4th Indian Horticulture Summit -cum-International Conference-2026

Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health and Economic Resilience

28-30 January 2026

SOUVENIR

Organized by

SOCIETY FOR HORTICULTURAL RESEARCH AND DEVELOPMENT

Uttar Pradesh, India

at

RANI LAKSHMI BAI CENTRAL AGRICULTURAL UNIVERSITY

Jhansi, Uttar Pradesh, India

Co-Sponsors

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शिवराज सिंह चौहान
SHIVRAJ SINGH CHOUHAN

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सत्यमेव जयते

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ग्रामीण विकास मंत्री
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MESSAGE

Horticulture has emerged as a critical pillar of India's agricultural economy, contributing nearly one-third of agricultural Gross Value Added while providing substantial employment opportunities, particularly for small and marginal farmers. Leveraging India's rich agro-climatic diversity, the sector supports agricultural diversification, enhances farmer profitability, strengthens exports, and supplies essential inputs to food processing and allied industries. Focused interventions in quality planting material, high-yielding varieties, protected cultivation, precision farming and climate-resilient practices are central to improving productivity, resource-use efficiency and income stability, while simultaneously addressing challenges of climate variability, soil health and water scarcity.

The Indian Horticulture Summit-cum-International Conference-2026, with its emphasis on indigenous and underutilized horticultural crops, reflects a farmer-centric, science-driven and market-linked approach aligned with the vision of Viksit Krishi aur Samruddh Kisan. By promoting clean and high-quality planting material, modern production technologies, and climate-adaptive strategies, the Summit seeks to ensure sustainable growth and nutritional security. Equally important is the thrust on entrepreneurship and Farmer Producer Organizations (FPOs), which will enable aggregation, value addition, reduced post-harvest losses and stronger market linkages, thereby ensuring that farmers secure a higher share of consumer value. I am confident that the deliberations will lead to a practical and implementable roadmap for strengthening India's horticulture sector, and I convey my best wishes for the grand success of the Summit.

(Shivraj Singh Chouhan)

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भागीरथ चौधरी
BHAGIRATH CHOUDHARY

सत्यमेव जयते

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राज्यमंत्री
भारत सरकार
MINISTER OF STATE FOR AGRICULTURE
& FARMERS WELFARE
GOVERNMENT OF INDIA



Message

Horticulture is the primary source of nutritional security, supplying vital vitamins, minerals, and dietary fiber through fruits and vegetables, which directly addresses malnutrition. Additionally, the sector is highly labor-intensive, generating substantial rural employment, especially for women. By yielding higher per-unit returns, horticulture facilitates farm income diversification, promotes exports and feeds raw materials to the growing food processing industry, making it crucial for India's economic resilience and agricultural sustainability. The 4thIndian Horticulture Summit-cum-International Conference-2026 is poised to be a rallying cry for the holistic development of India's high-value agriculture sector, directly reflecting the government's commitment to farmer welfare and national self-reliance as a Developed Nation by 2047. The benefit of optimal resource management and yield predictability; embracing techniques like poly-houses, hydroponics, and advanced micro-irrigation systems allows farmers to create controlled micro-climates, significantly improving water use efficiency, enabling year-round and off-season production of high-value crops (like exotic vegetables and flowers), and using data-driven, sensor-based precision farming methods to optimize inputs like fertilizers and water, moving towards adaptation to extreme weather events; including the large-scale adoption of climate-resilient crop varieties, promoting Natural Farming (NF) principles to improve soil carbon and water retention capacity and the use of weather-based agro-advisories to minimize crop losses, ensuring the stability of both the national food supply and the individual farmer's income in the face of climate change.The Entrepreneurship Development and Farmer Produce Organizations (FPOs) in Horticulture Sectors providing the benefit of collective market power and enhanced value capture; FPOs empower smallholder farmers by enabling collective bargaining for inputs, accessing creditand jointly investing in crucial post-harvest infrastructuresuch as cold storage, primary processing units, and logistics which significantly reduces post-harvest losses, one of the biggest drains on the farmer's income.

I am sure that the 4th Indian Horticulture Summit cum International conference will provide a common platform for scientists and stakeholders to discuss and deliberate on scientific innovations and come out with specific recommendations at the end of this event.

I wish the SHRD Organizing Committee all the success in their efforts for holding the 4th Indian Horticulture Summit.

(Bhagirath Choudhary)

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सचिव
Dr. Devesh Chaturvedi
Secretary

सत्यमेव जयते

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कृषि एवं किसान कल्याण विभाग
Government of India
Ministry of Agriculture & Farmers Welfare
Department of Agriculture & Farmers Welfare



Message

The horticulture sector has increasingly positioned itself as a pivotal engine of growth in the Indian agriculture, contributing substantially to economic expansion and generating diverse employment opportunities among the primary, secondary, and tertiary domains. Horticultural crops exhibit exceptional resilience to climatic fluctuations, while vegetables predominantly cultivated by small and marginal farmers, play a critical role in elevating household incomes and strengthening rural livelihoods. Beyond its economic significance, the horticulture sector is indispensable for ensuring access to a varied, nutrient-rich, and balanced diet, thereby supporting the health and well-being of the nation.

Despite its immense promise, the horticulture sector continues to encounter persistent production-related constraints that impede optimal productivity and profitability. However, recent advancements in horticultural science encompassing cutting-edge technologies, improved crop varieties, climate-smart interventions, and precision-based management practices have created new pathways to enhance efficiency, sustainability, and economic returns. The Indian Council of Agricultural Research (ICAR) has been instrumental in driving this transformation, consistently fostering innovation and spearheading technology-led growth across multiple dimensions in horticultural research and development.

In this context, the convening of the **4th Indian Horticulture Summit-cum-International Conference-2026,** focused on the theme ***"Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health, and Economic Resilience,"*** scheduled from **28 to 30 January 2026** in collaboration with **Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh,** stands as a forward-looking and highly commendable initiative. This prestigious event seeks to facilitate deep scientific deliberations on the enhancement of production and productivity across a broad spectrum of horticultural crops while addressing emerging challenges and tapping into future opportunities. I am confident that the discussions, research contributions, and expert interactions will be meaningfully captured in the Souvenir, offering valuable insights for the wider horticultural community.

I sincerely believe that the outcomes of this summit will significantly enrich scientists, researchers, students, policy makers and all stakeholders by fostering a more dynamic, inclusive, and impactful horticulture sector. The exchange of innovative ideas and state-of-the-art technologies will undoubtedly catalyze progress toward making horticulture more resilient, accessible, and transformative for the society at large.

I extend my warmest wishes for the resounding success of the **Indian Horticulture Summit cum-International conference-2026** and trust that the event will achieve its objectives with exceptional distinction and scientific merit.

(Dr. Devesh Chaturvedi)

New Delhi
January 6, 2026

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Secretary (DARE) & Director General (ICAR)

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कृषि एवं किसान कल्याण मंत्रालय, कृषि भवन, नई दिल्ली

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MESSAGE

Indian agriculture by all dimensions is now not only a insignia of sustenance, but vividly positioned as a dynamic engine of employment-led growth, poverty- alleviation, nutritional advancement and self-reliance having pan-India impacts. Within this transformation, Horticulture has emerged as a sector to reckon with glaring pride, that any Indian can boost of such extraordinary feat. The iconic trajectory of horticultural research and development in India has undergone a dynamic transformation, anchoring this sector as a driver of food and nutritional security, preventive health- care and sustainable livelihoods. Pouring evidences ably substantiate that India would be attaining the status of a Developed Nation by 2047. No doubt, in the recent past, Horticulture has emerged as a cornerstone of agricultural and rural transformation with production distinctively surpassing 367.7 million tonnes, contributing ~ 34% to the agricultural GDP.

The Horticulture sector now faces a new challenge of meeting an estimated demand of 777.7 million tonnes by the year 2047, calling for a paradigm shift from conventional production systems toward climate-smart, nutrition-sensitive and technology-driven approaches that integrate sustainability with profitability. The key drivers of this transformation include innovation in varietal development for higher productivity, resilience, and nutritional enhancement; adoption of protected cultivation and precision farming for efficient resource-use efficiency and sustainable intensification aligned with bio- and -circular economy principles. Equally critical are investments in post-harvest management, cold- chain infrastructure and value- chain development, which will collectively reduce post-harvest losses, enhance farmers' 'income, and strengthen India's competitiveness in global markets.

Horticultural crops also offer unique opportunities in preventive healthcare, therapeutic nutrition and wellness-focused diets, contributing to national health and well-being. In this perspective, a definitive role of indigenous and under-utilized horticultural crops is envisioned for sustainable development, health and economic resilience, in addition to retrofitting them into organic and natural farming as green technology option having zero carbon budget.

In this context, Society for Horticultural Research and Development (SHRD), Uttar Pradesh, is organizing its 4th Indian Horticulture Summit-cum-International Conference -2026 on a theme "***Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health and Economic Resilience"*** *during* 28-30 January 2026 at the Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh. I compliment the organizers, and hope that the outcome of the Summit-cum-International Conference-2026 would ensure accelerated horticultural growth, and strongly align with the broader goals of sustainable livelihoods, environmental stewardship and economic transformation.

(M. L. Jat)

Dated the 6th January, 2026
New Delhi

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Message

It gives me immense pleasure to extend my warm greetings to all delegates, scientists, academicians, entrepreneurs, farmers, policy- makers, and students participating in the 4th Indian Horticulture Summit-cum-International Conference- 2026. This summit provides a timely and meaningful platform for deliberation on the evolving challenges and emerging opportunities in the horticulture sector, which plays a pivotal role in ensuring nutritional security, income generation, and sustainable horticultural research and development in our country.

Horticulture in India has witnessed remarkable growth over the past decades, contributing significantly to farmers' livelihoods, export earnings, and diversification in agriculture. However, issues such as climate change, resource degradation, post-harvest losses, market volatility, and the need for value- addition demand innovative, science-based, and inclusive solutions. In this context, the theme, **Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health, and Economic Resilience,** and technical sessions of this summit are highly relevant, as they aim to integrate cutting-edge research, modern technologies, digital interventions, and policy perspectives for strengthening the horticulture value chain.

I am confident that the interaction among researchers, industry leaders, start-ups, extension professionals, and progressive farmers during this summit will foster meaningful collaborations and generate actionable strategies. Such collective efforts are essential to promote climate-resilient horticulture, enhance productivity and quality, encourage entrepreneurship, and empower farmers, especially youth and women. Again, I commend the organizers for their vision and dedication in bringing together national and international experts under one platform. I sincerely hope that the recommendations emerging from the deliberations will contribute significantly to policy formulation, research prioritization, and sustainable growth of the horticulture sector.

I wish the Indian Horticulture Summit-cum-International Conference -2026 every success and hope that it proves to be intellectually enriching and impactful for all participants.

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Message

Systematic research on horticultural crops, though gained priority relatively late, but once it picked up, took over the foodgrain production by fair margin, with all time historic high production of 356 million tonnes. As a consequence, these crops started serving as promising alternative to impart additional nutritional security, besides food security. The sustained acceleration in growth of horticultural crops, with an annual rate of 5–6% considered essential to meet the exponentially growing demands of a rapidly urbanising, increasingly health-conscious and income-diverse populations in India.

Such a milestone was not achieved so easily, shifting research priorities to the integrated use of remote sensing tools for scientific crop planning ; value-addition; storage facility development; systematic land-use planning in large *Jhum*-affected areas; geomatics applications for modelling impact of climate change ably demonstrated for crops like potato, apple; modern breeding techniques coupled with biotechnological tools leading to varietal development; protected cultivation; micro-irrigation plus fertigation and sensor integrated pest and nutrient management practices, all culminated into enhanced resource- use- efficiency. Simultaneously, the role of urban and peri-urban horticulture, including rooftop gardens, vertical farming, hydroponics and aeroponics, integration of digital tools (farm sensors, satellite-based crop monitoring, AI-driven decision support systems, and blockchain-enabled traceability) are pivotal in redefining the production and supply-chain management in horticultural crops. Such scientific wisdoms are likely to perch India as front runner to become a developed nation i.e. Amrit Kal through contribution of horticultural crops in the national GDP.

The Society for Horticultural Research and Development (SHRD), Uttar Pradesh, has been upfront over the years in brining important issues related to horticultural research and development to a national dialogue. Scheduling 4th Indian Horticulture Summit-cum-International Conference -2026 during 28-30 January 2026 at the Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh, is one such thoughtful example where brilliant brains engaged in Horticulture sector will discuss and thrash out the potential of horticultural and allied crops in harnessing the sustainable development of Horticulture sector.

