Level	Electrical conductivity (dS m^{-1}) of irrigation water			
	Canal (0.3)	2.5	5.0	Mean
75% RDN	0.56	2.64	4.15	2.45
RDN	0.44	2.44	4.06	2.31
125% RDN	0.39	2.38	3.86	2.21
Mean	0.46	2.49	4.02	

125% recommended dose of nitrogen in saline water conditions under surface drip system

Soil EC

The data on soil EC_e under nitrogen and salinity levels (Table 6) with drip irrigation revealed that highest mean values of ECe of 4.15 dS m^{-1}were observed in saline water irrigated plots of ECiw 5.0 dS m^{-1} at 75% RDF followed by ECe of 4.06 in saline water irrigated plots at RDN. Electrical conductivity of saturated extract increased with increasing the saline water *i.e* canal to 5dS m^{-1}. The mean ECe is varied from 0.46 to 4.02 dS m^{-1}. Minimum mean value of ECe 2.21 dS m^{-1} was observed in treatment where 125%RDN was applied and maximum value of ECe 2.45 dS m^{-1} was observed in treatment 75% RDN.

Conclusions

Based on the results it is concluded that irrigation water with an EC of 2.5 dS m^{-1} is suitable for onion cultivation with the recommended dose of nitrogen, while for water with an EC of 5.0 dS/ m, a 25% increase in nitrogen application (125% RDN) is recommended for optimal production. These findings may motivate farmers to adopt fertigation practices for onions using saline water. Additionally, future research should assess the suitability of other vegetables for fertigation under saline conditions.

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On-farm Assessment of Halophilic Microbial Bio-formulation on Productivity of Mustard Crop in Sodic Soils of Indo-Gangetic Plain

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ABSTRACT

The impact of halophilic microbial bio-formulation on mustard crop productivity during *Rabi*, 2020-21 to 2022-23 under cluster front line demonstration (CFLD) on sodic soils of Hardoi was assessed. A total of 278 CFLDs on Integrated Crop Management (ICM) in mustard with salt tolerant variety CS-60 and the use of bio-formulation (Halo Mix) were undertaken in 47.0 ha across 43 villages of Bharawan, Benhadar and Sandila Blocks of Hardoi district. The salt-tolerant variety of mustard, CS-60 is specifically recommended for cultivation in saline soils with an electrical conductivity (EC) of up to 12.0 dSm^{-1} and in alkali soils with a pH of up to 9.5. Based on three years data, the average extension gap, technology gap and technology index were 353.33 kg ha^{-1}, 382.33 kg ha^{-1}, and 15.72%, respectively. The economic analysis of demonstrations revealed the viability of enhanced technology, with a net return of 68575.67 Rs ha^{-1} and benefit-cost ratio (BCR) of 2.79, compared to 52532 Rs ha^{-1} and 2.44 (BCR) in farmers practice.

Key words: Sodicity, Halo mix, bio-formulation, CFLD, Impact, Mustard, Net return, Gap analysis

Introduction

India has 6.73 million hectares of salt-affected areas, with 2.95 million hectares spread across 16 states. Major salt-affected areas include Gujarat, Uttar Pradesh, Maharashtra, Tamil Nadu, Haryana, and Punjab, which together account for 80% of India's total sodic lands (Wicke *et al.,* 2012). In India, 75% of the saline and sodic soils are found in Gujarat (2.23 million hectares), Uttar Pradesh (1.37 million hectares), Maharashtra (0.61 million hectares), West Bengal (0.44 million hectares), and Rajasthan (0.38 million hectares). Water quality in these areas is poor (Singh, 2009). In Uttar Pradesh, salinization has become a major factor hindering agricultural output. The accumulation of salts in irrigated lands is the leading cause of soil degradation in the region.

The degradation of soils is largely attributed to the low-quality water used for irrigation. Salt-affected soils are predominantly found in arid and semi-arid regions but can also occur temporarily in areas where climatic conditions and salt mobility lead to saline waters and soils (Tanji, 1990). Reclaiming sodic soils is essential to enhancing crop productivity and restoring soil fertility. Additionally, the development of salt-tolerant crop varieties is crucial for sustaining agriculture in salt-affected regions and boosting current yields. Halophilic microorganisms, capable of thriving in high-salt environments, present potential solutions in such challenging conditions (Arora *et al.*, 2021).

