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Content

Breeding Cotton for Mechanical Harvesting in India: Opportunities, Challenges and Strategic Roadmap

.Kannan N, Karthik P, Arunkumar R, Mayur L. Khetre, Ramasami M 1

Microbiomes and their role in soil health and cotton productivity

K. Velmourougane 14

Calcareous soils and their management for sustainable cotton production

M.V. Venugopalan¹ and P Tiwary² 24

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Breeding Cotton for Mechanical Harvesting in India: Opportunities, Challenges and Strategic Roadmap

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Abstract

India, despite having the world's largest cotton cultivation area, continues to experience low productivity due to rainfed farming, degraded soils, pest resurgence, labour shortages, and the widespread use of long duration hybrids. Integrating High Density Planting Systems (HDPS) with mechanical harvesting presents a transformative opportunity to address these constraints. HDPS, based on compact early and synchronous maturing plant types, improves boll uniformity, productivity, and suitability for mechanization. Rasi Seeds, through the Rasi Max Project, has made significant progress in developing ideotype based HDPS hybrids with early duration, compact architecture, high boll retention, and strong responsiveness to plant growth regulators and defoliants. Multi-year trials across states consistently showed 20–40% yield advantages over conventional systems. Optimized agronomy, precise canopy management, effective defoliation, and improved picker compatible plant types further enhance efficiency. Scaling mechanization requires supportive policies, affordable pickers, pre-cleaning infrastructure, and training. Collectively, HDPS compatible genetics and mechanization offer a viable pathway to enhance productivity, profitability, and sustainability in Indian cotton production.

Key words: HDPS, ideotype, synchronous boll opening, defoliation, plant growth regulator

Introduction

Cotton is a key agro-industrial fibre crop supporting the global textile value chain through its durable, biodegradable

fibre and extensive employment across cultivation and processing. In 2024, global production was dominated by China (28.2 million bales), India (25.0 million bales),

the United States (14.4 million bales), Brazil (16.7 million bales), and Pakistan (5.5 million bales). Despite having the largest cultivation area, India continues to show low productivity. The introduction of Bt cotton in 2002 triggered a rapid production surge, nearly tripling national output by the 2013–14 crop season, but yields have stagnated over the past decade due to pest resurgence, climate variability, and inconsistent agronomic practices. In 2023–24, cotton occupied 12.68 million ha and produced 32.5 million bales, with an average national yield of 448 kg/ha. Current lint yields of 450–500 kg/ha remain far below the global average of 760–800 kg/ha and significantly lower than the 1,200–2,000 kg lint/ha achieved in the United States, Australia, China and Brazil. This persistent yield gap is primarily driven by predominant (65%) rainfed cultivation, declining soil health, high incidence of sucking pests and pink

bollworm, and the widespread use of long-duration hybrids. Around 72 % of the cotton area comes under low (<300 Kg/ha) and medium productivity (370 - 455 Kg/ha) (Table 1). Manual harvesting drastically increases production costs and reduces profitability. In contrast, leading cotton-producing countries have integrated high-density planting systems (HDPS) with mechanical harvesting, thereby achieving yield gains of up to 30% and drastically reducing labour dependency. These contrasts highlight the urgent need for India to adopt HDPS-compatible, short-duration, machine-harvestable cultivars and accelerate mechanization to enhance productivity and long-term sectoral sustainability. Scaling up of HDPS, a global best practice, in suitable growing environments with appropriate genotypes and tailored agronomy is a prerequisite for mechanical harvesting (Prasad and Majumdar, 2024).

Table 1: India Cotton productivity categorization

Category	Area (%)	Production (%)
Low Productivity <300 Kgs/ha	37.4	22.3
Medium Productivity 370-455 Kgs/ha	34.9	41.4
High Productivity >536 Kgs/ha	27.8	36.3

Source: Department of Agriculture, Cooperation & Farmer's welfare (Season 2017-18)

Concerns in Indian Cotton Cultivation

Cotton production in India is constrained by a combination of rainfed farming, degraded soils, labour shortages,

pest resurgence, and climatic variability. Nearly 65% of the area is cultivated under rainfed conditions on Vertisols and Vertic intergrades and Alfisols with low nitrogen

and organic carbon, limiting water and nutrient availability and restricting boll retention and overall productivity. Heavy dependence on the Southwest monsoon makes the crop highly vulnerable to intra-seasonal variability; irregular rains during September–December frequently causes boll rot, hard-locked bolls, seed discolouration, and fibre quality deterioration. These constraints are amplified by widespread use of long-duration hybrids, which extends crop exposure to late-season weather risks and incidence of pink boll worm (Prasad, 2021).

Labour scarcity further undermines productivity and profitability, especially during the critical 30–45 day weeding window and during harvest, due to multiple pickings. Pest pressure has also increased: sucking pests such as jassids, whiteflies, thrips, and aphids peak during August–September, while pink bollworm has resurged in Bt hybrid-dominated regions due to prolonged crop duration and resistance development. Consequently, farmers rely heavily on sequential insecticide sprays, escalating costs and accelerating resistance build up in pests, while reducing long-term sustainability. Together, these agronomic, ecological, and socio-economic constraints limit yield stability and highlight the urgent need for

mechanization, HDPS-based short-duration cultivars, and integrated pest and soil management strategies.

Mechanization in Other Crops: Lessons for Cotton

Indian farmers have rapidly adopted mechanization in crops like paddy, maize, wheat, sugarcane, soybean and pulses through sowing machines, transplanters, boom sprayers, herbicide tolerance and combined harvesters, reducing labour dependency and improving operational efficiency. Cotton, however, remains an exception despite being equally labour-intensive. For farmers facing acute labour shortages, rising wages and delayed picking, this gap directly affects profitability. As a result, many farmers are shifting towards alternate crops that support complete end-to-end mechanization, ensuring timely operations and stable returns. This trend is also increasing pressure on cotton acreage, making the adoption of mechanical harvesting essential for sustaining cotton production in India.

Overall Constraints and Strategic Needs

Cotton production in India continues to be constrained by deteriorating soil health and soil moisture stress in rainfed Vertisols (including Vertic Intergrades) and Alfisols. heavy dependence on

manual labour adds to production costs. Erratic monsoon, characterized by late-season rains adds to the misfortune. Vulnerability to insect pests such as pink bollworm and sucking insects and diseases like Cotton Leaf curl virus, Tobacco streak virus, *Corynespora* leaf spot and other foliar diseases further compounds the problem. These challenges collectively limit yield potential, reduce fibre quality, and narrows profit margins for farmers. Addressing them requires a system-level shift that includes the development of compact, early-maturing cultivars, wider adoption of mechanization for timely and cost-effective operations, and strengthened integrated pest and disease management strategies to build a more resilient and productive cotton production system.

Scope for Improvement through HDPS and Mechanization in Indian Cotton Production

The High-Density Planting System (HDPS), a global best management strategy (Venugopalan et al., 2013) has gained increasing attention as an agronomic strategy that aligns with the requirements of mechanization. Under HDPS, short-duration, semi-compact cotton hybrids are planted at a density of 60,000–75,000 plants per hectare. Typical spacing involves 90 cm between rows (adjusted based on soil type and growing

conditions) and in several regions 75 cm row spacing are now increasingly adopted in several regions to support higher plant density, with 15–17.5 cm between plants within a row, achieving an optimal plant stand of 5–7 plants per metre of row length. In contrast, the conventional planting pattern adopted by most Indian farmers accommodates only 18,000–24,000 plants per hectare, with spacing varying widely across regions—commonly ranging from 90 × 45 cm to 120 × 60 cm depending on soil characteristics and management practices.

The central principle of HDPS is to maximize boll production per unit area in the quickest possible time rather than more bolls per plant (Kumar et. al, 2021, Prasad et al., 2023). With fewer bolls per plant, a shorter fruiting window of 4 - 5 weeks, and an early maturation tendency, HDPS hybrids produce more uniform and synchronous boll opening. This uniformity is crucial for mechanical harvesting, which requires a concentrated maturity window for efficient operation.

Synergy between HDPS and Mechanization

The integration of HDPS with mechanization yields several advantages:

- **Mechanization-friendly plant type:**
Compact, shorter-duration plants reduce

lodging and allow smoother movement of machinery, thereby facilitating the efficient operation of sprayers, fertilizer spreaders, interculture equipment, and mechanical harvesters, while also improving spindle penetration during mechanical picking.

- **Uniform boll maturity:** Synchronised flowering and boll opening allow for one- or two-pass mechanical harvesting, reducing labour costs drastically.
- **Higher productivity potential:** Increased plant population compensates for lower per-plant yield, resulting in higher overall lint yield per hectare.
- **Uniform fibre quality:** Due to a short fruiting window, the cotton bolls mature early uniformly and the synchronous boll opening ensures cotton fibres with uniform quality parameters
- **Feasibility of a second crop after cotton:** HDPS and mechanical harvesting leads to early termination of the crop. Wherever, supplementary irrigation is available, farmers can opt for a second crop in sequence, thereby increasing system productivity and profitability.

Mechanization is equally critical for revitalizing cotton profitability in India. Cotton harvesting/picking by hand is a

time-consuming and labor-intensive process (Mishra et al, 2023). Under the present conditions, two to five manual pickings are done and this accounts for 30 to 35 percent of total variable cultivation cost. Labour scarcity becomes severe during the harvest season, leading to rapidly increasing wage rates and rising production costs. Manual picking alone is nearly ten times more labour-demanding than other field operations, making it economically unsustainable in many regions. Although mechanization offers a practical solution to reduce labour dependency and stabilize profitability, its adoption is constrained by small and fragmented landholdings as well as the tall, indeterminate growth habit of most commercially cultivated hybrids. Effective mechanization requires hybrids with compact architecture, shorter duration, and synchronous maturity. Integrating HDPS with end-to-end mechanization from field preparation to planting to spraying and harvesting provides a coherent pathway to overcome labour limitations and enhance overall productivity, but this transition depends on breeding and promoting machine-friendly cotton cultivars suitable for the varied agro-eco zones of India.

Ideotype for HDPS and Mechanical Harvesting

An efficient cotton ideotype tailored for High Density Planting Systems and mechanical harvesting must combine compact growth, early and synchronous maturity, and uniform boll distribution to support high plant populations and single-pass harvest efficiency. Such an ideotype

should minimize excessive vegetative growth, reduce plant height and branching, and promote rapid canopy closure without compromising boll retention. The following table outlines the key traits and their desirable expressions that collectively shape an ideal plant type for successful HDPS cultivation and seamless mechanical harvesting.