I congratulate the organizers for taking up such initiative and wish a grand success for the 4th Indian Horticulture Summit-cum-International Conference -2026.

22/1/2026

(Sanjay Kumar Singh)

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डॉ. प्रभात कुमार
Dr. Prabhat Kumar
बागवानी आयुक्त
Horticulture Commissioner



सत्यमेव जयते

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कृषि एवं किसान कल्याण विभाग
Government of India
Ministry of Agriculture & Farmers Welfare
Department of Agriculture & Farmers Welfare

MESSAGE

Horticulture occupies a pivotal position in the transformation of global agriculture, contributing significantly to economic growth, nutritional security, and ecological sustainability. Its expanding role has brought together scientists, farmers, policy-makers, and other stakeholders to strengthen agricultural systems, with horticulture increasingly acknowledged as a catalyst for innovation and resilience. India stands as a notable example; despite a substantial rise in population since Independence, the nation has successfully ensured food and nutritional security through the dedication of its farmers, sustained scientific advancements, and visionary policy support.

In the contemporary global landscape, societal well-being and health resilience are inseparable from progress in horticultural science and technology. The development of climate-resilient, resource-efficient innovations is imperative to address the complex challenges posed by climate change. Equally important is facilitating the effective adoption of these technologies by farmers. Evidence-based and forward-looking policy interventions remain crucial to strengthening livelihoods, enhancing productivity, and ensuring long-term sustainability in the face of increasing climatic and economic uncertainties.

The initiative of the Society for Horticulture Research and Development (SHRD) in organizing a platform for scientific interaction, knowledge exchange, and focused deliberations on this vital theme is highly commendable. I am confident that the 4th Indian Horticulture Summit-cum-International Conference–2026 will serve as a significant forum for generating insightful discussions and actionable strategies that will shape the future of horticultural research, development, and innovation in India.

It is a privilege to convey my message to the distinguished participants of this conference on the theme "Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health, and Economic Resilience," scheduled to be held from 28 to 30 January 2026, in collaboration with Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh. The conference offers a valuable opportunity to deliberate on emerging scientific developments, share innovative perspectives, and chart strategic pathways for enhancing the growth and global competitiveness of the horticulture sector.

I extend my sincere best wishes to the organizers for the successful conduct of the Indian Horticulture Summit–2026 and trust that the deliberations will lead to meaningful outcomes with enduring scientific and societal impact.

Kumar
(Dr. Prabhat Kumar)

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MESSAGE



Horticulture has emerged as a pivotal sector in ensuring prosperity, nutritional well-being, and environmental security for humanity across the globe. Recognizing its growing significance, scientists, farmers, policy-makers, and other stakeholders have been making concerted efforts to strengthen agricultural systems with horticulture assuming its prominent and transformative role. India stands as a remarkable example despite a substantial rise in its population since Independence.

In the present era, prosperity and health security are increasingly linked to advancements in horticultural technologies. It is imperative for researchers to generate innovations capable of mitigating the adverse impacts of climate change and the farmers must be empowered to adopt these technologies effectively. Guided support from policy-makers is crucial in securing sustainable livelihoods and stable incomes for farmers, especially in the era of rapidly evolving climatic change and economic challenges.

The platform provided by the organizers for meaningful discussions, research presentations, and in-depth deliberations on this highly relevant theme is highly commendable. I am confident that the 4th Indian Horticulture Summit—International Conference 2026 will offer valuable insights and generate feasible, forward-looking recommendations essential for shaping the future roadmap of horticultural research and development globally.

It is my pleasure to extend a message to the distinguished delegates participating in the event on the theme *"Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health, and Economic Resilience,"* scheduled from January 28 to 30, 2026, in collaboration with Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh. This event represents an excellent opportunity to exchange knowledge, explore innovations, and chart new directions for accelerated growth in the horticulture sector.

I convey my heartfelt best wishes to the organizers for the grand success of the Indian Cum-International Conference-2026 and hope the event will achieve its objectives with excellence and far-reaching impact.

(Sudhakar Pandey)

डा. विश्व बन्धु पटेल
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INDIAN COUNCIL OF AGRICULTURAL RESEARCH
Krishi Anusandhan Bhavan-II, Pusa, New Delhi-110 012

Date: 22.12.2025



Message

Horticulture plays a vital role in the Indian economy by contributing significantly to agricultural Gross Value Added (GVA), improving nutritional security, generating rural employment, and enhancing farmers' incomes. As a major driver of diversification, the sector has emerged as a key engine of agricultural growth and export earnings, particularly in fruits, vegetables, plantation crops, and spices. At present, horticulture contributes nearly 34% to India's agricultural GVA, underlining its strategic importance.

In 2024–25, India's horticulture production is estimated at 369 million tonnes from about 29 million hectares, reflecting improved productivity and efficient land use. The sector enables small and marginal farmers to adopt high-value crops, supports rural livelihoods including women's participation, strengthens nutritional security, and fuels growth in allied sectors such as food processing, exports, and supply chains.

Indigenous and underutilized horticultural crops offer a sustainable pathway to strengthen agrobiodiversity, climate resilience, and ecosystem health. These crops, rich in nutrients and well adapted to local agro-ecologies, can play a crucial role in improving dietary diversity, community health, and livelihood security. Strategic research, value addition, and market integration of such crops will enhance farmers' incomes while promoting inclusive and resilient rural economies.

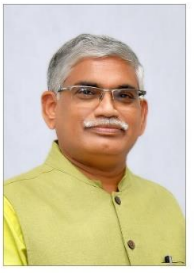
In this backdrop, the organization of the 4th Indian Horticulture Summit-cum-International Conference-2026, on the theme "Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health and Economic Resilience", scheduled from 28 to 30 January 2026 in collaboration with the Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh, is a welcome initiative. I am confident that the event will stimulate meaningful deliberations on the challenges, opportunities, and future prospects of the horticulture industry, and that the souvenir brought out for the occasion will reflect these insights effectively.

I extend my warmest wishes for the grand success of the Indian Horticulture Summit-Cum-International Conference-2026 and trust that it will achieve its objectives.

(V.B. Patel)

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MESSAGE

It is indeed a matter of great strength and pride that the Society for Horticultural Research and Development (SHRD) is organizing the 4th Indian Horticulture Summit-cum-International Conference-2026 on the theme *"Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health and Economic Resilience"*, scheduled from 28 to 30 January 2026 in collaboration with Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh. This prestigious event reflects a collective commitment to advancing horticultural science and addressing emerging challenges in the sector.

Horticultural crops constitute a vital component of Indian agriculture, contributing significantly to the nation's economic resilience and nutritional and livelihood security. With rising demand for diverse, safe, and high-quality horticultural produce, there is an urgent need to enhance productivity, improve product quality, and substantially reduce post-harvest losses. Key concerns that merit focused attention include low or inconsistent crop yields, high post-harvest wastage due to inadequate handling and storage, pronounced price volatility, and the overall economic viability of horticultural enterprises.

In this context, the theme of the event is exceptionally relevant. I am confident that the deliberations led by eminent scientists, researchers, and stakeholders will provide valuable insights and pave the way for developing robust research programmes, innovative technologies, and strategic interventions. These discussions will be instrumental in strengthening production systems, promoting climate-resilient horticulture, improving market efficiency, and enhancing farmer profitability.

I extend my warmest wishes to the organizers and participants and am optimistic that this Summit will significantly contribute to the scientific advancement and sustainable growth of the horticulture sector. I wish the event a resounding success.

T. Janakiram

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Dr Balraj Singh
Ex-Vice Chancellor,
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MESSAGE

The 4th Indian Horticulture Summit-cum-International Conference-2026, the theme, "Harnessing Indigenous and Underutilized Horticultural Crops for Sustainable Development, Health, and Economic Resilience," represents a visionary and timely platform to unlock the immense potential of India's diverse horticultural biodiversity. Indigenous and underutilized crops constitute a treasure trove of nutritional, genetic, and ecological resources. Strategically promoting and scientifically integrating these crops into mainstream agriculture presents unparalleled opportunities to enhance food and nutritional security, strengthen rural livelihoods, promote economic resilience, and build climate-resilient and sustainable production systems.

In today's rapidly changing environmental and economic landscape, challenges such as climate variability, soil degradation, limited natural resources, and shifting market dynamics underscore the urgency for innovation. The development and adoption of advanced technologies, precision farming practices, improved crop varieties, post-harvest innovations, and efficient value-chain mechanisms are pivotal. This summit provides an ideal forum for scientists, researchers, policy makers, extension professionals, entrepreneurs, and farmers to exchange knowledge, explore novel solutions, and forge collaborative strategies for the sustainable production, processing, and commercialization of invaluable horticultural crops.

Focusing on indigenous and underutilized horticultural species not only safeguards agro-biodiversity but also addresses emerging nutritional, health, and economic demands. These crops offer new avenues for income generation, market diversification, ecosystem conservation, and the promotion of resilient food systems. By seamlessly integrating traditional knowledge with cutting-edge scientific advances, this conference inspire us to make a robust roadmap for inclusive, sustainable, and forward-looking horticulture.

I am confident that the deliberations, research presentations, and interactive discussions at the Summit will generate actionable insights, stimulate innovation, and catalyze transformative solutions for the horticulture sector. Such collective efforts have the potential to enhance productivity, strengthen sustainability, and create a vibrant economic and social impact. I extend my heartfelt best wishes to participants, and all stakeholders for the grand success of the Indian Horticulture Summit-cum-International Conference-2026.

Balraj Singh 13/01/26

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Message

It gives me immense pleasure to extend a warm welcome to all delegates, researchers, policy-makers, entrepreneurs, farmers, and students to the 4th Indian Horticulture Summit-cum-International Conference-2026. On behalf of the SHRD, I express my sincere gratitude to every stakeholder who has contributed to making this important national and international platform possible.

The Indian horticulture stands at a transformative crossroads. With its vast diversity of fruits, vegetables, flowers, spices, plantation and medicinal crops, the sector plays a pivotal role in nutritional security, income generation, export earnings, and sustainable rural livelihoods. The 4th Indian Horticulture Summit-cum-International Conference-2026 has been envisioned as a forum to deliberate on emerging challenges and opportunities, share scientific innovations, promote climate-resilient practices, and strengthen linkages among research, industry, and farming communities.

This summit brings together eminent scientists, progressive farmers, industry leaders, startups, policy-makers, and international experts to exchange knowledge and experiences on themes such as precision horticulture, protected cultivation, value -addition, post-harvest management, digital technologies, and sustainable supply chains. The deliberations and recommendations emerging from this summit will, I am confident, contribute meaningfully to policy formulation, technology dissemination, and inclusive growth of the Horticulture sector in our country.

The SHRD remains committed to advancing horticultural research, capacity building, and technology transfer for the benefit of farmers and society at large. We believe that collaboration, innovation, and youth engagement are the keys to unlocking the full potential of Indian horticulture in the years to come.

I sincerely hope that the 4th Indian Horticulture Summit-cum-International Conference-2026 serves as a catalyst for new partnerships, actionable outcomes, and a shared vision for a resilient, profitable, and sustainable horticulture ecosystem. I wish the summit every success and a fruitful deliberation for all participants.

Som Dutt

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R&D in Horticulture in India: Institutions, Innovations, Impacts and Future

Balraj Singh

Former Vice-Chancellor, SKNAU, Jobner and A.U.Jodhpur, Rajsthan

Abstract

Horticulture has been a major contributor towards the substantial progress made towards food and nutritional security in India after Independence, the significant development has taken ground mostly after 2005. In the recent years, horticulture sector has become a driver of economic growth and slowly taking shape of an organized industry with key linkages to seed business, processing, value-addition and export leading to job-oriented growth. Horticulture provides an opportunity for much needed diversification and intensification for adequate nutritious food, augmenting the income of our farmers. Horticultural research in India initiated in 1954, with the establishment of Division of Botany at IARI. Over years, several institutions and AICRPs were operationalized with the research agenda relevant to the national plans and priorities for dedicated development of horticulture across states and regions. Today, horticultural research is conducted through 23 Institutes/Directorates/NRCs, 13 AICRPs and 6 Network Projects/Outreach programmes and is one of the most organized R&D set-ups in the NARES system in India. The Horticulture in India comprising diverse crops and commodities, viz. fruits & plantation crops; vegetables including potato, tuber crops, mushroom; ornamental plants; spices including seed spices and medicinal and aromatic plants, honeybee rearing, bamboo, etc. has emerged as major, alternatives for diversification and are contributing 34% to the agricultural GDP. The developing new varieties and management practices of the horticultural crops over the past 78 years has contributed immensely to the growth of horticulture sector. At present the sector is increasingly moving towards development of industries and commercialization. However, newer challenges such as emerging pests and diseases, declining and degrading land and water resources, climate change, scarcity of water resources, natural calamities, high costs of agricultural inputs and transport, competing use of land and water, and decline of investment in agriculture are emerging challenges and needs immediate attention and action. Promotion of crop diversification in small-holder horticultural farming had been successful in many Asian countries and technology being size neutral effective technology transfer paid quick dividends, needs to be adopted in India. Precision horticulture including protected cultivation is also progressing in several areas and there are several success stories even under harsh condition, commodity-based cluster approach is also with a good pace in various states and regions.