Rapeseed (*Brassica campestris*) and mustard (*Brassica juncea*) are key Rabi oilseed crops in India, contributing significantly to the country's oilseed production. Together, they account for approximately 18% of India's total oilseed output. Mustard cultivation spans 6.78 million hectares, yielding 9.12 million tons with an average productivity of 1345 kg ha^{-1}. These crops are vital for edible oil production in India, with their oil widely used for cooking and frying, particularly in northern regions. The seeds and oil also serve as condiments for pickles and flavor enhancers for various dishes. Byproducts like oil cake are utilized as cattle feed and organic manure, while green stems and leaves are valuable sources of fodder. Young mustard leaves are consumed as green vegetables, providing essential sulfur and minerals. Halophilic plant growth-promoting micro-organisms offer promising solutions for managing salt affected soils. These microbes support vegetation growth under salt stress by enhancing crop resilience and improving yields. They also play a role in soil recovery through the production of organic acids (Krishnaprabu, 2020). However, mustard productivity in the region is hindered by several challenges, including the limited adoption of salt-tolerant high-yielding varieties, inadequate agricultural practices, and insufficient plant protection measures. Biotic stresses, such as insect pests (e.g., aphids, mustard sawfly, and painted bugs), diseases (e.g., Alternaria blight and white rust), and weed infestations, also contribute significantly to reduced crop yields.

The Government of India has taken initiatives towards achieving self-dependency in edible oils by launching various schemes through ICAR and SAUs for the quick and effective transfer of improved oilseed crop technologies to farmers' fields. The role of KVKs in agriculture and related sectors is critical as they are well-positioned to disseminate field-tested proven technologies with suitable adaptations to meet location-specific challenges and address current natural and socio-economic conditions, requirements, and priorities.

In light of the foregoing, CFLDs on mustard employing the latest salt-tolerant high-yielding crop varieties, sulfur-based fertilizers, and new plant protection measures were initiated to demonstrate the productive potential of new production technologies in real-world conditions compared to locally cultivated practices. Keeping this in view, the present CFLDs were organized in a participatory mode with the objective of enhancing the production potential of mustard crops.

Materials and Methods

The current study was carried out by ICAR-CSSRI, Krishi Vigyan Kendra, Hardoi-II, at farmers' fields in various villages of the Hardoi district, Uttar Pradesh, over three years, from Rabi 2020-21 to Rabi 2022-23. The study covered 43 villages in the Bharawan, Benhadar, and Sandila Blocks of Hardoi district. A total of 278 demonstrations on improved mustard cultivation practices, using the salt-tolerant variety CS-60, were conducted across 47 hectares in these areas. This variety is recommended for saline soils with an electrical conductivity (EC) up to 12.0 dSm^{-1} and alkali soils with a pH up to 9.5. The soils typically have a sandy to sandy loam texture with low levels of essential micronutrients and organic carbon. Table 1 lists the materials and practices used in cluster frontline demonstrations (CFLDs) and farmers' practices.

This microbial technology, utilizing halophilic microbes in liquid formulations, enhances crop growth and yield while maintaining the health of problematic soils. Therefore, the Bio formulation Halo Mix was used in demonstration plots alongside all recommended packages and practices (Arora *et al.*, 2021; Duary *et al.*, 2021). Sowing took place from mid to late October under irrigated conditions, with harvesting occurring from the first to the third week of March. Farmers received key inputs such as seed, fertilizer, need-based plant protection chemicals, and the Bio formulation Halo Mix, as listed in Table 1. Frequent visits by scientists to the demonstration fields ensured that farmers received correct guidance. Farmers selected for CFLDs received comprehensive training on improved scientific methods. In contrast, farmers were allowed to follow their own practices in the case of the farmer's practice or local practices. Field days and farmer meetings were held to showcase the benefits of the demonstrated varieties and technologies to other farmers. Data on different parameters, such as seed yield and percent insect-pest incidence, were collected separately from both improved practices (IP) and farmers' practices (FP) for comparative analysis.