TRAITS	PREFERRED TYPE
Duration	Early (140 days)-Early to medium (145-150 days)
Plant type	Compact & semi compact, erect types along with Semi dwarf /medium tall
Plant height	80 cm - 120 cm
Plant width	≤ 60cm
Stem	1. Sparse Hairy to Glabrous 2. Flexible but should not break
Leaf	Size-Small to medium with optimum foliage Angle- Upward/Erect/wavy leaf margin Leaf trichome density- Sparse to Glabrous Others- Natural senescence
Bract size	Small or medium
Boll retention	High
Monopodial branches	0-1 (0 monopodia is Highly Preferred)
Sympodial arrangement	First sympodia should be above 20cm from ground for smooth picker header clearance
Boll	Size- Big boll (Uniform boll size from bottom to top) Locule Retention- High Opening- fluffy
Ginning percentage	>40% along with optimum seed index (10)
Response to PGR (Plant growth Regulators) and defoliant	High degree of response to PGR and defoliant
Pest tolerance	Jassid, Thrips, Whitefly and Bollworm complex
Disease tolerance	CLCuV (North Zone), Tobacco Streak Virus, Grey mildew, BLB, Alternaria, Verticillium Wilt, Corynespora leaf spot, Fusarium Wilt and Boll rot
Abiotic stress	Drought/Salinity, Para Wilt

Breeding for HDPS and Mechanical Picking

Experiences from other cotton-growing countries show that the successful adoption of HDPS and mechanical harvesting depends on developing compact, uniform, and early-maturing plant types. These insights guided Rasi Seeds in framing an appropriate ideotype for HDPS hybrids suited to Indian conditions (Kannan et al. 2022). The breeding strategy involved developing female lines with agronomically superior traits, early to medium duration, synchronized maturity, GMS integration, wide adaptability, and enhanced tolerance to biotic and abiotic stresses to ensure good producibility and seed recovery. The male line development focused on incorporating essential HDPS traits, including early and synchronized maturity, compact to semi-compact architecture, and high boll retention. These lines also featured large, fluffy-opening bolls, high ginning percentage, and strong responsiveness to plant growth regulators and defoliant. The resulting hybrids were evaluated for suitability to HDPS, yield advantage, and stability across varying environments.

Breeding to Develop Suitable HDPS Genotypes

With the above-mentioned objectives, Rasi Seeds initiated a focused breeding

programme in 2009 to develop parental lines suited for HDPS hybrid development. Exotic germplasm was introgressed with Indian germplasm to incorporate traits such as dwarf and compact plant architecture, early maturity, big boll size, high ginning outturn (GOT), and synchronous boll bursting. Tolerance to sucking pests and foliar diseases was retained from the Indian germplasm sources. This effort resulted in lines with dwarf and compact growth habit, early maturity, large bolls (>5.0 g), synchronous boll opening, and tolerance to jassids, moderate tolerance to thrips, and fungal leaf diseases. Subsequently, these developed lines are improved for high productivity along with fibre quality characters like upper half mean length (≥ 30 mm) maintaining high ginning outturn (>42 percent).

Advantages of Hybrids in HDPS

Hybridization is an effective approach to break yield barriers in cotton, with hybrids often yielding about 50 percent more than traditional varieties due to their heterotic potential. Hybrids offer a broader genetic base and wider adaptability, combining favourable traits from both parents for superior performance across diverse environments. In India, hybrids perform particularly well in rainfed areas with poor soil and limited irrigation

because of their early vigour and strong response to optimized crop management. They combine multiple beneficial traits, including higher yield, improved fibre quality, and greater resilience to biotic and abiotic stresses, making them especially valuable for farmers with poor soils and marginal landholdings.

HDPS Hybrid development progress in Rasi through Rasi Max Project:

- In 2010, HDPS suitable line development breeding program was initiated.
- In 2015, First research screening trial conducted in four locations (Aurangabad and Amaravati (Maharashtra), Warangal (Telangana) and Attur (Tamilnadu)
- In 2016, second multi-location trials were conducted at more than 20 locations in Central and South zone. From these trials, two hybrids namely CT-255 and CT-256 were identified for largescale trial. Among these two hybrids, CT-255 was promoted further due to relatively superior stability and field performance, and existing normal spacing hybrid Rasi Neo was identified

for HDPS cultivation in Akola region of Maharashtra.

- In 2017, the HDPS project was initiated in three clusters with 9 acres each with closer hand holding on agronomy.
- In 2018, HDPS project was expanded to 63 locations with 800 plus acres. This trial has been showcased to more than 3000 farmers.
- In 2019, this project was expanded to five clusters of four states with an area of 12800 acres excluding 450 acres demonstrations.
- In 2020, this project was expanded to seven clusters in four states with an area of 12000 acres excluding 800 acres demonstrations.
- In 2021, we maintained closer to 9500 plus acres apart from 850 acres of demonstrations.
- In 2022, we conducted HDPS cultivation in 14265 acres and 800 acres of demonstrations in five states.

In 2023, we HDPS cultivation is carried out in 16150 acres and 900 acres of demonstrations in 106 clusters in 31 districts of six states.

Rasi HDPS product details

Stage	Hybrid Name(s)	Special Features
I	RCH608 BGII, CT-256	Early duration, big boll, medium-tall plant type, synchronized maturity, high response to PGR and defoliation, moderate tolerance to sucking pests, susceptible to TSV, ginning outturn 35–36%.

Stage	Hybrid Name(s)	Special Features
II	THCT-5380, THCT-5376	Early duration, big boll, medium-tall plant type, synchronized maturity, stay-green, drought tolerant, high response to PGR, strong defoliation response in THCT-5376, high tolerance to sucking pests, moderate tolerance to TSV, ginning outturn 36–38%.
III	RCH929 BGII, RCH1096 BGII, RCH1066 BGII	Early duration, big boll, medium-tall plant type, synchronized fluffy boll bursting, high response to PGR and defoliation, high tolerance to jassids, moderate tolerance to thrips, high tolerance to TSV, ginning outturn 36–42%.

Sustained Yield Superiority of HDPS Compared to Conventional Planting Methods

Over the four-year period from 2019 to 2022 (Table 2), the High-Density Planting System (HDPS) consistently demonstrated superior yields compared to conventional planting systems. On average, HDPS hybrids outperformed conventional hybrids and this consistent performance highlights the effectiveness of HDPS in enhancing productivity. The

percentage yield advantage of HDPS relative to conventional systems ranges from 20.2% to 40.23% (Table 1), the system's ability to consistently deliver higher yields across all years suggests that HDPS remains a highly effective method for improving agricultural output. These findings emphasize the potential of HDPS as a sustainable and high-yielding approach to modern farming.

Table 1. Seed Cotton Yield Differences between HDPS and Conventional Hybrids.

Year	Cluster (Area)	No. of Locations	Seed Cotton Yield (Q/Acre)		Percent Yield difference between HDPS Hybrids over Conventional Hybrids
			HDPS	Conventional	
2019	Akola (Division in Maharashtra)	83	8.68	6.19	40.23
	Maharashtra (Other than Akola)	8	9.57	7.35	30.20
	Gujarat	13	8.33	6.68	24.70
	Telangana	14	9.28	6.88	34.88
	Andhra Pradesh	9	7.69	6.15	25.10
2020	Akola (Division in Maharashtra)	74	7.52	5.69	32.16
	Telangana	32	7.86	6.16	27.60
	South Rajasthan	8	7.01	5.63	24.51

Year	Cluster (Area)	No. of Locations	Seed Cotton Yield (Q/Acre)		Percent Yield difference between HDPS Hybrids over Conventional Hybrids
			HDPS	Conventional	
2021	Akola (Division in Maharashtra)	88	8.36	6.04	38.41
	Maharashtra (Other than Akola)	22	8.74	7.11	22.93
	Gujarat	11	8.61	7.16	20.25
	Telangana	46	8.16	6.24	30.77
	South Rajasthan	9	8.50	6.63	28.20
2022	Akola (Division in Maharashtra)	60	9.08	6.62	37.00
	Telangana	76	8.32	6.61	25.80
	South Rajasthan	20	9.24	7.11	23.00

Optimizing Agronomic Practices for HDPS in Cotton

High-Density Planting System (HDPS) relies on compact, early-maturing cultivars planted at closer spacing of 80 × 15 cm to 90 × 15 cm with plant populations up to 30,000 plants/acre. Precision sowing ensures a uniform stand and creates a harvest-friendly canopy. For mechanical picking, plants must maintain a height below 110 cm and a narrow, uniform canopy to allow picker units to operate efficiently. Shorter sympodial branches and reduced monopodial branches help prevent boll entanglement and minimize trash content. Canopy optimization is achieved through genetics and timely agronomic interventions. Mepiquat chloride is the primary PGR

used to restrict vegetative growth, applied in splits based on top 5 internode measurements to improve canopy compactness, enhance boll retention, and increase picker efficiency. Topping improves architecture by removing apical dominance, promoting uniform maturity required for single-pass mechanical harvest. Although HDPS naturally suppresses monopodia, genetic selection and occasional manual removal ensure a clean, upright canopy. Well-managed canopies improve light distribution, reduce shading, enhance spray penetration, limit boll rot, and synchronize maturity, which is essential for maximizing picker efficiency.

Defoliation Management for Mechanical Harvest

Defoliation is a critical pre-harvest step in HDPS cotton to improve fibre quality, reduce trash, and enable clean spindle entry during mechanical picking. Common defoliant include thidiazuron (TDZ), TDZ + diuron, desiccants such as paraquat and carfentrazone, and boll openers like ethephon. Ideal timing is at 60–70% boll opening, or when the top boll becomes firm and seed coats turn brown. Two-step programs (defoliant followed by ethephon) provide the most uniform results, while tank mixes suit time-limited situations. Balanced nutrition, avoiding application of nitrogen fertilizer late in the season, good pest control, and compact HDPS canopies greatly improve the efficacy of defoliation. Clean defoliation enhances ginning efficiency, reduces trash, and improves lint grade.