The horticulture sector consists of fruit crops, vegetable crops, potato and tuber crops, ornamental crops, medicinal and aromatic crops, perennial spices, seed spices and plantation crops. India, with its wide variability of climate and soil, is highly favourably placed for growing many horticultural crops across the country. It is the fastest growing sector within agriculture, contributing towards poverty alleviation, nutritional security. It provides ample scope for farmers to increase their income and is helpful in sustaining a large number of agro-based industries which generate huge employment opportunities. Presently horticulture contributes 33.0 - 34.0 % of agricultural gross domestic product (GDP), while using only 15.0 - 18.0 % of the cropped area in India. India has emerged as the world's largest producer of coconut and tea and the second largest producer and exporter of tea, coffee, cashew and spices. Only 8.0 - 9.0 per cent of the horticulture produce is processed,1.0 - 1.5 per cent is exported and 20.0 - 22 per cent is lost or get wasted in the market chain after harvesting. Exports of fresh and processed fruits, vegetables, cut flowers, and dried flowers have also been picking up. India is required to increase the production of horticultural crops looking to increasing population and changing food habits up to 750.0 - 800.0 million tonnes by 2047 from the current level of 369.05 million tonnes. On the demand side, the increasing purchasing power and more working women have positive impact on the changes in lifestyle and food consumption habits of the Indian population. The National Sample Survey (NSS) suggests that there has been a significant decline in per capita cereal consumption since the early1970s. Thus, using a 30-day reference period for food consumption, the average monthly per caput cereal consumption in urban areas of India appears to have fallen from 12.0 kg in 1972-73 - 8.0 kg in 2022-23 and the corresponding rural figures are 13.40 and 15.26 kg during 1970 reduced to 9,40 kg per person on monthly basis. The major reasons for decline in consumption of cereals are: 1, economic growth: increased incomes allow for richer, more varied diets;2, lifestyle changes: more availability of processed foods and on-the-go options; dietary diversification: increased consumption of protective fresh foods in form of vegetables, fruits and animal products; 4, policy and awareness: while less direct, awareness of

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nutritional needs and dietary shifts plays a role**.**

It is estimated that to fulfil the increased demand for high-value horticultural crops in South Asia, the production of these crops must be increased by around 200 per cent by 2050.

Rapidly the growing demand for horticultural products especially burgeoning market for processed fruits and vegetables as well as booming floriculture market is evidence of the scope for accelerating horticultural growth in our country. Consequently, horticulture is set to assume a greater role and importance within the agriculture sector and eventually in the national economy. As a result of a number of thoughtful research, technological and policy initiatives and inputs, horticulture in India, today, has become a sustainable and viable venture for the small and marginal farmers. It is a matter of satisfaction that their food consumption levels and household income have increased. Besides, sector has also started attracting entrepreneurs for taking up horticulture as a commercial venture. Therefore, there is great scope for accelerating agricultural development through expansion of horticultural crops.

Thus, India's horticulture sector has moved from being a "diversification option" to a **core growth engine** for farm incomes, nutrition, jobs, and agro-industry. Two headline indicators show the scale of transformation:

- **Production:** Horticultural output rose from **280.70 million tonnes (2013–14)** to **369.05 million tonnes (2024–25**, including **114.51 million tonnes fruits** and **219.67 million tonnes vegetables**.
- **Economic weight:** Horticulture contributes about **33% of agriculture GVA** (despite a much smaller share of cropped area than cereals).

This transformation is not accidental. It is the cumulative outcome of seven decades of **research investments to coordinated networks in mission-mode development with private innovation to extension and markets**.

Evolution of Horticulture R&D since Independence

Early foundations (1947–48 to late 1960s): germplasm, basic crop improvement, institutional building

Post-independence R&D initially focused on food security staples, but horticulture research quietly built its foundations through:

- **Germplasm collection and conservation**
- Plant introduction and evaluation
- Early work on crop improvement and plant protection
- Nursery systems and orchard management

A landmark was the establishment of **ICAR–Indian Institute of Horticultural Research, Bengaluru, (ICAR-IIHR)** in **1967** (shifted to Bengaluru in 1968), widely seen as the first major national institute dedicated to horticulture research.

Potato and tuber research also became organized early, notably through **ICAR–Central Potato Research Institute (CPRI)**, established in **August 1949** (Patna) and shifted to Shimla in 1956.

Network era (1970s–1990s): coordinated projects and commodity institutes

From the 1970s onward, India expanded from "single institutes" to **national coordinated networks**. For example, the **AICRP on Fruits** traces its early expansion to **the early 1970s** and then grew into a multi-centre national evaluation and technology pipeline.

This period also saw strengthening of commodity and regional institutes (tropical/subtropical/temperate/arid horticulture; plantation crops; spices; tubers; floriculture; MAPs), and stronger SAU-based research capacity (breeding, agronomy, plant protection, post-harvest).

Mission-mode scaling (2000s–2010s): NHM to MIDH, plus value chain infrastructure

A major "R&D-to-adoption accelerator" arrived with the **National Horticulture Mission (NHM)**, launched in **2005–06** as a centrally sponsored scheme to scale quality planting material, productivity technologies, and post-harvest systems.

In **2014–15**, India consolidated and broadened this approach through the **Mission for Integrated Development of Horticulture (MIDH)**, subsuming multiple horticulture schemes and pushing a more integrated value-chain lens.

2020s: biosecurity, quality planting material, clusters, and "tech + logistics" integration

In the last few years, the R&D agenda has shifted decisively toward:

- Disease-free, traceable planting material systems
- Export-readiness (SPS compliance, packhouses, cold chain, protocols)
- Climate resilience + resource efficiency
- Mechanization, sensors, digital advisories
- Commercialization and startup pathways

Concrete examples include:

- **Clean Plant Programme (CPP):** creation of a national disease-free planting material backbone (clean plant centres + quarantine).
- **Centres of Excellence + cluster development:** demonstration + training hubs and cluster-based value chain strengthening.

The current R&D architecture in Horticulture

India's horticulture R&D ecosystem is best understood as a **multi-layered pipeline**:

National Research System (NARS)

- **ICAR institutes** (core science + national coordination; breeding, production, protection, post-harvest, mechanization)
- **AICRPs/Network projects** (multi-location testing, varietal pipelines, regional recommendations)
- **Krishi Vigyan Kendras (KVKs)** for adaptive trials and last-mile extension (via ICAR-ATARI network)

ICAR's institute listings show multiple horticulture-science institutes (e.g., IIHR, CIAH, CITH, CISH, etc.) and allied engineering/post-harvest institutes supporting horticulture value chains.

State Agricultural Universities (SAUs) + Central Agricultural University system

- breeding programme for region-specific hybrids/varieties
- agronomy and IPM packages
- protected cultivation and precision horticulture modules
- post-harvest and processing innovations at state level

Development missions as "scale-up engines" in Horticulture

- **MIDH** finances and mainstreams tech adoption (nurseries, micro-irrigation, protected cultivation, packhouses, cold chain, etc.).

Private sector and startups

- hybrids, tissue culture planting material, fertigation solutions
- packhouse/cold chain tech, ripening, coatings, packaging
- digital platforms, traceability, and quality analytics What horticulture R&D has delivered Production and productivity outcomes (macro impact)
- Total horticulture production: **369.05 Mt (2024–25)**
- Productivity (all horticulture): **12.10 t/ha (2019–20) → 12.56 t/ha (2024–25)**

These gains are tightly linked to:

- improved genetics and planting material
- micro-irrigation + fertigation
- protected cultivation and season extension
- IPM and better diagnostics
- post-harvest systems that reduce economic loss and expand market windows

Genetic improvement and varietal pipelines (breeding → adoption)

A visible marker of the breeding pipeline is the periodic release of improved varieties/hybrids. For example, the Government/ICAR system publicized **109 varieties across 61 crops released in August 2024**, including **horticultural crops**.

Direction of R&D in genetics (typical focus areas):

- high yield + quality traits (TSS, firmness, color, shelf life)
- pest/disease resistance (viral complexes in vegetables; wilt complexes; fruit flies; nematodes)
- climate resilience (heat tolerance, drought tolerance, salinity tolerance)
- processing suitability (chips/fry-grade potato; dehydration-grade onion; paste-grade tomato; spice oleoresin suitability)

Quality Planting Material as a national priority: nurseries → clean stock → quarantine

A decisive shift in the 2020s is treating planting material like "seed security":

- The **Clean Plant Programme** is designed to supply **disease-free, authentic planting material** at national scale. Government communications indicate **9 clean plant centres** planned, with examples like Maharashtra's centres (grapes/oranges/pomegranate) highlighted for investment scale.

This matters because horticulture yield ceilings are often set by:

- latent viruses/viroids
- systemic bacterial/fungal infections
- nursery-level contamination and varietal admixtures

Clean plant systems + quarantine infrastructure are essentially "biosecurity R&D translated into infrastructure."

Post-harvest, value-addition, and loss reduction (R&D meets logistics)

Post-harvest losses remain a major drag, but India now has clearer measurement and a larger technology toolkit.

- Government-cited ranges (based on ICAR-CIPHET and later studies) show losses of **~6–15% in fruits** and **~5–12% in vegetables** (ranges vary by commodity and supply chain).

To address this, the development system has scaled infrastructure alongside R&D:

- Over the past five years, under MIDH, **55,748 post-harvest management facilities** and **11,140**

marketing infrastructure units were reported established.

Core R&D-to-adoption domains here include:

- maturity indices and harvest protocols
- packhouse engineering, grading, precooling, ripening systems
- improved packaging, coatings, and shelf-life extension
- reefer logistics, cold rooms, CA storage for select crops
- primary processing: drying, pulping, minimal processing, IQF, dehydration (where viable)

Export readiness: protocols, SPS, and market-linked R&D

Exports are the "stress test" of horticulture R&D because they demand consistent quality + residue compliance + cold chain discipline.

- APEDA reports that during **2024–25**, India exported **fresh fruits and vegetables worth USD 1,818.56 million**.