Further, data tabulated and analysed by using statistical tools like frequency and percentage. The

Table 1. Details of mustard cultivation practices implemented under CFLDs compared to existing practices.

S. No.	Operation	Farmer's practice	Demonstration
1.	Seed & seed rate	Use of old variety (Kanti & Varuna) with high seed rate @5-6 kg ha^{-1}	CS-60, it is recommended for saline soil up to soil salinity level (EC up to 12.0 dSm^{-1} and in alkali soils up to pH 9.5) with seed rate@4-5 kg ha^{-1}
2.	Seed treatment	Generally, not practiced	Carbendazim @2 g kg^{-1} seed or Metalaxyl @6 g kg^{-1} before one day sowing followed by *Trichoderma viridae* @ 10g kg^{-1} seed
3.	Sowing time	15 Oct. to 5th Nov.	10th to 31st Oct.
4.	Sowing method	Broad casting	Line sowing: R x P = 45 x 10cm
5.	Manure & Fertilizers	FYM: None 100:80: 0 (Kg. N: P: K ha^{-1})	FYM: 10 t ha^{-1} 80: 40: 40:20 (Kg N: P: K:S ha^{-1}) 250 kg Gypsum ha^{-1}
6.	Bio-formulation	No practice	Liquid Haro-Mix @250ml ha^{-1}
7.	Irrigation	4-5 irrigations	2-3 irrigations
8.	Weed management	One hand weeding at 25-30 DAS and pre-emergence uses of Pendimethalin @1.0 kg ha^{-1}	Hand weeding/intercultural done twice at 20 and 40 days after sowing (DAS) or use of Fluchloralin@1.0 kg ha^{-1} in spray 600-800 litre water at Pre Plant in Corporation stage (PPI stage)
9.	Plant protection	Broadly used old chemical pesticides (Dimethoate and Dithane M-45)	• Two foliar spray of Neem oil 1500 ppm @ 40 ml in 15 litre water, followed by Thiamethoxam 30 FS @ 6g in15 litre water for the control of aphid • One spray of carbendazim 50 WP @ 2g L^{-1} water two manage the Alternariablight and rust diseases

gross returns, net returns, benefit cost ratio (BCR), extension gap, technology gap, and technology index were worked out using the Samui *et al.* (2000) equations.

1. TG = PY – DY
2. EG = DY - FP
3. TI (%) = [(PY - DY)/PY] × 100
4. AR= Demo Return – FP Return
5. NR= GR – COC
6. BCR = GR /COC

(Where as TG= Technology gap, PY= Potential yield, DY=Demonstration yield, EG= Extension gap, TI= technology index, FP=Farmer Practice, AR=Additional Return, NR=Net returns, GR=Gross returns, COC=Cost of cultivation, BCR =Benefit Cost Ratio)

Results and Discussion

Impact of Halophilic Microbial Bio-formulation on yield

The impact of bio-formulation and variety on the yield of mustard in demonstration plots and local farmers' practices is shown in Table 2 and Fig. 1, 2. The average seed yield was significantly higher (20.37%) in CFLD plots, with an additional yield of 354 kg ha^{-1}. The average mustard yield in CFLD plots was 2118 kg ha^{-1} compared to the local check (1764 kg ha^{-1}) during the study period. During the Rabi seasons of 2020-21, 2021-22, and 2022-23, the average seed yield recorded under improved practice (IP) was 1954, 2134, and 2265 kg ha^{-1}, respectively, compared to farmer's practice (FP), where it was 1548, 1850, and 1895 kg ha^{-1}, respectively. Similar trends of yield enhancement in frontline demonstrations on mustard and other oilseeds have been reported Singh and Tetarwal (2022), Ghintala *et al.* (2018); Kumar *et al.* (2019); Sharma *et al.* (2020); Singh *et al.* (2023) and Singh *et al.* (2024).

Increased awareness and acceptance of the complete package of practices, including timely sowing, line sowing, use of prescribed fertilizer doses, thinning, better weed control, and need-based plant protection measures, may explain the higher yield in CFLD plots.