Mechanical Picker Requirements for India

Mechanized picking in India requires machines adapted to narrow row spacing of 75–90 cm, high plant populations, and small, fragmented landholdings. Compact, affordable pickers equipped with headers compatible with 75 cm, and 90 cm rows are essential. Adjustable picking units, spindle speed control, and efficient trash-

handling systems help manage compact canopies while minimizing fibre contamination. Lightweight, low-HP pickers can improve manoeuvrability and reduce soil compaction. Domestic manufacturers are developing 2-row pickers with improved suction units, ruggedized spindles, and better cleaning modules to handle variable boll size and distribution.

Pre-cleaning of Machine-Harvested Cotton

Mechanically harvested seed cotton contains 10 -15 % trash which includes burs, sticks, leaves, grasses, motes, etc. (Nimbalkar et al., 2022). This prevents farmers from receiving fair market prices. Field-level pre-cleaners must reduce trash content to below 2%, comparable to manually picked cotton. Portable pre-cleaners will allow farmers to sell machine-harvested seed cotton directly in local mandis without financial loss.

Government Interventions and Policy Needs

Adopting mechanical harvesting at scale requires strong policy support. Subsidies for single row and double row compact pickers, and the strengthening of Custom Hiring Centres and FPOs, will improve accessibility for small farmers. Policies should prioritise the timely

registration of quick effective defoliants and provide special subsidies for establishing pre-cleaning infrastructure at the village level. Additionally, the promotion of early, compact, HDPS-compatible hybrids and varieties through national and state seed programs and include mechanization readiness as a varietal release criterion. Training through Krishi Vigyan Kendras (Farm Science Centres) and Agricultural Universities on defoliation, canopy management, and precision agronomy is essential. Improving rural infrastructure, field access roads, and machinery service networks will ensure reliable operation. Incentives for trash-free cotton and quality-linked procurement can further support adoption. Public-private partnerships and research on picker modifications for Indian conditions will accelerate innovation.

Conclusion

Mechanical harvesting is an economic necessity for Indian cotton. With rising labour costs, unpredictable monsoon patterns, and high pest pressure, the integration of compact and early HDPS cotton combined with mechanical picking offers a practical and scalable path to higher productivity and profitability. Comprehensive approach driven by strategic breeding, optimized agronomy like proper HDPS spacing, precise canopy

management, effective defoliation and pre-cleaning along with supportive policy frameworks can collectively transform India's cotton sector into a more efficient and sustainable production system.

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Microbiomes and their role in soil health and cotton productivity

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Abstract

In the era of climate change and anthropogenic-induced environmental deterioration, crop production has become challenging to meet the ever-growing population demands for land, food, fiber, fuel, and other essential human needs. The continuous and indiscriminate use of chemical inputs in agriculture to meet the demands has created environmental footprints in terms of chemicalization, contamination, greenhouse emissions, and pollution, resulting in the decline of soil physical, chemical, and biological properties. Deterioration of soil health due to chemicalization affects crop productivity and product quality through contamination with xenobiotics, pesticides, and heavy metals, among others, causing health concerns and affecting product consumption and export value. Despite present-day agriculture and its allied sectors adopting ecofriendly, environmentally safe, and sustainable approaches in agricultural production systems, nutrient-poor and stressed soils demand higher external inputs to sustain crop productivity. Although several commercial agricultural inputs are available and used to alleviate and mitigate biotic and abiotic stresses in crop production and protection, they are mostly chemical in nature, which aggravates environmental pollution and affects long-term soil and crop health, apart from expensive for farm use. Hence, safer alternatives and sustainable strategies are needed to sustain ecosystem health and crop productivity. Among several approaches, the use of

microbiomes in agriculture to enhance soil and crop health is promising and is now becoming popular and widely adopted. Several reports have been published on the use of microbiomes for cotton growth promotion, yield enhancements, and biocontrol aspects with respect to the use of plant growth-promoting microorganisms, biological control agents, waste management, etc. This review primarily discusses the further prospective use of microbiomes in less focused areas in sustaining soil health and cotton production.

Microbiome and its role in soil and crop health management

The global population is predicted to reach 8.5, 9.7, and 11.2 billion by 2030, 2050, and 2100, respectively. The availability of cultivable land is diminishing, putting greater pressure on agriculture and global food security. Although agricultural innovations significantly contribute to higher crop productivity, chemical-free agriculture remains a challenge in terms of managing environmental pollution and consumer health. Soils not only provide anchorage to the crop plants but also act as a source of essential nutrients to sustain crop growth and productivity. In recent years, climate-induced stresses (heat, drought, waterlogging, salinity, and metal stress) have made soil highly vulnerable, necessitating site-specific management to restore its health to support life forms, including crops. Furthermore, stressed environments weaken crop growth and

metabolic functions, such as the composition of biochemical constituents, altered rhizodeposition, biological activities related to plant-associated microbes, and microbial community structure, etc. However, production targets, anthropogenic activities, and the increased, continuous, and irrational use of agri-inputs (e.g., chemical fertilizers, plant protection chemicals, and growth hormones) have resulted in soil degradation, affecting the soil's innate attributes and rendering them inefficient to support crop productivity. Therefore, soil health protection in terms of functionality, fertility, and degradation is essential for sustainable agriculture. Disturbances in the soil properties in terms of physical (disruption of soil structure, hydraulic properties, infiltration, aeration, and moisture retention), chemical (nutrient transformations and uptake), and biological activities make them a hostile environment for normal plant functions

and productivity. This situation has forced society to look for a safer biological alternative to supplement agricultural chemical inputs. Microorganisms and microbial technologies are a favorite savior for enhancing soil and agricultural production. Evolutionary adaptations acquired by microbiomes play an essential role in soil health restoration to support crop plants under climate change.

Microorganisms in general and bioinoculants, biopesticides, bioherbicides, and bioremediators act as an eco-friendly and cost-effective technology, which aids in soil and crop health restoration and crop productivity enhancement through beneficial plant-soil-microbial interactions, including nutrient fixation, solubilization, and mobilization of plant essential nutrients, plant growth promotion, alleviation of stresses, production of compatible solutes, polysaccharides, antioxidant and plant defense enzymes, scavenging of reactive oxygen species, and production of molecules involved in natural plant immunity and suppression of pest and pathogens. The adoption of diverse and environmentally safe soil and crop management practices, such as minimum soil disturbances, residue recycling, mulching, cover crops, crop rotations, intercropping systems, and nutrient and

water management based on crop needs, has been reported to conserve inherent soil properties and provide wider substrates for microbiome survival, proliferation and maintaining their diversity resulting in multiple benefits to soil and crop health, rather than adopting monocropping and other soil and crop ill practices resulting in poor soil health resulting in dominance of particular microbial species in the soils. Recent advances in synthetic biology, soil-plant-microbiome engineering, crop-specific core microbiomes, plant-microbe signaling, microbial biofilm technology, quorum sensing, and the identification of genes involved in nutrient use efficiency and stress tolerance further enhance our understanding of microbial-based services for enhancing soil and crop productivity under climate change situations.

Microbiomes and abiotic stress management in cotton

Cotton is highly sensitive to moisture stress during the vegetative and reproductive stages. Drought stress in cotton has been reported to reduce aboveground biomass accumulation by decreasing root volume density, root mass density, and root length density. The water deficit in the upper soil profile has been reported to lead cotton roots to deeper penetration for greater exploration of moisture and nutrients. Similarly, terminal

drought is a major problem in cotton-growing regions worldwide and is reported to significantly affect cotton yield by inhibiting carbon assimilation and biomass accumulation. Terminal drought has also been reported to inhibit carbohydrate production coupled with the depletion of stored reserves (starch) due to continuous respiration and reduce the translocation of assimilates to reproductive organs, consequently inducing abscission of reproductive structures and boll size reduction. Drought stress during cotton fiber development also affects the fiber properties. Since the Bt cotton hybrids occupy a higher area with respect to the total cotton cultivated, the problem of drought and its effects on cotton became more serious as the root system of Bt cotton (*Gossypium hirsutum*) is generally shallow, creating a moisture deficit compared to native cotton species (*G. arboreum*). Drought stress affects the physiological, biochemical, and molecular processes of cotton plants, resulting in a loss of up to 50%–73% of seed cotton yield and fiber quality.

Similar to drought stress, waterlogging is another major constraint to cotton production as cotton does not have aerenchyma, which alters and affects the hormonal status of the shoot and root, nutrient uptake stomatal conductance, leaf

water potential, and photosynthesis, resulting in accelerated leaf and root senescence and an increase in the number of aborted flowers, squares, and bolls, affecting cotton yield. However, lenticels and lysigenous aerenchyma produced by waterlog-tolerant cotton genotypes mitigate waterlog stress in cotton by enhancing oxygen uptake to maintain stable root activity. Waterlogging worsens when cotton is grown in heavy clay soil with low drainage conditions, particularly in irrigated furrow systems. In severe cases, waterlogging is reported to cause yield reductions of up to 40%.

Breeding stress-tolerant crops is one of the most commonly used strategies. Stress is a polygenic trait controlled by multiple genes, and genetic manipulation by genetic engineering is difficult to achieve. Although several cotton-growing countries are developing stress-tolerant cotton through conventional breeding and genetically modified (GM) technologies, the public acceptance of GM crops is still under question. Moreover, recent health concerns of consumers about GM technology and its impact on the environment and human health have made the transgenic technology to take back seat. Hence, there is an urgent need to develop an ecofriendly and cost-effective technology to alleviate abiotic

stress in cotton considering future climate-change situations. In recent years, efforts have been directed toward harnessing beneficial soil microorganisms to improve crop production under a changing climate. Although the role of microbes in agriculture is well known, their role in alleviating abiotic stress has recently gained importance. Although bioinoculants are being explored for drought alleviation in crops, no large-scale field studies have been conducted on the use of native microbial consortia in alleviating drought stress in cotton.

Research efforts should focus on the identification of native drought-tolerant plant growth-promoting microorganisms, which can improve innate plant vigour through the production of growth hormones, drought-mitigating chemicals, such as antioxidant defense enzymes, compatible solutes, osmolytes, and inhibitory molecules that suppress plant pathogens, etc., apart from the production of extracellular polymeric substances (EPS), which can improve plant root colonization and accumulation of moisture and plant nutrients near the rhizosphere for plant uptake. In recent years, research has focused on utilizing microbes that can produce ACC deaminase, which helps in the breakdown of ACC (1-Aminocyclopropane-1-carboxylate), the

precursor of ethylene (growth-inhibiting plant hormone) into α -ketobutyrate and ammonia, thereby reducing the harmful effects of ethylene and mitigating plant stress.