Export-linked R&D priorities typically include:

- GAP and traceability systems
- residue management packages and lab testing
- irradiation/vapour heat/hot water treatments where required
- protocol development for specific fruit fly / pest pathways
- varietal selection for long-distance shipping (firmness, shelf life)

Milestones in research and development of horticultural crops after Independence in India

- 1947 Rubber Board was established under Ministry of Commerce and Industry through Rubber Board Act-1947 at Kottayam, Kerala.
- 1949 Central Vegetable Breeding Station at Kullu Valley was established, for seed production of temperate vegetable crops.
- 1956 Central Potato Research Institute initially established at Patna later shifted to Shimla, Himachal Pradesh.
- Kufri Ganga-late blight resistant, Kufri Neelkanth-purple colour and Kufri Lima-early,tolerant to hopper and mite burn are some promising varieties developed by CPRI.
- 1954 Establishment of Tea Board in Kolkata under Ministry of Commerce and Industry through Central Tea Board Act 1953.
- 1956 Division of Horticulture at IARI established.
- 1958 Coorg Honey Dew 1st gynodioecious variety of papaya was released.
- Establishment National Agricultural Co-operative Marketing Federation at New Delhi.
- 1963 Central Tuber Crops Research Institute was started at Thiruvananthapuram, Kerala for research on crop improvement in tuber and root crops.
- Sree Harsha, Sree Athulya and Sree Apoorva triploid and high yielding cassava varieties were developed.
- 1966 Directorate of Cashew nut and Cocoa Development was established at Cochin, Kerala.
- Establishment of Directorate of Arecanut and Spice Research at Calicut, Kerala.
- 1967 Establishment of Indian Institute of Horticultural Research at Bengaluru with major focus on fruits and vegetable crop improvement.
- 1968 AICRP on Tuber Crops was started for research networking and extension activities in root and tuber crops.
- Kufri Jyothi variety of potato was released for commercial cultivation, which is still grown on a large area.
- 1970 Division of Fruits and Horticultural Technology was created at IARI.Release of Pusa Seedless grape variety.
- Pomegranate variety Ganesh was released by GKFRS, Pune.
- 1971 Initiation of All India Coordinated Vegetable Improvement Project (AICVIP).
- AICRP on Fruits was initiated to work on mango, grape, citrus, banana, papaya and pineapple.
- AICRP on Floriculture was established to carry out nation-wide interdisciplinary research by linking SAUs with ICAR institutes. Later upgraded to Directorate of Floricultural Research.
- AICRP on Spices was initiated at IISR, Kerala.
- Mallika-1st regular bearing mango variety was released by IARI.
- 1st Public sector hybrid in vegetable crops Pusa Manjari and Pusa Meghadoot of bottle gourd was released for commercial cultivation.
- 1972 The Central Institute for Subtropical Horticulture (CISH) was started as Central Mango Research Station at Lucknow, Uttar Pradesh.
- 1973 First release of private sector hybrids in tomato (Karnataka) and capsicum (Bharat) to the farmers by M/s Indo-American Hybrid Seeds, Bengaluru.
- 1974 Central Plantation Crops Research Institute (CPCRI) was established at Kasaragod, Kerala.
- VTLAH1, VTLAH2 and VTLAH3 early, dwarf and high yielding arecanut hybrids were developed.
- 1977 Establishment of National Horticultural Research and Development Foundation by National Agricultural Co-operative Marketing Foundation at New Delhi.

- 1979 Amrapali-mango variety suitable for HDP was released by IARI
- 1981 Coconut Board was established through Coconut Development Act-1979
- 1984 National Horticulture Board (NHB) was set up by Government of India on the basis of recommendations of the "Group on Perishable Agricultural Commodities", headed by Dr. M.S. Swaminathan.
- 1985 National Research Centre on Citrus was founded at Nagpur.
- Parbhani Kranti variety of okra resistant to YVMV was released which revolutionized
- okra cultivation in India.
- 1986 Project Directorate of Vegetable Research was created at IARI.New Delhi
- Directorate of Cashew research was founded with headquarters at Puttur, Karnataka.
- 1987 Spice Board was constituted under Spice Board Act-1986 with Headquarters at Kochi,Kerala.
- 1992 PDVR headquarters was shifted to Varanasi from IARI New Delhi.
- 1993 Establishment of National Research Centre on Banana, Udhayam (ABB) variety was released in 2005
- 1994 Establishment of National Research Centre for Onion and Garlic at Nasik, later in 2008 upgraded as Directorate of Onion and Garlic Research and shifted to Pune.
- Central Institute for Temperate Horticulture was established at Srinagar, to carryout research activities in temperate horticultural crops.
- 1996 Establishment of National Research Centre on Orchids at Gangtok, Sikkim.
- First Nematode resistant variety of tomato Pusa-120 was released by IARI.
- 1997 Establishment of National Research Centre on Grapes at Manjri, Pune. Manjari Medika and Manjari Naveen are some promising varieties were released in 2017.
- 1998 Centre for Protected Cultivation Technology was created IARI, to demonstrate technologies of protected cultivation in horticultural crops.
- 1999 Indian Institute of Vegetable Research was established at Varanasi, Kashi Krishna BlackCarrot variety was released.
- 2000 National Research Centre on Seed Spices was established at Ajmer.
- NRC on Arid Horticulture was elevated to full-fledged Institute as Central Institute for Arid Horticulture (CIAH), Bikaner, Rajasthan.
- Maru Samridhi new Lasoda and Maru Gaurav new Karonda, Goma Kirti in Ber varieties were developed.
- 2001 Establishment of National Research Centre on Litchi at Muzaffarpur, Bihar. Gandaki Sampada and Gandaki Lalima are promising varieties released.
- 2004 Arka Kalyan onion variety was released by IIHR, Bengaluru.
- 2005 Establishment of National Research Centre on Pomegranate, Solapur, Maharashtra.
- 2006 To recognise the scope for development of horticulture in NE region, Central Institute of Horticulture was established at Medziphema, Nagaland.
- 2013 India's first triple disease resistant tomato F1 hybrid Arka Rakshak was released for commercial cultivation.
- 2015 1st Biofortified variety of cauliflower Pusa Beta Kesari was released by IARI-RRS Katrain which is rich in β-carotene.
- 2017 Promising biofortified variety of pomegranate 'Solapur Lal' was released rich in Zn, Fe, Vit C and anthocyanins was released by NRC on Pomegranate.
- Biofortified Sweet potato Bhu Krishna (rich in anthocyanins), Bhu Sona (rich in β-carotene) were released by CTCRI-RRS Bhubaneswar.

The major landmarks of research in horticulture that supported the growth of the horticulture sector in this country include the following.

- Advanced propagation techniques have been developed in case of fruit crops (tissue culture with virus indexing in banana, shoot tip grafting etc

Horticulture R&D matters more now than ever.

Funding signals: Agricultural Research Capacity

Horticulture R&D is anchored within the broader national agri-research budget. India's **DARE/ICAR** allocations (Demand No. 2) are detailed in the Union Budget documents and show continued multi-year support at the scale of **~₹9,900–10,150 crore (2024–25 BE/RE ranges)** for DARE, with ICAR HQ as the major component.

(For horticulture specifically, the policy implication is that **prioritization**—not only total funding—matters: clean plant systems, diagnostics, protected cultivation packages, and post-harvest engineering are currently the "highest return" R&D bets.)

The unfinished agenda (2025 onward): where India's horticulture R&D must go to next levels

Even with production gains, the next phase is about **value per kg**, **loss avoided**, **quality consistency**, and **climate robustness**.

Top R&D priorities emerging from the 2020s trajectory:

Decade-wise timeline of key R&D and policy accelerators (high-level)

Decade	R&D / institutional milestones	Adoption & value-chain thrust
1950s–60s	Organized commodity research expands; IIHR established (1967).	Early orchard systems, nurseries, basic post-harvest handling
1970s–80s	Coordinated projects scale (e.g., AICRP Fruits roots in early 1970s).	Region-specific recommendations, expansion of area under horticulture
1990s	Stronger focus on hybrids, protected cultivation pilots, IPM, tissue culture	Early private seed/material sector growth, peri-urban vegetable intensification
2000s	NHM launched (2005–06).	Scale-up of nurseries, rejuvenation, post-harvest support begins
2010s	MIDH implemented from 2014–15.	Integrated value-chain approach: micro-irrigation, protected cultivation, cold chain
2020s	Clean Plant Programme + cluster development + export readiness focus.	Disease-free planting material backbone, packhouse/logistics expansion, digitalization

Biosecurity and clean stock at scale

- National clean plant centres + quarantine modernization
- Rapid diagnostics, certification, traceability in nurseries

Climate-resilient horticulture packages

- Heat stress, erratic winters, extreme rain events: new PoPs + varieties
- Protected cultivation that is energy-efficient and affordable

Post-harvest engineering as "income insurance"

- Commodity-specific packhouse protocols
- Cold chain optimization, packaging science, low-cost ripening and storage
- Targeted loss reduction where losses are highest (fruit/veg ranges remain significant).

Export-grade quality systems

- Residue compliance, labs, SPS pathways, protocol R&D
- Varieties and handling for long-distance shipping
- Export growth opportunity is real (fresh F&V export value in 2024–25 is sizeable).

Digital horticulture

- Remote sensing for orchard health, pest forecasting
- Advisory systems linked to clusters, FPOs, packhouses
- Traceability that is lightweight enough for smallholders

India's modern horticulture R&D focused on **intensified technology adoption (AI, IoT, automation), strengthening value chains (MIDH, CDP), promoting sustainable practices, and enhancing farmer incomes through better planting material (Clean Plant Programme) and infrastructure**. Key R&D areas include **smart farming systems, protected cultivation, biotechnology, post-harvest management (cold chains), and disease-free propagation**, driving significant production increases and improved productivity for enhanced nutrition and exports, with strong government backing via programs like MIDH (Mission for Integrated Development of Horticulture) and NHB (National Horticulture Board).

Key Focus Areas & Initiatives:

- **Technology Integration:** Use of AI, IoT sensors in smart greenhouses, robotics for harvesting, hydroponics, and aeroponics for higher yields.
- **Value Chain Development:** The Cluster Development Programme (CDP) strengthens pre-production, post-harvest, logistics, and marketing for competitive clusters.
- **Quality Planting Material:** The Clean Plant Programme (CPP) ensures disease-free saplings, crucial for productivity, with focus on diagnostics and nursery certification.
- **Water & Resource Efficiency:** Promoting micro-irrigation and water conservation techniques.
- **Farmer Empowerment:** Encouraging farmer producer organizations (FPOs) and skill development for rural youth in cold chains.
- **Sustainable and Organic Practices:** Support for organic farming and bio-inputs.

Achievements and Trends by 2025:

- **Production Growth:** Horticulture production exceeded 360 million tonnes, with significant increases in fruits and vegetables.
- **Productivity Gains:** Output per hectare rose due to better planting material and water use, reaching over 12.5 MT/hectare for horticulture overall.
- **Economic Impact:** Contributes ~33% to the agricultural GVA, boosting farmer income and employment.

- **Innovation Hubs:** Events like HortiConnect India 2025 and Indian Horticultural Congress (IHC) 2025 showcased advancements in tech and global collaborations.

Government Support:

- **MIDH (Mission for Integrated Development of Horticulture):** Supports holistic growth through research, tech promotion, irrigation, and market development.
- **NHB (National Horticulture Board):** Oversees programs like CDP and promotes scientific practices.

India's horticulture R&D at present time is characterized by a strong push towards smart, sustainable, and integrated systems, leveraging technology and policy to achieve higher productivity, better farmer livelihoods, and enhanced food security.

Improved varieties and hybrids of horticultural crops have played pivotal role in augmenting fruits and vegetables production for nutrition and augmenting income. ICAR has released 1,600 high yielding varieties and hybrids of horticultural crops (fruits, vegetables, ornamental plants, plantation and spices, medicinal and aromatic plants and mushrooms), which has made tremendous contributions in record production of 369.05 Mt (2024-25) from this sector. To boost the exports, good agricultural practices (GAP) and quality standards have been developed for apple, mango, grape, banana, orange, guava, litchi, papaya, pineapple, sapota, onion, potato, tomato, pea and cauliflower. The sea route transport protocols for banana and mango have been standardized to reduce the transportation cost in export. Improved techniques for production of disease-free quality planting material have been developed for citrus, banana, guava, potato, cassava and sweet potato. Micro propagation techniques have been standardized for various fruits, spices and other vegetative propagated plants and has been widely utilized for rapid and mass multiplication of various species. India is blessed with floral diversity, and Uttarakhand, Sikkim and Arunachal Pradesh are identified as cradle of flowering plants. Hybrids in vegetables have revolutionized vegetable production in the country, making it the second largest vegetable producer in the world, and increasing Indian Agriculture: Achievements and Aspirations of nutritional security. Highly productive hybrids have been developed in coconut, mango, ber, aonla and other fruits. India is the world leader in mango and in development and production of hybrid mango varieties. A series of hybrids with high productivity, attractive fruit size, colour, aroma and quality, regular bearing and suitable for varying orcharding designs and intensities have fortified country's leadership in the mango world. In vitro culture technique has revolutionized banana yield and production in the country. Today, 50.0 % of banana area in the country is planted to tissue-cultured plantlets. India is the largest producer of pomegranate in the word with nearly 80-90% of present area under Bhagwa and Super Bhagwa variety. Pomegranate export earnings increased from Rs. 21 crores (2003-04) to Rs. 688 crores (2021-22). Grape is one of the important export-oriented fruit crops of India. With the adoption of dogridge rootstock for raising grape crops, the productivity and profitability have increased significantly. Large-scale propagation and popularization of Kamalam (dragon fruit) have resulted in speedy adoption of this exotic fruit. Horticulture revolution hinges on the availability of quality planting material, which has been enhanced several folds in recent years.