Table 2. Year wise details and impact of halophilic microbial bio-formulation on yield (average of three years)

Year	Potential yield (kg/ha)	Demo (IP)* yield (kg/ha)	Local (FP)*yield (kg/ha)	% yield increased over FP
2020-21	2500	1954	1548	26.23
2021-22	2500	2134	1850	15.35
2022-23	2500	2265	1895	19.52
Mean	2500	2118	1764	20.37
S.Em ±	0.00	90.15	108.94	3.17
C.D (P=0.05)	0.00	0.04	0.06	0.16

*IP=Improved Practice; FP= Farmers Practice

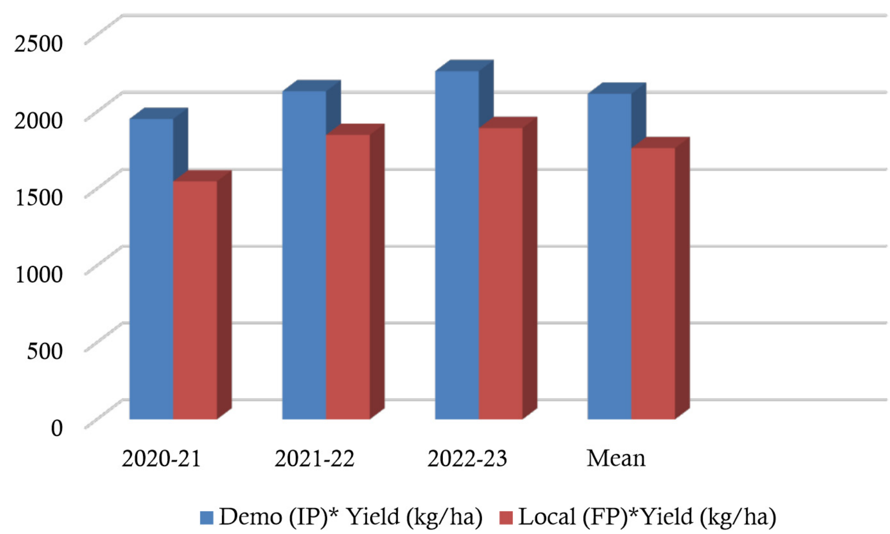

Fig. 1 Impact of halophilic microbial bio-formulation on yield of mustard

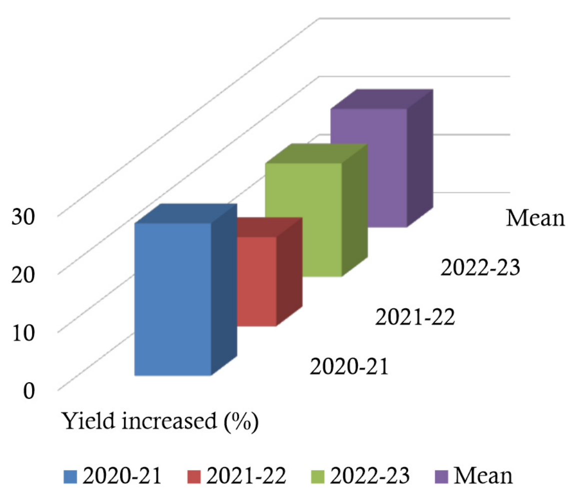

Fig. 2 Impact of halophilic microbial bio-formulation on yield increased (%)

Technological gap analysis in Yield

Technology gap

The average technology gap was recorded at 382.33 kg ha^{-1}, showing the difference between the potential yield and the yield achieved in demonstration plots. The highest gap, 546 kg ha^{-1}, was observed in 2020-21, followed by 366 kg ha^{-1} in 2021-22 and 235 kg ha^{-1} in 2022-23 (Table 3). This indicates that the full potential of improved practices has not been realized by participating farmers, highlighting a persistent gap in technology adoption. The technology gap observed is primarily due to disparities in soil fertility, agricultural practices, and climatic conditions. These findings align with the results reported by Singh and Tetrwal. (2022), as well as Singh et al. (2019).