Microbial-based volatiles for pest and disease management

Microorganisms produce several complex and dynamic volatile organic compounds (mVOCs) that have high vapour pressure under normal conditions to vaporize and enter the atmosphere. Generally, the dominant class of compounds emitted by bacteria include alcohols, alkanes, alkenes, ketones, esters, pyrazines, lactones, and sulphides, while fungi typically produce alcohols (e.g., butanol, pentanol, and octanol isomers), hydrocarbons, ketones, terpenes, alkanes, and alkenes. The mVOC emission is now recognized as an important aspect of plant-microorganism interactions. A database of bacterial and fungal volatiles has been compiled and is available online at <http://bioinformatics.charite.de/mvoc>

Chemical ecologists consider mVOCs as potential semiochemicals that can attract or repel insects, inhibit the growth of microorganisms competing with associated insects, stimulate oviposition, mimic plant hormones, or even induce plant resistance. Insects exhibit strong

aggregation behaviors to specific microbial communities, although few researchers have linked mVOCs directly as pheromonal signals for food sources, oviposition sites, or mating opportunities. Studies conducted on volatile application under open-field conditions showed that mVOCs can be explored to trigger defense against both pathogens and herbivores in crop plants apart from reducing hazardous chemical pesticide usage in agriculture. Several studies have reported the usefulness of plant volatiles as feeding attractants of insect pests. Similarly, kairomones have been studied for their potential in pest monitoring and trapping. In addition to inducing systemic resistance and gene regulation against pests and pathogens in plants, VOCs produced by several microbiomes have been reported to manage insect pests (as a repellent or attractant) and disease-causing plant pathogens. Although mVOCs were proven to manage cotton sucking pests through their attraction toward sticky traps, no mVOCs have been explored for the management of bollworms and sucking pests under cotton-based cropping systems. The development of microbial-based volatile formulations for biotic stress management, including the management of insect pests and diseases, will act as

a sustainable, ecofriendly, and cost-effective technology for the farming community to enhance the farm income through the reduction of chemical usage in cotton and associated insecticide resistance in pests and pathogens and reduce environmental footprint.

Microbial-based seed coating and encapsulation

Seeds are an important agricultural input, and their germination is affected by various biotic and abiotic factors. In the event of monsoon delay, early sowing of cotton makes it more vulnerable to moisture stress, while poor establishment of early sown cotton demands re-sowing, which adds to cultivation cost. Therefore, using precision tools to manage seed sowing and support germination is essential for establishing healthy plants. Seed treatments/coatings/encapsulation are one such innovation/techniques that modulate and help the seeds to carry additives (beneficial microbes, stickers, nutrients, osmoprotectants, etc.) in the form of formulations and deliver those inputs, which help in mitigating the environmental stress. Several natural and synthetic polymers (polysaccharides such as alginate, starch, agar, carrageenin, and celluloses, polyglucosamines such as chitin, and proteins such as collagen, gelatin, and casein), including seed

treatment chemicals (imidacloprid, bavistin, captan, thiram, etc.) have been employed for seed coating, dressing, or encapsulation to enhance protection against biotic and abiotic stresses and to deliver microbial inoculants, employing spray drying, freeze-drying, extrusion, and emulsion. However, these methods suffered major shortcomings in agro-settings in terms of adherence of bioinoculants to seeds, chemical nature and its effects on the environment, encapsulation of multiple strains, microbial survival, root colonization problems, etc. However, an ecofriendly technology to replace chemical/synthetic inputs for seed treatment has not yet been developed.

Recently, biological preparations (microbial inoculants viz., PGPRs) have been used in seed coatings to protect seeds from environmental stresses. In recent years, the use of multispecies microbial biofilms has gained importance, as they produce new types of extracellular polysaccharides (EPS) with different composition or other bioactive compounds compared with single-species microbiomes, which can have agricultural and industrial significance. The secretion of EPS by microorganisms has also been reported to help the microbes to colonize the roots in an effective way by forming

biofilms that protect them from biotic and abiotic factors, including desiccation due to water deficit and plant pathogens. Many microbial EPS have the property of trapping water in their polymeric matrix, which protects them from desiccation under drought stress by maintaining a hydrated microenvironment and regulating the diffusion of organic carbon from microbes to plants and vice versa. Although microbial biofilm inoculation has been proven in several crops for its prominent role in enhancing colonization, plant growth promotion, and biocontrol attributes, no studies have attempted to harness their utility as seed treatment options for alleviating stress, including management of seedling diseases in cotton. Although seed or soil treatment with chemicals has been reported to reduce the severity of seedling diseases, farmers do not usually follow cotton seed treatment. Hence, there is an urgent need to develop farmer-friendly eco-technologies to make cotton seed tolerant to biotic and abiotic stresses during the seedling stage. However, the seed-coated inputs, including microbial inoculants, lose their viability during extended storage periods. Therefore, developing microbial formulations for seed coatings that can boost seed germination and mitigate environmental stressors by combining the

attributes of preservation and controlled release of payloads is urgent.

Biofilm-based microbial inoculants

Microbial biofilms are microbial cell aggregates in a self-produced polymeric matrix attached to biotic and abiotic surfaces. Microorganisms generally form biofilms to overcome environmental stress, nutrient limitation, change in cultural conditions, competition, antibiotics, and disinfectants. Apart from being a stress avoidance strategy, the biofilm style of growth also confers a reproductive fitness advantage, making them better adapted to endure challenges, as compared to the free-floating cells (planktonic cells). Biofilm formation on the plant roots is an important trait of rhizospheric microorganisms, which prevents them from being detached from the plant caused by various natural processes occurring in the soil. Developing biofilms in situ or utilizing naturally occurring biofilms are promising technologies for future agriculture, as they have immense potential to provide multiple benefits (plant growth promotion, nutrient mobilization, biotic/abiotic stress tolerance etc.), through application of a single inoculant. In recent years, studies on multispecies biofilms have gained importance as they produce new types of polysaccharides with different

compositions and bioactive compounds, which can have agricultural and industrial significance, compared to single species biofilm. Since microbial biofilms are predominantly composed of polysaccharides; there is a possibility of improving soil physical properties through the application of microbial biofilm preparations, such as improved soil aggregation, reduction in bulk density, and better retention of applied water and nutrients in the crop rhizosphere. The application of microbial polysaccharides from the biofilms can also be tried as foliar spray or herbigation to protect crop plants from biotic and abiotic stresses. The use of microbial biofilms can be a novel option, in lieu of their preponderance, versatility in function, and resilience to environmental stressors. Microbial biofilms, by virtue of their resilience to environmental perturbations and stress can also be a promising option due to their dynamic nature and ability to persist in unfavourable environments. In future, microbial biofilm-based agents need to be integrated as a sustainable agricultural practice in crop nutrition, protection, and quality improvement programs.

Core microbiome-based synthetic microbial community (SynCom) formulations

A core microbiome is characterized as a set of microbiomes that are consistently

present over long periods of time and is more likely to be important for the development, health, and functioning of its host. Few studies have focused on crop species despite extensive studies on the roles of core microbiomes in animal systems. Identification of core microbiomes or keystone species is expected to mediate interactions between plants and native microbiomes. Manipulating crop rhizospheres/ phyllosphere via inoculation with synthetic core microbiome-based synthetic microbial community (SynCom) formulations is an emerging strategy for enhancing crop yield and resilience and has gained global importance. Although the manipulation of the core microbiome in agriculture is a promising approach, it is a relatively underexplored strategy. The identification and development of crop-specific core microbiome-based SynCom formulations can lead to the development of next-generation crops such as designer plants with increased plant productivity, enhanced resource use efficiency, and biotic and abiotic stress tolerance.

Rhizosphere engineering

The rhizosphere is the soil zone surrounding a plant root, where the root influences the soil's biology and chemistry. The rhizosphere is an area of

intense biological and chemical activity influenced by compounds exuded by the root (rhizodeposits) and microorganisms. Mucilage secreted by roots and EPS produced by microorganisms alter the physical, chemical, and biological properties of soil. The rhizosphere also acts as a communication hotspot between the plant and the microbiome. "Rhizosphere engineering" is an innovative approach for modifying soil biophysical properties to influence plant-microbiome-soil interactions. The basic components of rhizosphere engineering include soil, plants, and microbes. The rhizosphere properties could be engineered to optimize water and nutrient transport as well as microbial activity at the root-soil interface. Higher mucilage exudations by plants and subsequent action of microbes increase soil aggregation properties, which improves soil physical, chemical, and biological properties, aiding in better soil and plant health. Higher rhizodeposits by plants increase carbon sequestration in the rhizosphere, which in turn increases soil organic carbon content and enhances soil nutrient availability and plant uptake. Rhizosphere engineering can be achieved through three major approaches: a) soil engineering, wherein the physical and chemical properties of the soil are

modified through management practices to enhance biological activity to enhance soil and crop health: b) plant engineering, wherein the modification in crop root exudation and rhizodeposition is achieved through conventional and molecular breeding (genetic modification (GM)) to recruit specific groups of microbes for specific functionality; and c) microbiome engineering, wherein agro-ecological specific microbial inoculants with higher colonization efficiency, growth hormone, EPS, compatible solutes, and antimicrobial production are developed using conventional or GM.

Global initiatives have begun to focus on agricultural microbiomes to link crop productivity, product quality, and human health. According to recent statistics, the demand for agricultural production is expected to increase by at least 70% by 2050. Maintaining the quality of soil, a non-renewable resource that exerts many environmental and social functions, some of which are driven by soil microbes, is a

key issue in a sustainability context. Exploiting the interactions between soil microbial communities and crops is a relevant approach to increase agricultural production for the growing world population at the lowest environmental costs in the current global change scenario. Although several studies have established the beneficial roles of microorganisms in mitigating climate change with respect to soil and crop health, most of these studies are academic in nature and have not produced practical utility. The development and evaluation of microbial consortia with multiple benefits, such as plant growth promotion, soil nutrient availability, biocontrol control potential, elicitation of natural plant defense enzymes, and mitigation of environmental stresses, is the most beneficial strategy toward environment-friendly agricultural practices. Further, exploring carbon sequestering microbes in harsh environments and less GHG-producing microbes in wetland systems can increase soil health and reduce GHG emissions.