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Vegetable Improvement in India: Current Statues, Challenges, and Future Prospects for Stress Tolerance and Biofortification

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Abstract

Recent advancements have focused on enhancing productivity, shelf-life, and processing suitability while addressing nutritional deficiencies through biofortified vegetables rich in vitamins, minerals, and antioxidants. Despite significant progress, vegetable production faces major challenges, including climate variability, heat and drought stress, emerging pests and diseases, declining genetic diversity, limited access to quality seed, and inadequate adoption of modern production technologies. Indigenous and underutilized vegetables remain largely unexplored, despite their resilience and nutritional potential. Emerging tools in genomics, molecular breeding, phenomics, and biotechnology offer unprecedented opportunities to accelerate genetic gains for stress tolerance and nutritional enhancement. Integrating conventional breeding with marker-assisted selection, genomic selection, and gene editing is expected to transform vegetable improvement programs. Future strategies must prioritize climate-smart varieties, biofortification, conservation and utilization of genetic resources, and strong seed delivery systems to ensure sustainable vegetable production and improved dietary quality. Strengthening research–extension–farmer linkages will be critical to translating scientific advances into tangible benefits for farmers and consumers alike. Vegetables gained importance in the Indian daily diet to ensure food and nutritional security, rural livelihoods, and agricultural diversification. India is the world's second-largest vegetable producer, contributing nearly 15% of global production, with sustained growth driven by improved varieties and hybrids, and expanding market demand. Public sector institutions, particularly the Indian Council of Agricultural Research and State Agricultural Universities, have played a pivotal role in developing high-yielding, pest- and disease-resistant, and climate-resilient vegetable cultivars

Vegetables play a vital role in India's socio-economic structure, nutritional security, and agricultural diversification. Traditionally cultivated in home gardens for household consumption, vegetable farming in India has evolved into a dynamic, market-oriented enterprise supplying both domestic and international markets. With increasing awareness of health, nutrition, and income diversification, vegetables have gained prominence as high-value crops that support small and marginal farmers while contributing significantly to agricultural GDP.

The commercialization of vegetable farming accelerated with the development of improved cultivars, enhanced market infrastructure, and institutional support. Organizations such as the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs) have been instrumental in developing high-yielding, pest-resistant, and climate-resilient vegetable varieties. Although the Green Revolution primarily focused on cereals, it indirectly supported vegetable cultivation by improving irrigation, input availability, and land productivity (Singh, 2013; Sharma, 2024).

Vegetables are indispensable components of a balanced diet, providing essential vitamins, minerals, antioxidants, and protective nutrients. According to the Indian Council of Medical Research (ICMR), an average adult should consume 125 g of green leafy vegetables, 100 g of roots and tubers, and 75 g of other vegetables daily to meet nutritional requirements (Koirala, 2023). However, India's per capita vegetable intake remains below recommended levels, underscoring the need for increased production and improved accessibility.

India achieved a record vegetable production of 204.96 million tonnes during 2023–24 from approximately 11.35 million hectares, with an average productivity of 18.04 t/ha, accounting for nearly 14–15% of global vegetable production (National Horticulture Board [NHB], 2023). India ranks second globally after China, and India is the leading producer of crops such as okra, peas, and chillies, while ranking second in tomato, potato, onion, cauliflower, and brinjal production (FAO, 2022). The vegetable sector provides employment to millions and significantly strengthens rural livelihoods.

Vegetable exports have shown steady growth, with fresh and processed exports collectively valued at ₹15,511.59 crores during 2023–24. Processed vegetables have expanded more rapidly than fresh exports, driven by cucumbers, gherkins, preserved potatoes, and dried onions (APEDA, 2023). Major importing countries include the UAE, Bangladesh, Malaysia, Sri Lanka, Nepal, and the United Kingdom.

Despite substantial progress, vegetable production in India faces challenges such as climate variability, pest and disease pressure, germplasm erosion, inadequate infrastructure, and limited farmer awareness of modern production technologies. Indigenous and underutilized vegetables remain largely neglected, despite their

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nutritional richness and adaptability to marginal environments (Ebert, 2014). Advances in genomics, molecular breeding, phenomics, and biotechnology are now transforming vegetable improvement strategies (Priyanka & Lakshmi, 2019; Manjunathagowda et al., 2023). In 2024, the official notification of 70 new vegetable varieties and hybrids highlights the strong momentum in Indian vegetable research. The released varieties offer a critical opportunity to enhance productivity, resilience, and nutritional quality, positioning vegetables at the core of sustainable agriculture and national food security.

Challenges In Vegetable Crops

Breeding for combined resistance or tolerance to multiple diseases key avenues to improve vegetable crop productivity. In tomato, durable resistance to tomato leaf curl disease is achieved by pyramiding multiple resistance genes (*Ty-1/Ty-3, Ty-2, ty-5, ty-6*) into backgrounds already resistant to fungal and bacterial diseases (Hanssen et al., 2010; Vidavski et al., 2008). In chilli, resistance to leaf curl virus must be combined with resistance to *Phytophthora capsici*, *Colletotrichum* spp., and tolerance to thrips to ensure stable field performance (Rai et al., 2014). In brinjal, breeding priorities include developing fruit rot resistance while maintaining bacterial wilt resistance, as both diseases severely limit yield (Singh et al., 2018). Okra improvement requires pyramiding resistance to major viral diseases such as yellow vein mosaic virus (YVMV), okra enation leaf curl virus (OELCV), and tobacco streak virus (TSV), which frequently occur together and cause heavy losses (Venkataravanappa et al., 2016).

Cucurbit crops also demand integrated resistance breeding. Watermelon and muskmelon improvement should target combined resistance to Fusarium wilt, gummy stem blight, and viral or downy mildew diseases, while cucumber breeding must focus on resistance to downy mildew, powdery mildew, and gummy stem blight (Lebeda et al., 2011). Resistance to mosaic viruses is crucial in squash and pumpkin, whereas leaf curl virus resistance is a major priority in gourds, especially ridge and bitter gourd.

In legumes such as beans and peas, resistance to rust and powdery mildew is essential, and achieving durable multi-disease resistance requires coordinated pre-breeding efforts carried out in a network mode (Singh & Schwartz, 2010).

Progress and Future Perspectives of Stress Tolerance

On 11 August 2024, the Hon'ble Prime Minister of India, Shri Narendra Modi, formally released 109 improved varieties of field and horticultural crops at Pusa, New Delhi, marking a significant milestone in India's agricultural research and innovation ecosystem. These varieties were developed through sustained efforts of the Indian Council of Agricultural Research (ICAR), State Agricultural Universities (SAUs), and allied research institutions across the country. The released varieties represent 61 different crops, comprising 34 field crops and 27 horticultural crops, covering vegetable crops. The newly released cultivars incorporate key traits such as higher yield potential, enhanced nutritional quality, and tolerance to biotic and abiotic stresses presented in Table 2 (ICAR, 2024). This landmark release underscores the

Table 1: Major traits to be focused in breeding of vegetable crops

Crop	Key Traits / Breeding Focus
Tomato	Resistance to bacterial wilt, tomato leaf curl virus, and heat stress
Brinjal	Resistance to bacterial wilt and Phomopsis fruit rot
Chilli	Tolerance to leaf curl disease, heat stress, and anthracnose fruit rot
Capsicum	Resistance to soil-borne diseases and development of male-sterility–based hybrids
Onion	Kharif-season suitability, resistance to purple blotch and twister diseases, improved shelf life
French bean	Resistance to rust and yellow mosaic virus; tolerance to high temperature
Dolichos bean	Lack of photo-thermo–insensitive varieties in suitable market segments
Cucumber	Resistance to downy mildew
Moringa	Non-availability of varieties suitable for high-density planting
Curry leaf	Lack of high-aroma, high-density–suitable varieties
Cluster bean	Absence of varieties suitable for year-round cultivation
Gourds (pointed & teasel)	Low multiplication rate and lack of high-yielding varieties
Ridge gourd	Non-availability of high-yielding public-sector varieties suitable for Odisha
Watermelon	Development of icebox types with dark green rind and red flesh
Radish	Tolerance to high-temperature conditions
Leafy vegetables	Limited availability of diversified leafy vegetable varieties

Government of India's commitment to strengthening farmers' income, food and nutritional security, and sustainable agricultural development highlights India's growing leadership in crop improvement and its strategic focus on innovation-driven, climate-smart agriculture.

This landmark release reflects India's strategic focus on climate-resilient and nutrition-sensitive agriculture, demonstrating effective translation of research outputs

Table 2: Prominent vegetable varieties / hybrids released against to the different stresses

Crop	Variety / Hybrid	Type	Developed by	Recommended regions	Characteristics	Yield potential
Tomato	Pusa Shakti	Open-pollinated variety	ICAR–Indian Agricultural Research Institute (IARI), New Delhi	Chhattisgarh, Odisha, Andhra Pradesh, Telangana	Suitable for open-field cultivation (May–October); thick pericarp (~6 mm); moderate TSS (4.8 °Brix); good lycopene content; **tolerant to high temperature;** good transportability	~351 q/ha
Tomato	Pusa Tomato Hybrid 6	Hybrid	ICAR–Indian Agricultural Research Institute (IARI), New Delhi	Chhattisgarh, Odisha, Telangana, Andhra Pradesh	**Resistant to ToLCD, Fusarium wilt, and bacterial wilt;** heart-shaped fruits (80–90 g); thick pericarp (~0.5 cm); TSS >4.5 °Brix; high lycopene (~9.5 mg/100 ml juice); suitable for kharif and rabi (130–150 days)	900 q/ha (kharif); 600 q/ha (rabi)
Bottle gourd	Kashi Shubhara	Open-pollinated variety	ICAR–Indian Institute of Vegetable Research (IIVR), Varanasi	Uttar Pradesh, Bihar, Jharkhand, Punjab	**Suitable for kharif and zaid seasons; performs well under low tunnel/protected cultivation**; light green, smooth, cylindrical fruits (28–30 cm); good keeping quality; suitable for export	~600 q/ha
Indian bean	Kashi Bouni (Sem-207)	Open-pollinated variety	ICAR–Indian Institute of Vegetable Research (IIVR), Varanasi	Punjab, Uttar Pradesh, Bihar, Jharkhand, Rajasthan, Gujarat, Haryana, Delhi	Bushy growth (≈60 cm); first picking at 90–95 DAS; pods 8–10 cm long and 2.5–2.8 cm wide; **tolerant to YMV and high temperature**	~236 q/ha (5 pickings)
Indian bean	Arka Vistar	Open-pollinated variety	ICAR–Indian Institute of Horticultural Research (IIHR), Bengaluru	Karnataka	**Climate-resilient; pole-type; photo-insensitive**; long, thick, broad green pods	~37.0 t/ha
Muskmelon	Thar Mahima	Open-pollinated variety	ICAR–Central Institute for Arid Horticulture (CIAH), Bikaner	Rajasthan	Round fruits (780–900 g); high TSS (~11.8 °Brix); salmon-orange flesh; well-netted fruits with sutures; **tolerant to high temperature and arid conditions**	~200 q/ha
Potato	Kufri Bhaskar	Vegetatively propagated, self-pollinated	ICAR–Central Potato Research Institute (CPRI), Shimla, Himachal Pradesh	Haryana, Punjab, plains of Uttarakhand, Uttar Pradesh (early season planting); Central plains of Rajasthan, Gujarat, Chhattisgarh (main planting)	**Heat-tolerant variety** with **moderate leaf burn tolerance;** early- to medium-maturing (85–95 days); produces white-cream tubers with shallow to medium eyes and cream-coloured flesh; good keeping quality under ambient conditions	30–35 t/ha

into farmer-ready technologies. Stress-tolerant vegetable varieties help stabilize productivity under adverse environments, reduce crop losses, and lower dependence on chemical inputs, thereby improving farm profitability and environmental sustainability (Priyanka & Lakshmi, 2019). The inclusion of nutritionally enriched cultivars also highlights the growing convergence of stress tolerance and biofortification as complementary breeding objectives aimed at improving dietary quality and public health (Koirala, 2023).

Looking ahead, future progress in vegetable stress tolerance breeding will increasingly depend on genomics-assisted breeding, marker-assisted selection, high-throughput phenotyping, and gene-editing approaches, combined with effective utilization of indigenous and underutilised vegetable germplasm (Ebert, 2014; Manjunathagowda et al., 2023). Strengthening germplasm conservation, seed delivery systems, and research–extension–farmer linkages will be critical for scaling the impact of these innovations. Overall, the 2024 variety release underscores the Government of India's strong commitment to enhancing farmers' income, food and nutritional security, and sustainable agricultural development, while reinforcing India's leadership in innovation-driven, climate-smart vegetable crop improvement.