Extensions gap

The extensions gap were observed higher 406 kg ha^{-1} in 2020-21 followed by 370 kg ha^{-1} and 284 kg ha^{-1} in 2022-23 and 2021-22, respectively (Table 3). The average extension gap was observed as 353.33 kg ha^{-1} in this findings and it may be over

Table 3. Extension gap, technology gap and technology index of mustard under CFLDs

Year	Extension Gap (kg ha^{-1})	Technology Gap (kg ha^{-1})	Technology Index (%)
2020-21	406	546	21.84
2021-22	284	366	14.64
2022-23	370	235	10.68
Mean	353.33	382.33	15.72
S.Em ±	36.19	90.15	3.27
C.D (P=0.05)	0.10	0.24	0.21

bridged by various extension methods like maximum use of the latest improved technologies with high yielding salt tolerant varieties of oilseed crops. The CFLDs play a crucial role in promoting the adoption of advanced production and protection technologies. This aligns with the findings previously reported by Singh *et al*. (2019) Singh and Tetrwal (2022).

Technology index

The technology index, defined as the ratio between the technology gap and potential yield expressed as a percentage, reflects the practicality and acceptability of demonstrated technologies. A lower technology index indicates greater adoption of the technology by farmers. In this study, the technology index was lowest (10.68%) in 2022-23 and highest (21.84%) in 2020-21, with an average value of 15.72%. This suggests that the demonstrated techniques were largely practical and well-accepted by farmers. The variation in the technology index highlights the influence of factors such as soil fertility, weather conditions, and crop mismanagement. By adopting improved agricultural practices, the technology gap can be minimized, leading to a further reduction in the technology index. Similar trends have been reported in studies by Katare *et al*. (2011), Papnai *et al*. (2017), Kalita *et al*. (2019), Singh *et al*. (2019), Singh and Tetarwal (2022), Singh *et al*. (2023), and Singh *et al*. (2024), showcasing the influence of Front Line Demonstrations (FLDs) on diverse crops.

Impact of halophilic microbial bio-formulation on economic

The impact of halophilic microbial bio-formulation on the economics can be significant. Halophilic microorganisms are adapted to high-salt environments and have potential applications in agriculture, bioremediation, and industrial processes. In agriculture, the use of halophilic microbial bio-formulations can improve soil fertility and crop productivity in saline-affected areas. This can lead to increased agricultural output and potentially boost the local economy by providing more food resources or enhancing cash crops. Additionally, these bio-formulations may contribute to sustainable agricultural practices by reducing the need for chemical fertilizers and mitigating soil salinity issues, resulting in cost savings for farmers.

The primary necessity of a newer technology exhibited on farmers' fields to assess the profit over existing technology is economic viability. The cost of mustard cultivation and production data were

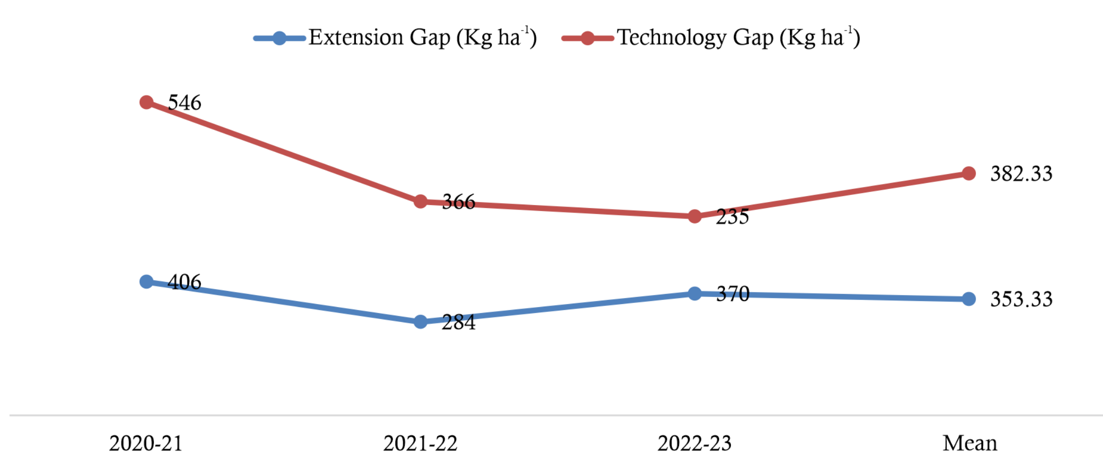

Fig. 3 Extension gap and technology in CFLD of Mustard

Table 4. Impact of halophilic microbial bio-formulation on economic analysis of cluster frontline demonstrations on mustard-2020-2023