Calcareous soils and their management for sustainable cotton production

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Abstract

Calcareous soils, defined by the presence of free calcium carbonate (CaCO_3), are widespread in arid and semi-arid regions and account for nearly one-third of the global land surface. In India, these soils occupy about 69% of the geographical area and constitute a major production environment for cotton (*Gossypium* spp.) production. This paper discusses the genesis, spatial distribution, key physicochemical and biological properties of calcareous soils, and their effects on cotton productivity. High soil pH, strong buffering capacity, low organic matter, and widespread deficiencies of phosphorus and micronutrients such as iron, zinc, manganese, and boron are major constraints to cotton growth and yield. Physical limitations, including surface crusting, subsurface carbonate hardpans, reduced infiltration, and restricted root proliferation, further exacerbate moisture and nutrient stress, particularly under rainfed conditions. Despite these limitations, calcareous soils offer considerable potential for cotton cultivation due to their favourable soil structure, deep effective rooting depth, high calcium status, and moderate to high water-holding capacity, especially in Vertisols and associated soil groups. The review synthesises proven management strategies, including organic amendments, conservation agriculture, soil acidification, balanced and site-specific nutrient management, micronutrient supplementation, and bio-fertiliser use, which significantly improve cotton yield, fibre quality, and nutrient-use efficiency. The role of calcareous soils in carbon sequestration and climate-resilient cotton production is also highlighted. Integrated soil and nutrient management is essential to sustainably exploit the productive potential of calcareous soils for cotton-based agro-ecosystems.

Key words: *Calcium carbonate, soil organic matter, soil properties, nutrient availability.*

Introduction

Soils that contain a significant amount of free calcium carbonate (CaCO_3) in their control section are called calcareous soils. In such soils, the CaCO_3 may occur either as a chalky white powder, or in the form of irregular nodules, either distributed throughout the profile or as a distinct concrete layer in the sub-soil or as surface soil crusts or as a caliche/calcretes (hardened layer of CaCO_3 with thickness ranging from a few inches to several feet). Therefore, not all calcareous soils contain a specific calcic horizon.

All calcareous soils produce effervescence, due to the release of CO_2 , when treated with dilute (0.1 N HCl). However, this reaction with dilute HCl does not distinguish calcareousness formed under different modes of genesis, such as fluvial, pedogenic, or groundwater (Dhir, 1995).

According to the Food and Agriculture Organisation (FAO), calcareous soils are those having 15% or more CaCO_3 either throughout the soil profile or in any of its horizons. This

definition is crucial from a management perspective. Such soils hamper optimal production and may need specific management interventions to realise their potential productivity. In Egypt, soils that contain 14-17% or more of total CaCO_3 or 4-7% or more of active CaCO_3 are considered calcareous (Wassif & Wassif, 2021). In India, depending on the CaCO_3 content, these soils are further categorised into slight ($< 5\% \text{CaCO}_3$), moderate (5-15% CaCO_3) and strong ($> 15\% \text{CaCO}_3$) calcareous soils (Tamgadge et al., 1996).

The formation of calcareous soils (Fig. 1) is a crucial pedogenic process in many arid and semi-arid regions of the world (Pal et al., 2000). During the formation of calcareous soils, the CaCO_3 may be directly inherited from the parent material (primary) or may be precipitated (secondary). The weathering of calcareous rocks and fossils (chalk, marl, limestone, etc.) results in the formation of calcareous soils. Soils can also become calcareous through long-term irrigation with water containing dissolved CaCO_3 , which can accumulate over time.

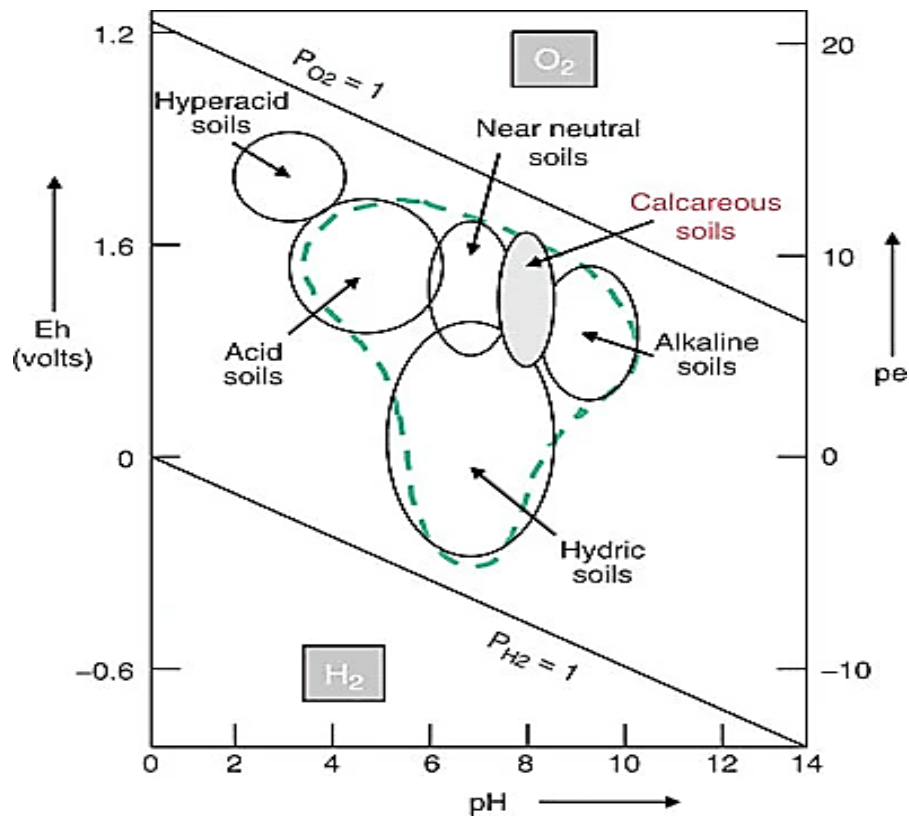


Fig 1. Redox-pH space showing occurring of different mineral soils, (Chesworth et al., 2008)

Under arid and semi-arid bio-climatic regimes, where precipitation is low and consequently, the leaching of salts is limited, the conversion of $Ca(HCO_3)_2$ to $CaCO_3$ in soils renders them calcareous (Balpande et al., 1996). Layers of caliche form when salts leach down through the soil by rainwater to a specific depth, where carbonates precipitate. Caliche layers are also formed by upward movement of salts along with the water table, originating from irrigation, and their subsequent deposition near the soil's capillary fringe (Devi et al., 2022). Calcareous soils are also formed through the aeolian geological process, wherein $CaCO_3$ -rich sediments

are transported and deposited by wind action.

Pal et al. (2000) observed that in the humid regions of India, calcareous soils are formed through the weathering of calcareous parent materials (Fig 2 a). On the other hand, calcareous soils in arid and semi-arid regions of India (Punjab, Haryana and Rajasthan) and ferruginous soils in India contain pedogenic $CaCO_3$ (Fig 2b). In contrast, the coastal soils of Gujarat have lithogenic $CaCO_3$. Several cotton-growing soils in India's semi-arid bio-climate are becoming both calcareous and sodic due to regressive pedogenesis (Bhattacharya et al., 2013).

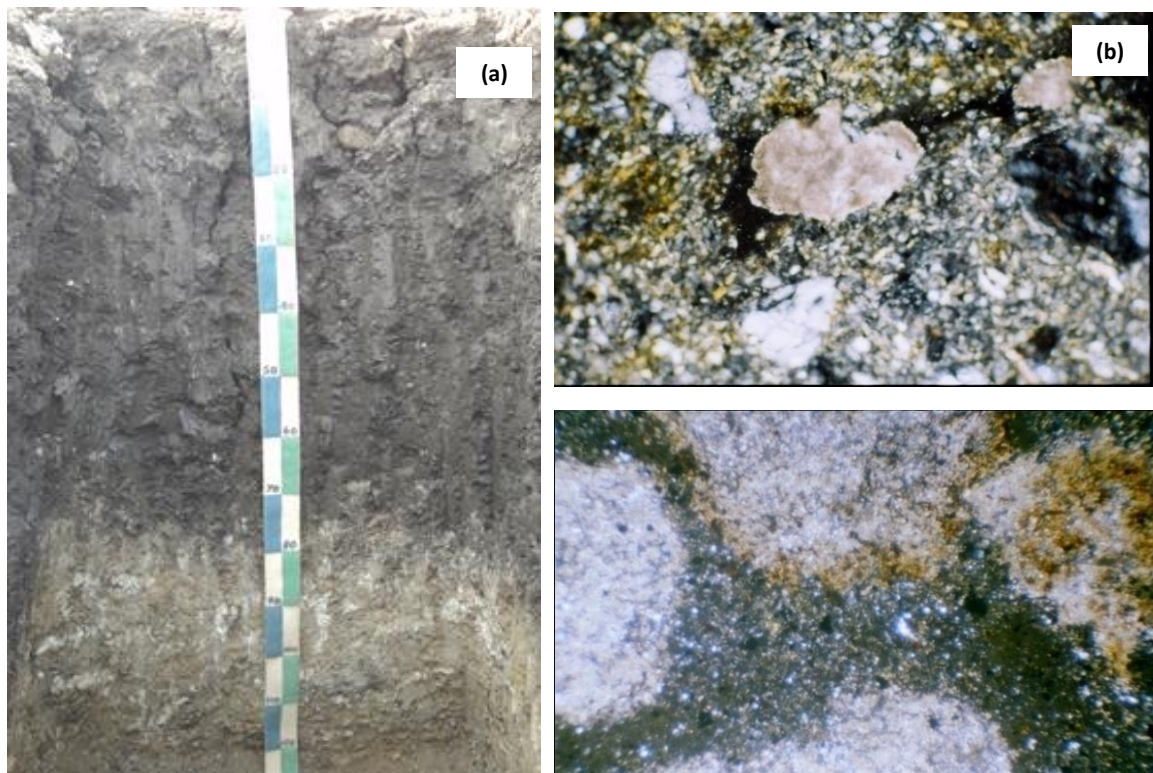


Fig 2. (a) A soil profile of calcareous soil and (b) SEM image of calcium nodules

Calcareous soils are dominant in the drier parts of the earth, and hence the soils of the arid and semi-arid regions are predominantly calcareous. These soils cover almost one-third of the world's land surface area (Bolan et al., 2023). It is estimated that more than 30% of the world's soils are calcareous (Taalab, 2019). Leytem & Mikkelsen (2005) reported that more than 1.5 billion acres of the global soils are calcareous. More recent estimates indicate that more than 500 million hectares of the soils worldwide are calcareous (Bolan et al., 2023).