Perspectives of Biofortified Vegetable Crops

Biofortification of vegetable crops in India is an effective strategy to combat micronutrient deficiencies and improve dietary quality by enhancing nutrient content through breeding, biotechnology, and agronomic approaches (HarvestPlus, 2019). Vegetables are ideal targets for biofortification due to their wide consumption and natural richness in vitamins, minerals, and antioxidants (Yadava et al, 2018). Nutrient-enriched vegetables contribute to improved human growth, metabolism, and overall well-being, as many essential nutrients cannot be synthesized by the human body (WHO, 2021). Biofortification delivers nutrients in natural food matrices, improving bioavailability and reducing anti-nutritional factors (Bouis & Saltzman, 2017). In addition to nutritional benefits, biofortified vegetables often show enhanced plant vigor, stress tolerance, and yield stability (Yadava et al, 2022).

Thus, vegetable biofortification supports both nutritional security and sustainable agricultural production in India (Global Nutrition Report, 2020). The Indian Council of Agricultural Research (ICAR) has played a key role in promoting biofortification, with increasing emphasis on vegetable crops alongside staple foods. Ongoing programs aim to integrate biofortified vegetables into national nutrition initiatives, such as Poshan Abhiyaan, and encourage farmer adoption through quality seed availability, subsidies, and policy support, thereby strengthening food and nutritional security in India (Yadava et al 2022).

More than two billion people worldwide suffer from deficiencies of essential vitamins and minerals due to limited access to diverse, nutritious diets, biofortified foods. This "hidden hunger" leads to increased children, and higher maternal mortality risks. In India, it is severe; (Global Nutrition Report 2020), highlights that 52% of women aged 15–49 are anaemic, (Thakkar et al 2023).

Crop biofortification complements this approach by genetically enhancing nutrient-rich crops such as iron, zinc, protein-rich and vitamin A–rich vegetables in the diet. Special efforts to popularize biofortified varieties among the masses include awareness campaigns, farmer training programs, demonstration trials, and inclusion in government nutrition schemes. These initiatives highlight their nutritional benefits, yield potential, and affordability, encouraging adoption by farmers and acceptance by consumers to combat micronutrient malnutrition effectively.

The effectiveness, cost-efficiency, and positive impact of biofortified crops, providing valuable evidence to support large-scale adoption, which in turn effectively addresses hidden hunger, with proven improvements in micronutrient status, health, and cognitive and physical performance among women, adolescents, and children (NITI Aayog 2022). The conventional breeding can enhance nutrient content without affecting yield or consumer-preferred traits, farmers readily adopt biofortified crops. In India, biofortified crops such as iron, zinc, calcium and vitamins rich vegetables are being bred to reduce micronutrient deficiencies through regular consumption.

Biofortified vegetables included cauliflower (1 variety), potato (2 varieties), sweet potato (2 varieties), and greater yam (2 varieties), enriched with essential nutrients to enhance dietary quality and address micronutrient deficiencies (Yadava et al., 2022).

Biofortification ease for :

- Sustainable and cost-effective approach to combat malnutrition.
- Provides nutrients in natural form within the food matrix.
- Affordable to consumers with no additional market cost.
- High-yielding like traditional varieties, ensuring no yield loss to farmers.
- Requires no elaborate infrastructure or distribution

Table 3: Prominent public sector biofortified vegetable crops varieties identified and released in India

Institute	Crop	Name of the Variety	Category	Biofortified traits
IARI	Cauliflower	Pusa Beta Kesari 1	Pure line variety	Provitamin-A 8.0-10.0 ppm
IARI	Cauliflower	Pusa Purple Cauliflower		Anthocyanin
IARI	Carrot	Pusa Asita	Variety	Anthocyanin
IARI	Carrot	Pusa Rudhira	Variety	High carotenoid (7.41 mg per 100g)
IARI		Kashi Krishna	Variety	Rich in anthocyanins (275–300 mg/100g FW),
IARI	Radish	Pusa Gulabi	Variety	High total carotenoids, Anthocyanin
IARI	Radish	Pusa Jamuni	Variety	Anthocyanin
IARI	Amaranth	Pusa Lal Chaulai	Variety	Anthocyanin
CPRI	Potato	Kufri Manik	Variety	Anthocyanin 0.68 ppm
CPRI	Potato	Kufri Neelkanth	Variety	Anthocyanin 1.0 ppm
CPRI	Potato	Kufri Jamunia	Variety	Anthocyanin
CTCRI	Sweet Potato	Bhu Sona	Variety	Provitamin-A 14.0 mg/100g
CTCRI	Sweet Potato	Bhu Krishna Sree Kanaka	Variety	Anthocyanin 90.0mg/100g high beta carotene
CTCRI	Greater Yam:	Sree Neelima	Variety	Anthocyanin 50 mg/100g Protein 15.4 % Zinc 49.8 ppm
CTCRI	Greater Yam	Da 340	Variety	Anthocyanin (141.4 mg/100g) Iron (136.2 ppm) Calcium (1890 ppm)
CTCRI	Tapioca	Sree Visakham	Variety	Carotene content in tubers is 466 IU 100gm-1
IIHR	Watermelon	Selection -4	Variety	*b*-carotene
KAU	Watermelon	Swarna	Hybrids	Beta-carotene content varied from 0.037 to 7.423 µg/g,
IIVR	OKRA	Kashi Lalima	Variety	Anthocyanin

systems.

- Eliminates additional costs for food enrichment or supplementation.

Conclusion

Vegetable improvement in India has made substantial progress in recent decades, contributing significantly to food and nutritional security, rural livelihoods, and agricultural sustainability. Advances in conventional breeding via varieties and hybrids development, and genomics-assisted approaches have enabled the development of high-yielding, stress-tolerant vegetable varieties adapted to diverse agro-climatic regions. Public sector institutions, particularly ICAR and State Agricultural Universities, have played a pivotal role in addressing key production constraints, including biotic and abiotic stresses. Nevertheless, challenges such as climate change, emerging pests and diseases, limited adoption of improved technologies, and erosion of genetic diversity continue to constrain the full potential of vegetable productivity.

Micronutrient deficiencies, especially of vitamins and minerals, remain a major public health concern in India, disproportionately affecting women and children. Biofortification through vegetable crop improvement offers a sustainable and cost-effective strategy to combat hidden hunger while complementing conventional food fortification programs. Ongoing collaborative efforts among government agencies, ICAR institutes, and SAUs have demonstrated that nutrient-dense vegetable varieties can be developed without compromising yield, stress tolerance, or consumer acceptability. Integrating biofortification traits with resilience to climatic stresses ensures that nutritional gains are maintained even under adverse growing conditions.

Looking ahead, the future of vegetable improvement

in India lies in the strategic integration of climate-smart breeding, biofortification, and modern tools such as genomics, phenomics, and gene editing. Strengthening germplasm conservation, enhancing seed delivery systems, and improving farmer awareness and adoption will be crucial for translating research advances into large-scale impact. With effective policy support and coordinated implementation, stress-tolerant and biofortified vegetable crops have the potential to significantly reduce malnutrition, enhance farm incomes, and improve the health and well-being of millions, thereby reinforcing the role of vegetables as a cornerstone of sustainable and nutrition-sensitive agriculture in India.

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Seed Systems in Vegetable Crops: Opportunities and Challenges for Ensuring the Availability of Quality and High-Yielding Seeds

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Abstract

The Indian vegetable seed market is experiencing robust growth, with a value of USD 740.70 million in 2025 and projected to reach USD 970 million by 2030, at a compound annual growth rate (CAGR) of 5.54%. This surge is propelled by the accelerated adoption of hybrid vegetable seeds, which accounted for 79.4% of the market in 2024 (Mordor Intelligence, 2025). Historically, the vegetable seed sector has evolved from a modest annual turnover of around ₹40 crore in the late 1980s, dominated by public entities and with seed replacement rates (SRR) below 25%, to a sophisticated industry exceeding ₹5,000 crore today, with SRR > 90%, driven by private-sector innovations following the Open General License (1989), which facilitated imports and in-house research. This transformation mirrors broader trends in seed systems, where formal and informal channels interplay to deliver improved genetics, though financial disparities between public and private firms underscore ongoing vulnerabilities, as evidenced by comparative analyses revealing private entities outperforming public ones in stability and innovation metrics from 2015 to 2023. In parallel, market-driven transitions in vegetable seed sectors highlight how private actors specialize in seed system functions such as variety development, production, dissemination, and use, fostering complementary roles that enhance overall sector plurality and farmer access to advanced seed types. India has solidified its position as a global horticultural hub, ranking second worldwide in vegetable production, behind China, and leading in crop yields, such as peas and okra (Anonymous, 2018). While the Dietary Guidelines for Indians (ICMR-NIN, 2024) recommend a daily vegetable intake of 400 g, the gross per capita availability is estimated at 397 g/day, based on the Third Advance Estimates for 2023-24 (Ministry of Agriculture & Farmers Welfare, 2024). However, actual consumption is often lower due to significant post-harvest losses. Underpinning this progress is a dynamic seed industry that adeptly navigates the promise of cutting-edge hybrids against persistent economic and environmental constraints. High-quality seeds, contributing approximately 20-25% to overall productivity, remain indispensable to this ecosystem.

The vegetable seed market in India is multifaceted, underscoring the preeminence of hybrid technologies and traditional cultivation practices. In breeding technology, hybrids dominate the market with a 79.4% market share, attributable to their superior yields, enhanced disease resistance, prolonged shelf life, and versatility across diverse agro-climatic zones. This hegemony aligns with global patterns observed in market-driven seed transitions, in which hybrids catalyze productivity gains by meeting farmers' demand for resilient varieties, often through public-private investments that enable the progressive adoption of hybrid over open-pollinated varieties (ter Steeg & Louwaars, 2024). Cultivation mechanisms further highlight the structure of the sector, with open-field methods commanding a staggering 99.5% share, reflecting the reliance of smallholder farmers comprising over 80% of the agricultural base on capital-efficient approaches amid economic constraints. Crop family segmentation reveals unclassified vegetables, which account for 34.2% of the market, a testament to India's diverse culinary traditions and regional preferences that prioritize adaptable, high-value produce. Regionally, Bihar stands out as the frontrunner in 2024, accounting for 13.5% of revenue, bolstered by expansive planting areas and hybrid-centric subsidy frameworks that echo successful public-private synergies in seed dissemination (Government of India, 2025). These segments not only delineate current market contours but also project a trajectory of sustained growth, informed by historical benchmarks in which private-led hybrid introductions doubled yields in key crops such as tomato, from 15 t/ha in the 1990s to 25 t/ha by 2019 (Tiku, 2023).

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Fastest-growing segments

Among the burgeoning facets of the Indian vegetable seed market, protected cultivation emerges as a vanguard, projected to grow at a CAGR of 11.1% through 2030, driven by government subsidies for greenhouses and polyhouses that mitigate climatic risks and enable year-round production (Department of Agriculture and Cooperation, 2024). This shift parallels observations in other developing contexts, where controlled environments amplify hybrid potential through precision inputs such as sensor-based fertigation, enabling companies to specialize in dissemination and use functions tailored to niche markets. The Solanaceae family, encompassing tomatoes and chilies, is poised for a 6.7% CAGR, propelled by escalating demands from processing industries and export markets that value uniform, disease-tolerant varieties developed via marker-assisted breeding (Mordor Intelligence, 2025).

Geographically, Tamil Nadu is projected to experience the fastest growth at a 7.3% CAGR, driven by digital agronomy tools, such as precision farming applications, and an export-oriented ethos that fosters niche market viability (Government of Tamil Nadu, 2024). The high-speed changes in this sector show a shift toward technology-focused models. Private investments in research and development average 10-12% of revenue, which is higher than public investments. Financial data from 2015 to 2023 indicate that private companies have higher Altman Z-scores, indicating greater efficiency and more effective risk management (Tarun et al., 2025).