Year	Gross cost(Rs ha^{-1})		Gross Return(Rs ha^{-1})		Net Return(Rs ha^{-1})		B:C Ratio	
	IP*	FP#	IP	FP	IP	FP	IP	FP
2020-21	37300	35450	98677	78174	61377	42724	2.65	2.21
2021-22	38500	36450	107767	93425	69267	56975	2.80	2.56
2022-23	39300	37800	114383	95697	75083	57897	2.91	2.53
Mean	38366.67	36566.67	106942.33	89098.67	68575.67	52532.00	2.79	2.44
S.Em ±	981.19	980.89	4552.64	5501.57	3971.65	4802.49	0.07	0.18
C.D(P=0.05)	0.03	0.04	0.04	0.06	0.04	0.07	0.01	0.03

*IP=Improved Practice; #FP= Farmers Practice

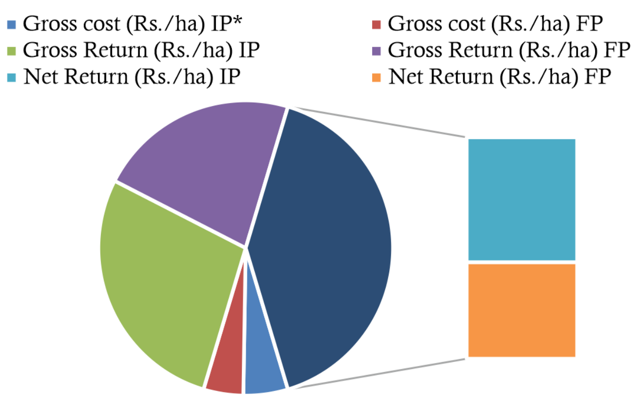

Fig. 4. Impact of halophilic microbial bio-formulation on economic analysis of cluster frontline demonstrations on mustard

gathered and analysed for gross return (Rs ha^{-1}), net return (Rs ha^{-1}), additional income (Rs ha^{-1}), and B:C ratio in CFLDs. The results of the mustard cultivation economic analysis (Table 4) revealed that enhanced technology yielded a greater average gross return of Rs 106942.33 ha^{-1} over the study period, it was higher than the farmer's practice (Rs 89098.67 ha^{-1}).

The illustrated plot demonstrated an average benefit-cost ratio of 2.79, which exceeded that of the conventional practice (2.44). The findings of the economic study clearly showed that the exhibited technology is more profitable and economically viable. These findings align with the observations reported by Naveen *et al.* (2017); Kumar *et al.* (2024); Papnai *et al.* (2017); Kalita *et al.* (2019); Sangwan *et al.* (2021); Tetarwal and Singh (2021); Singh *et al.* (2023) and Singh *et al.* (2024).

Conclusion

The three-year impact study of cluster frontline demonstrations (CFLDs) indicates that mustard crop productivity and economic returns can be significantly improved by implementing a high-yielding salt-tolerant variety, adopting an enhanced package of practices, using balanced fertilization, applying appropriate plant protection measures, and utilizing bio-formulation. The increased net return and benefit-cost ratio highlight the economic viability of these demonstrations and affirm that KVK's interventions are beneficial for farmers. The findings also demonstrate that CFLD programs were effective in influencing other farmers to adopt salt-tolerant varieties and improved agricultural practices. To further close the adoption gap and boost farmer income, it is essential to expand the dissemination of this advanced technology through widespread demonstrations and awareness campaigns in collaboration with relevant departments.

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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: ______________________________

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4. Mailing Address : ______________________________

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Telephone No. (Prefix ISD/STD code) Office : ______________ Residence : ______________

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6. Date of Birth : ______________ Nationality: ______________

7. Academic Qualifications: ______________________________

8. Field of Specialization: ______________________________

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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)**

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Category of Membership*	Subscription Rate		Admission fee (only one time)	
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