It is estimated that about 17% of the soils of the USA are calcareous (Leytem & Mikkelsen, 2005). These soils are mainly distributed in Western and Northern America and intermittently in the other regions. Calcisols and related calcareous soils are widely prevalent in large parts of the African continent (Botswana, Ethiopia, Namibia, Somalia), the Mediterranean region, West Asia, Central Asia; Western, Central and Southern Australia (Mckenzie et al., 1999) and sparingly in the less humid regions of Latin America (Sanchez & Isbell, 1978).

In Egypt, the calcareous soils are extensively distributed in the desert regions, particularly in the northwestern coastal zone and Sinai (Wassif & Wassif, 2021). Rasha (2005) reported that the area under calcareous soils in Egypt was 0.65 million Feddans (0.27 million hectares). The Ministry of Agriculture, Egypt estimated that about 25-30% of Egypt's soils are calcareous and the CaCO_3 content ranges from 15-30% in the Nile River valley to 30-80% beyond the Fringe zone. Rashid & Rafique (2017) observed that approximately 22 million hectares of Pakistan's soil are calcareous.

Calcareous soils constitute nearly 229 million hectares (69%) of India's geographical area. These soils are widely distributed in the states of Rajasthan, Punjab, Uttar Pradesh, and Haryana in the north, as well as in Maharashtra, Madhya Pradesh, and Gujarat in the central region, Bihar in the east, and Andhra Pradesh (including Telangana) and Tamil Nadu in the south (Pal et al., 2000) (Fig. 3). The states of Uttar Pradesh and Bihar together

have 1.3 million ha of calcareous soils (Basu et al., 2016).

Distribution of cotton on calcareous soils:

Cotton (*Gossypium spp.*) is grown in around 31 million hectares in more than 80 countries. Since the cotton crop is tolerant to drought and moderately tolerant to salinity/alkalinity, it is a preferred crop of arid and semi-arid eco-regions. Calcareous soils are also fairly widespread in these eco-regions. Cotton is widely cultivated on calcareous soils in India, Pakistan, China, parts of the USA and Australia, in the Mediterranean region (Egypt, Israel, Turkey, Greece, Spain) Uzbekistan and Sudan (Table 1). In India, cotton plays a central role in agricultural economy, particularly in states like Maharashtra, Gujarat, Madhya Pradesh, and Rajasthan, where soils often exhibit calcareous characteristics. They are marked by distinctive pedogenic features such as *kankar* nodules, CaCO_3 accumulations in sub-surface horizons, and hardpan formations in some regions.

Table 1. Regions where cotton is grown on calcareous soils

Country	Regions
Egypt	EL Nubaria region in North west
China	Xinjiang Uyghur
USA	Oklahoma, Arizona, New Mexico, parts of Texas

Country	Regions
Turkey	Aegean region, southeastern districts
Pakistan	Punjab and Sindh
Spain	Ebro valley, Andalucia
Greece	Thessaly and other low land plains
Israel	Coastal plains and Negev
India	North (Punjab, Haryana, Rajasthan), Central (Gujarat, Madhya Pradesh, Maharashtra), South (Telangana, Andhra Pradesh, Tamil Nadu)
Uzbekistan	Fergana Valley, Tashkent, Samarkand, Jizzakh, Bukhara, Kashkadarya, Surkhandarya, and Khorezm

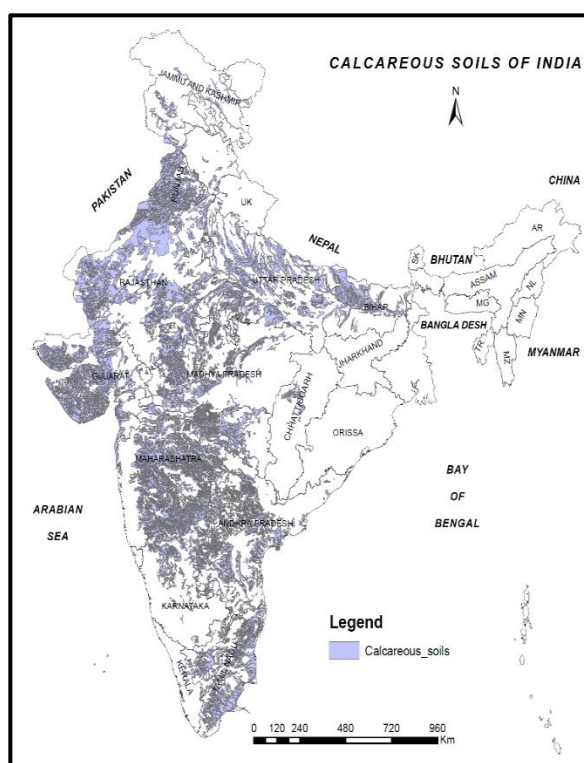
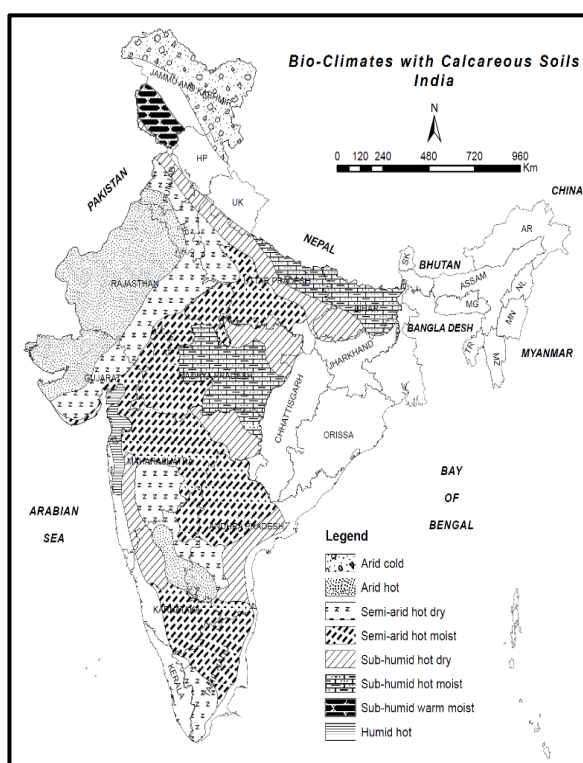


Fig. 3. Distribution of Calcareous soils in India

For cotton, key soil attributes include soil texture, depth, CaCO_3 distribution, exchangeable sodium percentage, and the availability of essential nutrients. While the soils often possess moderate to high reserves of calcium and magnesium, their

nutrient availability—especially iron (Fe), zinc (Zn), phosphorus (P), and sometimes boron (B)—is strongly constrained by the alkaline conditions. The pH buffering capacity of calcareous soils is high, often resisting acidification even under intensive

fertilization. Despite these limitations, the soils are inherently capable of supporting cotton due to their good rooting depth and stable structure in many regions. These soils pose serious challenges to cotton production due to their high alkalinity, poor micronutrient availability, and structural constraints. Understanding the interaction between cotton physiology and calcareous soil properties is critical to optimising yield, fibre quality, and economic returns. The distribution and formation of calcareous soils reflect a long history of basaltic parent material, limited leaching, and high evaporation, all of which promote carbonate precipitation. The site-suitability assessment conducted by Sehgal (National Bureau of Soil Survey & Land Use Planning) indicated that cotton performs optimally on rainfed calcareous soils when CaCO_3 content (in nodular form) remains below 20%, soil depth exceeds 60–100 cm, and the soil retains at least ~100 mm plant-available water (Sehgal, 1991).

Properties of calcareous soils affecting crop growth and productivity

Calcareous soils face various physical, chemical, and biological limitations that affect cotton growth and yield. A primary challenge is nutrient deficiency, particularly phosphorus. High levels of CaCO_3 cause phosphates to precipitate as

tricalcium or dicalcium phosphate, reducing P solubility and subsequent availability despite extensive fertiliser application. Cotton, which requires a significant amount of P, shows stunted growth, purple leaves, and delayed maturity when P is deficient.

Micronutrient deficiencies are a significant limitation, particularly for Fe, Zn, and Mn. Iron deficiency appears as interveinal chlorosis in young cotton leaves, often worsened by early-season cold spells or high soil moisture. Zinc deficiency is common in the calcareous Vertisols of Maharashtra and Madhya Pradesh, causing leaf bronzing and decreased boll setting. Although less common, boron deficiency affects flowering, boll setting and lint quality.

Physical properties

The physical properties of calcareous soils reflect the interaction between carbonate content, texture, and soil structure. High CaCO_3 levels often result in a light colour, crumbly consistency, and, in some cases, a high bulk density, especially where carbonate cementation has occurred. Soil physical limitations include poor aggregate stability in certain calcareous soils, decreased infiltration, crust formation, hardpan development, and low organic matter content. These constraints hinder root penetration and

reduce water availability, which is particularly harmful in rainfed cotton systems. The texture ranges from coarse sands to fine clays, depending on the parent material. However, many calcareous soils in semi-arid regions have silt loam to clay loam textures that influence water availability and infiltration. The dissolution of carbonates into bicarbonate ions and their subsequent precipitation upon drying promote the formation of a hard surface crust (Bolan et al., 2023). Crusting of the surface layer occurs due to the reorientation of soil particles and calcium carbonate precipitation during drying (Chattopadhyay & Singha, 2022). Surface crust and hardpan can impede water entry and drainage. Hard pans may also restrict root growth into subsoil layers. Calcareous soils tend to remain flocculated (granular). Flocculation in heavy (clay) soils enlarges pore spaces and enhances drainage, while in light (sandy) soils, it reduces water-holding capacity. In the Semi-arid tropics, pedogenic calcium carbonate can lead to soil sodicity, which may impair hydraulic properties (Pal et al., 2016). The surface colour appears pale due to the rapid breakdown of organic matter (Fey, 2010).

Water-related limitations occur in fine-textured calcareous soils, causing waterlogging in depressions and moisture

stress on upper slopes. Soil hydraulic conductivity is often reduced due to calcareous hardening or dense subsurface layers. Well-drained calcareous soils with high clay content may experience temporary water stagnation during occasional rains.