Structure of Indian seed system

The vegetable seed system in India comprises numerous public and private actors that collaborate through formal and informal channels. This system facilitates the transfer of genetic material from research to farms. It also adapts to changing market needs. The formal system governs a clear sequence of processes that includes public research organizations such as the Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs). It also involves seed production agencies and certification bodies that ensure seed quality. These organizations follow strict protocols to maintain the genetic quality, health, and analytical standards of the seeds. This structure facilitates the progression from breeder to certified seed, emphasizing legal compliance and quality control to bridge variety development and farmer adoption. In contrast, the informal system thrives on open-pollinated varieties (OPVs), in which farmers harvest, conserve, and exchange seeds through kinship networks or local bazaars, sustaining biodiversity and local adaptation but often at the expense of uniformity and scalability. This framework is strong but faces challenges in integrating the different parts. Following the 1988 liberalization, private involvement in disseminating information increased, but it also exposed weaknesses in public organizations. For example, the earnings compared to assets in these public entities fell below industry standards. (Tarun et al., 2025; Gadwal, 2003). The Indian system benefits from the different strengths of various groups. Public institutions typically focus on developing new crop varieties and producing seeds, whereas private companies excel at disseminating information and helping farmers use these crops effectively. This teamwork leads to better adoption of hybrid crops and makes the farming sector more inclusive. However, this process is continually evolving; business models operate across sectors, fostering collaboration to improve access for small farmers and support niche crop markets.

Role of public and private sectors

The public sector anchors the seed ecosystem through institutions such as the National Seeds Corporation (NSC), 14 State Seeds Corporations (SSCs), ICAR institutes, and SAUs, which have traditionally spearheaded production of OPVs and certified seeds for high-volume, low-margin crops, laying the groundwork for the Green Revolution's yield surges by ensuring foundational access to quality seed. Yet, this role has shifted toward enabling investments in breeding infrastructure, complementing private efforts within a pluralistic system in which public policies incentivize private adoption of advanced technologies. Since the 1988 liberalization, the private sector has expanded, encompassing approximately 850 firms, with about 50 boasting dedicated breeding capabilities, commanding the hybrid market in crops such as tomatoes, cabbage, brinjals, chilies, and cucurbits through specialized functions such as germplasm screening and recombinant breeding (Gadwal, 2003; Tiku, 2023). The public sector, primarily through AICRP-VC, contributed 598 releases (85.62%), dominating the development of open-pollinated varieties (351, 99.72%) and disease-resistant cultivars (57, 96.61%), highlighting its role in varietal diversification, resilience breeding, and farmer-oriented seed systems. In contrast, the private sector accounted for 86 releases (14.38%), with a pronounced emphasis on hybrid development (83, 44.39% share of total hybrids), reflecting its market-driven breeding strategy. (AICRP, Annual Report, 2023-24). A close look at finances shows that private firms are often better off than public ones. They have higher working capital-to-asset ratios and earnings before interest and taxes-to-asset ratios, indicating strong liquidity and profitability. This differs from public companies, which struggle with solvency issues. As a result, private firms tend to have an advantage in growing through innovation, especially under adverse market conditions. In this relationship, private companies typically focus on expanding their online sales and reach, while public firms handle regulatory oversight. This mix of different business models helps develop seed systems through specialized roles and teamwork.

The seed multiplication chain

Indian seed regulations follow a strict process to ensure quality as seeds move from breeders to farmers. This system combines different roles to maintain the genetic purity and health of the seeds. Breeder seed, the direct offspring of nucleus stock, is meticulously produced by ICAR-mandated breeders or affiliates, with

production calibrated against indentures from state governments and enterprises to prevent shortages and align with market projections. Foundation seed, derived from breeder material, is generated by NSC, SSCs, and sanctioned agencies under stringent certification protocols that verify genetic fidelity, often incorporating sanitary and analytical checks to meet farmer-defined quality perceptions. Certified seed, the progeny of foundation lots, is produced through state and private contract farming networks, resulting in commercial packets for farmers and emphasizing end-use adaptation through tailored dissemination strategies. This chain, while effective, hinges on seamless public-private coordination, as disruptions resembling those in transitional economies can erode trust. Financial analyses show that private multipliers achieve higher asset turnover, sustaining chain velocity and enabling hybrid transitions.

Strategic opportunities

Several key factors are driving the modernization of the Indian vegetable seed market. This change is creating new opportunities for farmers to increase their incomes and to make the sector more resilient. Technology is advancing rapidly, particularly with hybrid seeds, which can yield 25-40% more while being more stress-resistant and adaptable to diverse conditions. The ascent of protected cultivation, surging at 11.1% CAGR, is incentivized by the Mission for Integrated Development of Horticulture's 50-85% subsidies, optimizing hybrid genetics through regulated microclimates and precision agronomics, thereby spawning demand for tailored seeds in high-value niches where private actors specialize in production and use functions. Biofortification intersects with institutional imperatives, as the Pradhan Mantri Poshan Shakti Nirman scheme (2021-2026) caters to 118 million children, amplifying uptake of varieties like the β-carotene-rich Madhuban Gajar carrot, which has bolstered farmer revenues while combating malnutrition (Ministry of Science & Technology, 2020; Food Safety and Standards Authority of India, 2024). The Government of India is taking steps to improve agriculture, including allocating ₹100 crore in the 2025-26 Union Budget to the National Mission on High-Yielding Seeds. This initiative, along with e-commerce portals, helps farmers in remote areas access better seeds. Partnerships, such as Bayer and Solynta's potato seed project in 2024, are also facilitating logistics management (Government of India, 2025; Bayer & Solynta, 2024). Private companies have played a key role in this change. Since the 1990s, they have developed virus-tolerant hybrid crops, particularly tomatoes, which have doubled productivity and enabled year-round farming by enhancing seed systems (Tiku, 2023; ter Steeg & Louwaars, 2024).

Significant challenges for industry

The sector is growing, but it faces serious challenges that limit access, reduce trust, and increase risks for those involved. The high cost of hybrid seeds, which are 3-5 times more expensive than open-pollinated varieties (for example, Chilli costs 2500/kg compared to 25000/kg, Brinjal 3000/kg versus 15000/kg, and Tomato 4000/kg against 25000/kg), creates unfairness for small farmers. Smallholders constitute 80% of all farmers, and their situation is exacerbated by banks' reluctance to assess seed risks. There is a pressing need for viable business models that serve smallholder farms. Climatic perils, including aberrant monsoons that induce pollen sterility and pollinator attrition in hubs such as Karnataka, imperil yields, necessitating interventions such as bumblebee augmentation in enclosures to sustain production. Contract farming relies on small farmers, but it struggles because many lack knowledge about safety procedures and contamination risks. This situation highlights the need for better capacity-building support. Regulations also create problems, such as counterfeit seeds that undermine trust and transportation restrictions during outbreaks. These issues, along with mismatches with International Seed Testing Association (ISTA) standards, hinder trade, particularly for hybrid crops intended for export. Financial reviews from 2015-2023 highlight these challenges. Public companies have lower financial stability, with Z-scores below 1.8 indicating distress due to poor financial management (B and D ratios). Meanwhile, private companies perform better but struggle with seasonal cash-flow constraints, making it difficult for them to distribute products through informal channels (Tarun et al., 2025).

Strategic recommendations

- To achieve lasting success in the seed industry, we must adopt a comprehensive strategy. This approach entails updating policies, implementing new methodologies, and enhancing skills to improve all aspects of the seed system. Aligning India's Minimum Seed Certification Standards with international guidelines would facilitate access to export markets and strengthen the private sector's role in the global seed trade.
- Conducting research on plant responses to stress and investigating new avenues for off-season production are crucial for developing climate-resilient seeds. By merging public funding with private breeding initiatives, we can diversify production effectively.

- To enhance seed multiplication, establishing a National Seed Grid could help align supply and demand, striking a balance between public oversight and private flexibility, particularly for hybrid seeds.
- Modern technologies, such as QR codes for tracing seed origins and molecular markers to ensure seed purity, can play a pivotal role in preventing counterfeiting and ensuring quality.
- To combat labor shortages, we should establish seed clinics and provide training for young individuals in flower biology and quality assurance. Moreover, forging partnerships between the public and private sectors can expand the reach of improved seeds by leveraging successful collaboration models that serve niche markets.
- Advancements in post-harvest techniques, including the use of zeolite for storage and enhanced logistics, will ensure equitable access to quality seeds for farmers.

Conclusion

The growth of the Indian vegetable seed market is expected to reach USD 970 million by 2030. This growth depends on effective management of several factors, including expansion, the popularity of hybrid seeds, supportive policies, and agricultural changes. However, it also faces challenges like high costs, counterfeit products, and environmental stress. To navigate this complex landscape, cooperation between the public and private sectors is essential. The market must prioritize fair access to high-quality seeds, which are crucial for improving nutrition and economic conditions.

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Indian Grape Industry: Current status, Challenges and Future Opportunities

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Abstract

Grape (*Vitis vinifera* L.) is one of the most important fruit crops of India, occupying a unique position for its export potential due to high productivity, adaptability to diverse agro-climatic conditions, significant contribution to farmers' income and export earnings. Although grapes originated in temperate regions, its successful adoption to tropical and subtropical conditions made India one of the leading grape-producing countries of the world. The introduction of grapes in India dates back to ancient times. However, systematic grape cultivation began during the Mughal period when superior grape varieties were introduced from Persia and Afghanistan and grown in royal gardens of northern India. During the British era, grape cultivation expanded to peninsular India with the introduction of European varieties and the establishment of vineyards in Maharashtra, Karnataka, and Tamil Nadu.

A major transformation in Indian viticulture occurred with the development of organized research and extension systems. The initiation of research on grapes at Indian Institute of Horticultural Research, Bangalore with introduction of rootstocks, standardization of training and pruning systems and adoption of irrigation and nutrient management enabled grapes to be grown successfully under tropical conditions. Major grape growing area in country is concentrated in tropical belt only. Under the tropical condition, the practice of double pruning and single cropping is found beneficial.

The establishment of National Research Centre for Grapes, Pune further strengthened grape research in India leading to the development of improved varieties (Manjari Naveen, Manjari Medika, Manjari Kishmish and Manjari Shyama) and clones developed by the grape growers, rootstock-scion combinations, and production technologies tailored to different regions. As a result, India has emerged as a global supplier of high-quality seedless table grapes.

At present, grape cultivation in India is predominantly concentrated in Maharashtra, followed by Karnataka, Tamil Nadu, Telangana, Andhra Pradesh, Punjab, and Haryana. Indian viticulture is characterized by intensive management practices, widespread use of drip irrigation and fertigation, and a strong orientation towards export-quality production. The diversity of production systems, ranging from tropical to subtropical regions makes grape growing in India distinct from that of traditional grape-growing countries.

Area and production of grapes

In India, area under grape cultivation has a major influence on productivity. During 2002-03, total area under grape cultivation was on 52.1 ha with a production of 1247.8 tonnes/ha and total productivity of 24.0 tonnes/ha. The trend was increased and the total productivity of 23.5 MT with a total area was 80.0 ha and production 1878.0 MT in 2008-2009 was achieved. Total area under grape cultivation during 2009-10 was estimated at 106.4 ha with a total annual production at 880.7 MT and productivity of 11.1 tonnes/ha. It has been increased after six years with total area of 1.21 lakh ha and production 2590 MT while the productivity of 21.3 tonnes /ha. In the year 2016-17, total area was 136.6 ha with a production of 2921.7 tonnes /ha and total productivity of 21.4 tonnes / ha. It has been increased up to the productivity of 22.23 MT with a total area on 1.75 lakh ha and production 3910.94 tonnes in 2023-24 accounting for about 2.5% of the total fruit production area in the country.

Major grape-growing states

Maharashtra

Maharashtra is leader in grape cultivation with almost 70 per cent area and production in the state. The grape cultivation is concentrated in Nashik, Sangli, Solapur, Satara, Jalna, and Pune districts. Nashik is often referred to as the "Wine capital of India" and is known for its high-quality wine production as well as export quality grapes.

Karnataka

Next to Maharashtra, Karnataka is another major important state growing grapes mainly for quality raisin and local market. The grapes are grown mainly in the districts of Bijapur and Bagalkot. The best quality raisin is produced from the grapes cultivated in Bijapur district. The state is known for its table grapes as well as high quality raisin production.

Tamil Nadu

Tamil Nadu, particularly the districts of Theni, Krishnagiri and Dharmapuri is known for table grape cultivation.

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Mizoram

Major grape variety grown in this area is Bangalore Blue, a juice variety. The state also has two wineries functioning.