Aggregate stability can vary greatly, as the presence of carbonates can promote structural stability through flocculation while also restricting organic matter stabilisation, resulting in weak structures under intensive cultivation (Bronick & Lal, 2005). Hydraulic properties are equally complex: although infiltration may be moderate to high in well-structured calcareous loams, subsoil carbonate accumulations can limit percolation, creating perched water tables or hard layers that hinder root growth. In irrigated systems, these restrictive layers may also worsen salt build-up, increasing the risk of secondary salinization (Rengasamy, 2018).

Chemical properties

The chemical properties of calcareous soils are among their defining features, influencing their behaviour and fertility. Their pH is typically high, ranging from 7.5 to 8.5. In the presence of free sodium carbonate, the pH can exceed 9 (Bolan et al., 2023). High pH significantly impacts nutrient solubility and availability,

especially for micronutrients such as iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu). These micronutrients often precipitate as hydroxides or carbonates under alkaline conditions, leading to deficiencies that manifest as chlorosis, stunting, and reduced metabolic activity in the cotton plants (Alloway, 2008). Extremely high soil pH can also inhibit microbial activity, slowing organic matter decomposition and nitrogen mineralisation. Alkaline pH and high CaCO_3 content decrease the solubility and plant availability of phosphorus and many micronutrients (Fe, Zn, Mn, Cu, B) due to their reduced solubility (Bolan et al., 2001). Additionally, the chemistry of calcareous soils can affect the effectiveness and durability of soil-applied herbicides, insecticides, or fungicides for pest management in cotton

The dissolution of CaCO_3 in calcareous soils results in a high concentration of HCO_3^- in the soil solution, which buffers the soil at pH 7.5 to 8.5 (Bolan et al., 2001). Calcareous soils can be sodic, saline, or saline-sodic (Hassani et al., 2020) depending on the climate conditions. Therefore, all sodic soils are calcareous, but not all calcareous soils are sodic. Bhattacharyya et al. (2004) reported a threshold for mean annual rainfall of 850 mm, below which soils

become more calcareous, alkaline, and sodic. Clay minerals dominate their exchange complex, with a high cation-exchange capacity. Ca^{2+} and Mg^{2+} are the predominant cations on the exchange complex and in the soil solution (Wadu et al., 2013). High base status with minimal leaching of plant nutrients is another characteristic of calcareous soils.

Most calcareous soils have low organic matter content (0.5 - 1.0%). **Xiaolu** et al. (2024) observed a negative correlation between CaCO_3 and soil organic carbon. They further hypothesised that in calcareous soils, excess Ca^{2+} is transformed into forms that occupy the bonding sites for soil organic carbon on soil particles' surfaces, creating a pseudo-aggregate structure that hinders soil organic carbon stabilisation and build-up. Phosphorus (P) dynamics are challenging: soluble phosphate readily reacts with Ca^{2+} to form sparingly soluble calcium phosphate compounds, significantly reducing the effectiveness of applied fertilisers. The high carbonate environment also increases bicarbonate levels in the soil solution, further inhibiting micronutrient uptake by plant roots. Organic matter levels are often low in calcareous soils of arid and semi-arid regions due to slow decomposition, limited biomass production, and rapid mineralisation under

alkaline conditions. These factors collectively reduce cation exchange capacity (CEC) and nutrient retention. However, calcium carbonate may help buffer the soil, making it resistant to rapid acidification.

Biological properties

The biological properties of calcareous soils exhibit distinct patterns influenced by high pH, limited organic matter, and episodic moisture conditions. Low nutrient availability and biological activity are major challenges in calcareous soils with low soil organic matter (OM) content (Karimi et al., 2020). The alkaline pH of calcareous soils suppresses some beneficial microbial processes and decreases the mineralisation rates of organic N, slowing nutrient release and biological nutrient cycling. Bacteria typically dominate over fungi in such soils, with a higher prevalence of actinobacteria and other alkaliphilic microbial groups capable of functioning effectively under reduced nutrient conditions. High carbonate levels can also affect microbial enzymatic activities, especially phosphatases and dehydrogenases, which tend to show decreased activity in highly calcareous environments (Sardans & Peñuelas, 2015). Root-microbe interactions may be limited by reduced mycorrhizal colonisation under high pH

conditions, restricting nutrient acquisition, particularly phosphorus. The microbial degradation of pesticides is also reduced on calcareous soils. These biological constraints are significant in agricultural systems where crop productivity heavily relies on microbial-mediated nutrient cycling and turnover.

Potentials and limitations of calcareous soils with reference to cotton production

Potentials

Calcareous soils provide several natural benefits for cotton production when managed properly. Cotton naturally tolerates moderately alkaline conditions and can utilise the deep soil profile typical of calcareous Vertisols and related soils. Higher calcium levels improve cell wall strength, promote root growth, and increase stress resilience.

These soils often have high water-holding capacity, especially the medium- and deep-black calcareous soils of Maharashtra and Madhya Pradesh, enabling cotton to endure dry periods. The clay minerals in Vertisols provide strong nutrient retention abilities, reducing leaching losses of nitrogen, potassium, and sulphur. Calcium in calcareous soils improves soil structure and aggregation. Thus, most calcareous soils are well aggregated and possess favourable water-

retention characteristics. Cotton, being a long-season and deep-rooted crop, can benefit from these conditions. Calcareous soils are generally well-drained (unless sodicity impairs their hydraulic properties), and cotton prefers a well-drained soil over wet soils. Calcareous soils with high clay content have sufficient water-holding capacity to support a cotton crop, particularly under rainfed conditions. The natural buffering capacity of the soils protects cotton from sudden shifts in soil acidity and toxicity. High calcium levels also mitigate potential aluminium toxicity, which cotton is highly sensitive to in acidic soils.

Cotton crop can tolerate alkalinity up to a pH of 8.0 and hence is a preferred crop on such soils. When water availability, nutrient requirements, and soil physical constraints are managed, calcareous soils can support a good cotton crop because the majority of these soils have inherently good structure and high cation exchange capacity. The CEC is high in calcareous soils that are formed by the weathering of limestone and dolomite parent rocks. In such calcareous soils, clay minerals can bind cations and release them for plant absorption (Kumar & Kumari, 2025).

The carbonisation of Ca and Mg in organic matter stabilises the CO₂ produced

by soil respiration, helping calcareous soils sequester C (Sakin & Yanardag, 2024) and mitigate climate change. Pedogenic carbonates in calcareous soils are a significant component of global carbon dynamics (Batool et al., 2024). The enhanced potential for sequestering organic C is due to the high rate of PC (SIC) dissolution in these soils (Bhattacharyya et al., 2014). These features make carbon-positive cotton farming possible on these soils.

In irrigated tracts, such as the Narmada command, the Krishna basin, and parts of Gujarat, calcareous soils have excellent yields under balanced fertilisation and integrated management. Cotton grown in deep calcareous soils with adequate moisture often exhibits high staple length, strong fibre maturity, and high ginning outturn, making these soils favourable for quality cotton production.

Moreover, calcareous soils have a high potential for carbon sequestration when organic amendments, mulching, and conservation agriculture practices are adopted. This creates opportunities for climate-resilient cotton farming systems.

Limitations

Calcareous soils can be saline, sodic, or saline-sodic, and these conditions affect soil processes, imposing a range of

physicochemical and biological limitations on cotton growth and yield. Although cotton is classified as moderately tolerant of salinity, salinity stress can reduce its potential productivity. While salinity can cause osmotic stress and ion toxicity, leading to decreased root growth and limited water and nutrient uptake, sodicity causes soil particles to disperse and impairs hydraulic conductivity (Rengasamy et al., 2022).

Constraints to cotton cultivation occur when the zone of calcium carbonate accumulation coincides with the depth where cotton roots are concentrated, and significantly affects the nutrition of cotton plants. The presence of CaCO_3 directly or indirectly affects the availability of nitrogen, phosphorus, potassium, magnesium, iron, manganese and zinc to cotton. Additionally, the alkaline pH/salinity/sodicity may adversely affect seed germination and plant stand, plant growth and development and nutrient uptake (El-Metwally & Sakr, 2010).

High CaCO_3 leads to the precipitation of phosphates as tricalcium or dicalcium phosphate, reducing P availability even with large fertiliser applications. Cotton, being a P-demanding crop, shows stunted growth, purple leaves, and delayed maturity under low P availability.

Phosphorus fixation and low P use efficiency could lead to suboptimal early root development and lower boll set later in cotton. Poor phosphorus utilisation is a common limitation for sustainable cotton production (Cai et al., 2023). Additionally, the P fertiliser applied to calcareous soils is rapidly converted to dicalcium phosphate dihydrate or octacalcium phosphate (Leytem & Mikkelsen, 2005). Lime in calcareous soil also serves as a sink for surface-adsorbed P (Bolan et al., 2023). Hence, targeted P management is critical for cotton grown on calcareous soils.

Another limitation is the high pH-induced alkalinity effect, which can cause ammoniacal nitrogen volatilisation and worsen micronutrient deficiencies in calcareous soils (Bolan et al., 2001). The losses are greater in coarse-textured calcareous soils, where insufficient colloidal clay adsorbs NH_4^+ ions (Taalab et al., 2019). Cotton is also vulnerable to boron toxicity, which can occur in some calcareous soils with soluble B levels above the threshold levels.

Lower organic matter levels reduce agricultural productivity in calcareous soils due to the limited availability of essential nutrients (Bolan et al., 2023). Low organic matter and decreased

microbial activity increase dependence on external fertilisers and decrease resilience to various biotic and abiotic stresses in cotton. Reduced microbial activity and slower decomposition rates hinder nutrient transformations and soil resilience.

Micronutrient deficiencies are another critical limitation, especially Fe, Zn, and Mn. Iron deficiency manifests as interveinal chlorosis in young leaves of cotton crop cultivated on calcareous soils, often aggravated during early-season cold spells or under high soil moisture. Zinc deficiency is common in the calcareous Vertisols of Maharashtra and Madhya Pradesh, leading to leaf bronzing and reduced boll setting. Although less frequent, boron deficiency affects flowering and lint quality.

Soil physical limitations include poor aggregate stability in some calcareous soils, reduced infiltration, crusting, hardpan formation, and low organic matter. These constraints impede root penetration and reduce water availability, which is particularly detrimental in rainfed cotton systems. Extreme soil pH can also reduce microbial activity, slowing down organic matter decomposition and nitrogen mineralisation. Subsurface compaction caused by the formation of impermeable layers limits root penetration, water

infiltration (Davies & Lacey, 2011), and nutrient availability. The use of heavy tillage machinery in cotton fields may worsen compaction (Patrick, 2002). These conditions can lead to poor crop stands and reduced drought tolerance in cotton plants under rainfed conditions. Soil hydraulic conductivity is often reduced due to calcareous hardening or the presence of dense subsurface layers.

Plant disease and toxicity issues can be more prevalent, or disease-causing pathogens may behave differently under high-calcium, high-pH conditions, complicating control measures. For instance, the soil-borne fungus *Phymatotrichopsis omnivora*, which causes root rot in cotton, is widespread in the alkaline, calcareous soils of the southwestern USA (Oklahoma, Texas, New Mexico, and Arizona) and northern Mexico (Percy, 1983). The activity and efficacy of bio-control agents and bioinoculants could also be affected by soil calcareousness.

Management options for improving cotton productivity on calcareous soils

Calcareous soils can be highly productive for cotton when managed properly. Several interventions are available to ameliorate the physical (crusting, subsoil compaction, erosion,

impaired hydraulic properties), chemical (salinity/sodicity, P and micronutrient deficiencies, low nutrient use efficiency), and biological (soil organic matter, poor microbial diversity, and impaired root proliferation) limitations of calcareous soils. Some of these are briefly outlined below.

1. Minimising soil crusting through the addition of organic manures- compost, farm yard manure, crop residues or vegetative mulches. These organic amendments inhibit the formation of soil crust by promoting soil aggregation (Al-Nasser & Al-Kafagi, 2020). Conservation tillage methods also effectively reduce soil crusting and promote seedling emergence (Karayel & Sarauskis, 2024).
2. Reducing soil erosion by mulching, minimising tillage and adopting other conservation agriculture practices. Adoption of Conservation Agriculture (CA) on calcareous soils can bring a significant decrease in total soil inorganic carbon (calcareousness), indicating the advantage of CA in addressing soil fertility problems associated with calcareousness (Dey et al., 2018).
3. Overcoming sub-soil compaction through mechanical sub-soiling or deep ripping and growing deep-rooted crops.
4. Improving the physical properties of the soil through the addition of biopolymers and synthetic polymers. The application of synthetic polymers, viz. polystyrene and polyacrylamide, or biopolymers like cellulose improved the physical properties of the soil, including hydraulic conductivity and water holding capacity of calcareous soils (Maghchiche et al., 2010)
5. Soil pH and nutrient-related constraints can be overcome through the following interventions-
 - Elemental S can be applied to reduce the soil alkalinity and improve nutrient availability of calcareous soils (Jaggi et al., 2005). Barret-Lennard et al. (2021) recommended the combined application of gypsum and elemental S, along with inter-row water harvesting, to leach Na^+ ions and improve yields on sodic calcareous soils.
 - Calcareous soils developed under arid/ semi-arid climatic conditions

have certain properties that greatly influence P dynamics in soil. In alkaline and calcareous soils, having high levels of CaCO_3 and exchangeable Ca, reduces the P availability. Hence, in calcareous soils, the quantity of P-fertilisers has to be increased appropriately with an increase in the CaCO_3 content to maintain sufficient P concentration in soil solution to meet the plant's demand (Narayanswami & Biswas, 2000)

- The application of liquid P formulations like Phosphoric acid and ammonium polyphosphate in place of granular formulations like MAP and DAP is recommended to reduce P fixation and increase its availability on calcareous soils (McBeath et al., 2007)
- Application of biochar as a liming material improves nutrient availability. The application of biochar to calcareous soils lowers their pH and increases the bioavailability of soil P (Bolan et al., 2022). Biochar generated at high temperatures commonly exhibits an alkaline pH, and its application on calcareous soils can lead to further increases in pH, potentially worsening micronutrient

deficiencies. Hence, utilising biochars produced at lower temperatures (200–300°C) or acidified biochars may help alleviate this limitation (Begum & Gulser, 2024). The acidic functional groups present on the surface of biochar produced at low temperature (200°C) can counter-balance alkalinity and lead to a decrease in soil pH (Naeem et al., 2017).

- Multiple micronutrient deficiencies are serious yield-limiting factors on calcareous soils (Malakouti, 2008), and foliar sprays are effective in supplementing soil application of limiting micronutrients. Foliar application of Zn, Fe and Mn is useful in correcting micronutrient deficiency. Chelated forms of these micronutrients are more effective than the inorganic formulations, for both soil and foliar application on calcareous soils (Singare et al., 2022).
- It is recommended to place P and Zn fertilisers in separate bands to reduce their fixation and interaction and improve their bioavailability
- Bio inoculation with *Azotobacter* and *Bradyrhizobium* is effective in improving N uptake on calcareous soils (Ramadan et al., 2002)

- Pramanick et al. (2024) recommended soil test-based Site-Specific Nutrient Management (SSNM) as an effective strategy for improving crop yields as well as nutrient use efficiency on calcareous soils.
- Application of pressmud @ 5 tonnes/ha, once in three years, before planting can help ameliorate the physical and chemical properties of calcareous soils (Kumar & Kumari, 2025).
- Blending urea with non-edible cakes like neem (*Azadirachta indica*) and

karanj (*Pongamia pinnata*) and coating of urea with lac, sulphur or neem oil reduces volatilisation losses of N on calcareous soils, thus increasing the N use efficiency (Singh & Reddy, 2001). Ammonia volatilisation from calcareous soils can also be reduced by deep placement of urea or ammoniacal fertilisers (Patricia, 2000).

The performance of cotton under various nutrient management strategies in calcareous soils in various countries is summarised in Table 2.

Table 2 Management Interventions for cotton on Calcareous soils

S No	Location	Intervention	Result	Reference
1	Xinjiang, China	Acidic composted tea (CT)- a concentrated fermented organic liquid fertilizer.	CT application reduced soil pH by 1%, increased the soil's Olsen-P by 25.2%, mainly originating from NaOH-P dissolution, and increased the available Fe and Mn by 23.0% and 1.1%. CT also increased trace element accumulation in cotton plants, which significantly affected cotton dry matter and yield.	Luo et al. (2022)
2	Sakha and Noubaria region Egypt,	bio-fertilisers (<i>Bacillus Polymxa</i> , <i>Bacillus megaterium</i> , <i>Bacillus circulans</i> , <i>Azotobacter</i> and <i>Azospirillum</i>)	Soil application of biofertilizers, three times at 65, 85 and 105 days after sowing through the irrigation water improved yield and its components and ginned cotton properties	Ahmed et al. (2021)
3	Thessaloniki, Greece	Foliar application of Mn	Foliar Mn application can improve the lint and seed yield and also the seed quality of cotton grown for seed production on calcareous soils.	Dordas (2009)

S No	Location	Intervention	Result	Reference
4.	Bathinda, Punjab	Soil application of B	B application @ 1 mg/kg soil increased boron content in different plant parts, improved yield and fibre quality and increased content of different B fractions in the soil.	Kumar et al. (2021)
5	El-Nubaria Egypt	seed inoculation with <i>Bacillus megaterium</i> , <i>Bacillus circulans</i> , <i>Azospirillum Brasiliense</i> and foliar spray of algae extract at 65, 85, and 105 days after planting	A combination of bacterial inoculation, algae extract application along with 50% NPK resulted in the highest crop yield and fiber quality compared to 100% NPK fertilizer	Sadawe et al. (2025)
6	Multan, Pakistan	Zn nutrition	Soil application of 15mg Zn/kg soil (as Zn SO ₄) along with 2 foliar sprays of 1% Zn (as Zn SO ₄ at 25 and 50 days after emergence) was most effective in improving growth, yield, and fibre quality traits of cotton under alkaline calcareous conditions.	Ashraf et al. (2025)
7	Texas, USA	Soil acidification through H ₂ SO ₄ in irrigation water	soil acidification on calcareous soils may improve the soil physical conditions and result in increased cotton yields	Christensen & Lyerly (1954)
8	Exiphrates' basin, Syria	Green manuring, soil and foliar application of Zn and Fe.	Green manure of clover was effective in improving Ma, Zn and Fe nutrition of cotton. Iron and zinc sulphate application to soil caused 5 and 10% increases in the cotton yield, while their application to plants as sprays resulted in 12 and 23% yield increases respectively	Mohammad (1981)
9	Texas, USA	Fe nutrition using chelated forms	Application of only 5 and 10 mg Fe kg ⁻¹ soil rates of Fe-EDDHA produced similar growth increases to those receiving 200 mg Fe/ kg in the form of inorganic sources.	Matocha (1986)
10	El-Nubaria, Alexandria, Egypt	Cotton nutrition	Soil application with humic acid (95%) @ 2 kg/fed. followed by foliar application of [2 g zinc-EDTA (15% Zn) + 2 g boron-EDTA (12% B)]/liter. improved cotton productivity	El-Sayed & Kattosh (2023)

S No	Location	Intervention	Result	Reference
11	El-Nubaria, Alexandria, Egypt	Potassium nutrition	The soil application of K as Potassium humate fertilizer (20% humic acid and 8% K ₂ O) A 2l/fed with foliar application of potassium humate @ 1 L/fed sprayed three times at squaring, start and peak of flowering stages, increased earliness, and significantly increased number of opened bolls/plant, boll weight, seed cotton yield/plant and consequently seed cotton yield	Gomaa et al. (2014)
12	Nagpur, India	Application of bio-stimulant-sea weed extract	On rainfed calcareous soils, cotton responded positively to foliar application of Sagarika (sea weed extract) @ 0.002%	Raju et al. (2023)
13	Tashkent, Uzbekistan	Bio-stimulant	Seed treatment of Plant growth regulators Vitavax 200 and BIST (from bacterial strain of <i>Pseudomonas putida</i>) improved cotton productivity on semi-arid, calcareous soils	Abdualimov (2013)
14	Akola India	Organic amendments	Green manure (<i>Sesbania</i>) and crop residues improved the physio-chemical properties of sodic calcareous black soils under cotton-based cropping system	Shirale et al. (2017)
15	Sudan Gezira	Foliar application of micronutrients	Two applications of foliar fertiliser, containing Mn, Zn, Fe, B one at flowering and one three weeks after flowering, increased yield by 40–68% on alkaline calcareous soils	Ishag (1992)
16	China	P nutrition	Application of MAP, DAP and TSP could significantly increase cotton yield and economic benefit, with the effect of P fertilisers being in the order of MAP > TSP > DAP.	Qingjun et al. (2018)

These findings provide a basis for efficient management in calcareous soil to improve the productivity of cotton.

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