Major Export of grapes from India

India has made a remarkable progress in the export of fresh grapes over the past decade. Grape exports increased from 94,377 MT valued at ₹973 crore during 2014-15 to 343,982.34 MT valued at ₹3,460.70 crore in 2023-24 (APEDA, 2023-24). This substantial growth reflects the rapid expansion of export-oriented grape production systems in the country. Within relatively a short period, grapes have emerged as one of the leading horticultural export commodities, accounting for more than 20 per cent of India's total fresh fruit exports. Indian grapes are currently exported to over 30 countries, with a highly concentrated market structure. The United Kingdom, Netherlands, United Arab Emirates, Bangladesh, Germany, Belgium, Saudi Arabia, Kuwait, Sri Lanka, and Bahrain together account for nearly 98 per cent of the total export volume. Among these, the Netherlands is the largest importer, receiving about 33 per cent of India's grape exports, followed by Saudi Arabia (9.69%), United Kingdom (6.92%), Russia (6.65%), Bangladesh (5.63%), Malaysia (3.35%), and Germany (3.17%), as per agri-exchange.apeda.gov.in.

Varieties grown in ...

Grapes grown in different states and different regions are known for specific grape varieties. Some of the major grape varieties grown in different states are as below.

Maharashtra

Nashik districts: Nashik is known for cultivation of grapes for export. The major grape varieties grown in the district are Thompson Seedless, Tas-A-Ganesh, Clone-2A, Crimson Seedless, Flame Seedless, etc. In addition, the district is also known for wine grape cultivation with Cabernet Sauvignon, Sauvignon Blanc, Syrah, Merlot, etc. being grown as major wine varieties. Nashik is also called as wine valley.

Pune regions: This region grow varieties like Thompson Seedless, Tas-A-Ganesh, Clone-2A, Manjari Naveen, Sharad Seedless and its clones (Sarita Seedless, Krishna Seedless, Nana Saheb Purple Seedless, etc), Sonaka, Manik Chaman, Super Sonaka, Flame Seedless, Manjari Shyama, etc.

Sangli district: Thompson Seedless, Sonaka, Manik Chaman, Super Sonaka, SSN, Jyoti Seedless, Manjari Shyama, etc. are the major grape varieties grown.

Solapur district: This district has warmer climate with high temperature and low humidity. This region concentrates mainly for raisin making and local market. The major grape varieties grown are Thompson Seedless, Tas-A-Ganesh, Clone-2A, Nana Saheb Purple Seedless, Manjari Kishmish, Super Sonaka, Manik Chaman, etc.

Jalna district: Jalna district in Marathwada is an emerging region for grape cultivation. The region experiences the hot and dry climate always thus reducing the cost of production mainly on disease management. Being hot and dry weather, there is a scope of raisin industry. The district grows mostly Thompson Seedless, Tas-A-Ganesh, Sonaka, Super Sonaka and Manik Chaman variety.

Karnataka

Karnataka is the second largest state growing grapes in the country. The weather is hot and humid in majority of the areas. Bijapur, Bagalkot and Gulbarga are the major grape-growing areas. Popular grape varieties include Thompson Seedless, Tas-A-Ganesh, Clone-2A, Manjari Kishmish, Bangalore Blue, Sonaka, Super Sonaka, SSN, etc. The best quality raisin is produced from the grapes cultivated in Bijapur district. The state is known for its table grapes as well as quality raisin production.

Table 1: Improvement in area and production

States	Area (000 ha)			Production (000 Tonnes)			Share (%)	
	2012-13	2021-22	2023-24	2012-13	2021-22	2023-24	2021-22	2023-24
Maharashtra	90	118.94	123.79	2050	2466.29	2628.25	70.67	67.2
Karnataka	19.7	36.58	43.06	320.9	854.66	1093.2	24.49	27.95
Tamil Nadu	2.68	2	2.04	43.38	50.01	50.73	1.43	1.29
Andhra Pradesh	1.58	2.37	3.38	31.51	46.82	101.25	1.34	2.58
Mizoram	2.38	2.35	2.38	20.8	17.3	17.23	0.5	0.44
others	1.3	0.01	1.28	16.51	--	20.28	--	0.51
India	117.63	162.25	175.93	2483.09	3435.08	3910.94	97.09	99.97

Source: National Horticulture Board, 2023.

Andhra Pradesh

Anantapur, Chittoor and Kurnool districts are known for grape cultivation. Varieties like Thompson Seedless, Anab-E-Shahi and Manjari Naveen are being grown.

Tamil Nadu

Krishnagiri and Dharmapuri districts are major grape producing areas in the state with Muscat, Thompson Seedless, Manjari Medika and Flame Seedless as major grape varieties.

Table 2: State-wise varieties grown and their characteristics

State growing grape varieties	Varieties grown	Characteristics	
		Colour	Seeded/seedless
Maharashtra	Thompson Seedless and its clones (Tas-A-Ganesh, Clone 2A): Oblong type	White	Seedless
Maharashtra	Nana Saheb Purple Seedless (Oblong type), Fantasy Seedless (Elongated type)	Black	Seedless
Maharashtra	Krishna Seedless, Sarita Seedless, Jyoti Seedless (All are mutants from Sharad Seedless) - Elongated type	Black	Seedless
Maharashtra	Sharad Seedless	Black	Seedless
Maharashtra	Flame Seedless	Red	Seedless
Maharashtra, Karnataka	Crimson Seedless (Oblong type)	Red	Seedless
Maharashtra, Karnataka	Red Globe	Red	Seeded
Maharashtra and Karnataka	Sonaka, Manik Chaman, Super Sonaka, SSN, Anushka): Elongated type	White	Seedless
Karnataka	Bangalore Blue	Black	Seeded
Tamil Nadu	Gulabi	Purple	Seeded
Tamil Nadu	Muscat Hamburg	Purple	Seeded
Telangana and Andhra Pradesh	Anab-e-Shahi	White	Seeded
North India	Perlette, Pusa Seedless	White	Seedless
North India	Flame Seedless	Red	Seedless

Table 3. Area distribution, cropping pattern and grape availability in different states

State	Approx area (ha)	Purpose	Cropping pattern	Grape availability (period)	Major varieties grown
Maharashtra	1,20,000	Table, raisin	Double pruning single cropping	December to May	TS, TAG, Clone-2A, Crimson Seedless, Nana Saheb Purple Seedless, Flame Seedless, Super Sonaka, Sonaka, Manik Chaman, Manjari Kishmish, Manjari Shyama, etc.
Karnataka	35,000	Table & raisin	Double pruning single cropping	December to April	TS, TAG, Clone 2A, Crimson Seedless, Nana Saheb Purple Seedless, Flame Seedless, Super Sonaka, Sonaka, Manik Chaman, Manjari Kishmish, etc.
Tamil Nadu	14,000	Table & Juice	Double pruning & double cropping	Throughout the year	Muscat Hamberg, Gulabi, Manjari Medika
Mizoram	5,000	Wine	Single pruning & single cropping	June- July	Bangalore Blue
Punjab, Haryana	2,000	Table	Single pruning & single cropping	May-June	Flame Seedless, Perlette, Early Perlette, Pusa Seedless, etc.

The growth of exports since 2014 is given below

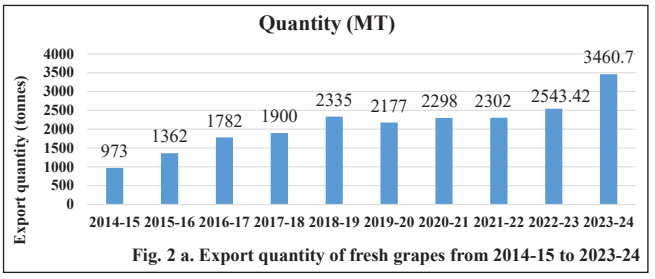


Fig. 2 a. Export quantity of fresh grapes from 2014-15 to 2023-24

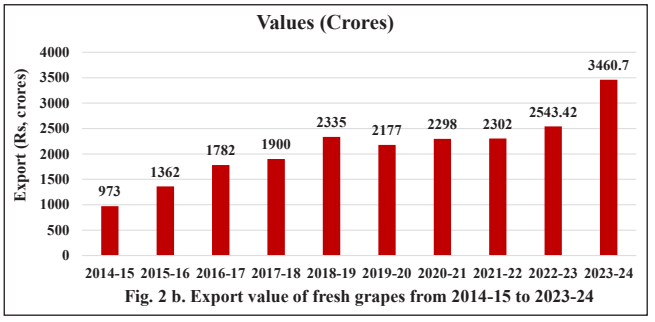


Fig. 2 b. Export value of fresh grapes from 2014-15 to 2023-24

Source: http://agriexchange.apeda.gov.in 2024

Grape exporting countries

Several countries across the world are actively engaged in the export of grapes to international markets. These countries possesses favourable agro-climatic conditions, advanced production technologies and well-developed supply chains that support the cultivation of a wide range of grape varieties for table, raisin, and wine purposes. The major grape-exporting countries are presented below.

Table 4: Major grape-exporting countries in world

Country	Major varieties exported
Spain	Table and wine grapes
Italy	Wine grapes
United States	Table, wine, and raisin grapes
Chile	Table and wine grapes
South Africa	Table and wine grapes
Australia	Wine grapes
Argentina	Wine grapes
Turkey	Table grapes
India	Table, raisin and wine grapes
Mexico	Table grapes
Peru	Table grapes

Improving Yield and Quality

Improvement in yield and fruit quality in grapes is achieved through the coordinated application of genetic, physiological, and cultural interventions. Among these, varietal improvement forms the primary pathway, as the genetic constitution of the cultivar largely determine its yield potential through bunch architecture and adaptability to different seasons. The development and adoption of new grape varieties, particularly seedless types with improved berry size have significantly contributed. Breeding efforts aimed to incorporate resistance to major diseases such as downy mildew and powdery mildew, as well as tolerance to abiotic stresses like drought, low temperature, soil salinity, etc. will help to reduce the production cost. Clonal selection within released/established varieties has further refined desirable traits leading to greater uniformity and market acceptability. Some of the important pathways are discussed below.

Rootstock

The use of appropriate rootstocks represents a complementary and equally important pathway in improving grape yield and quality, especially under challenging soil and climatic conditions. Rootstocks influence vine vigour, root system architecture, and the efficiency of water and nutrient uptake, thereby directly affecting vine balance and fruit development. Rootstocks play a crucial role in drought tolerance to grape varieties. One of the primary mechanisms underlying drought tolerance in grafted vines is the pattern and extent of root development. Drought-tolerant rootstocks (Dogridge, 110R) exhibit deeper and more extensive root systems, allowing efficient exploration of soil moisture under deficit conditions. Under water stress, such rootstocks demonstrate rapid root proliferation in relatively wetter soil layers, enhancing water uptake.

The presence of larger xylem vessels in tolerant rootstocks further improves whole-plant hydraulic conductance, facilitating sustained water transport to the scion and influencing stomatal regulation. Studies on root and shoot morphology under moisture stress have clearly shown that Dogridge rootstock maintains a higher root-to-shoot length ratio and root-to-shoot dry matter ratio, reflecting preferential dry matter allocation towards roots, which is advantageous under drought conditions. Physiological regulation through stomatal conductance represents an important mechanism underlying drought tolerance in grapevines. Reduced soil moisture availability induces partial or complete stomatal closure, thereby restricting transpirational water loss. Under mild water stress, the decline in photosynthesis is largely attributed to stomatal limitations, whereas under severe stress conditions, both stomatal and non-stomatal factors contribute to reduced photosynthetic activity.

The research work done at National Research Centre

for Grapes, Pune revealed that at the molecular level, drought tolerance in grape rootstocks has been elucidated through studies on differential gene expression. Enhanced expression of the Na^+/H^+ antiporter gene *VvNHX1* has been observed in drought and salt-tolerant rootstock 110R when subjected to moisture stress as well as combined drought and salinity stress. This upregulation was associated with reduced sodium accumulation and a higher K^+/Na^+ ratio compared to susceptible rootstocks such as 1613C. These findings provide molecular evidence supporting the role of specific rootstocks in conferring combined drought and salinity tolerance to grapevines. The long-term field evaluations have confirmed that Thompson Seedless grafted on Dogridge and 110R produced higher yields and larger berries compared to own-rooted vines and other rootstocks studied.

Overall, the enhanced performance of grafted grapevines under moisture stress is driven by integrated morphological, physiological, hormonal, and molecular mechanisms regulated by the rootstock with Dogridge and 110R proving particularly effective under drought-prone conditions under tropical condition.

Canopy management

The canopy management practices play an important role in producing the quality grapes under tropical condition. The canopy management practices followed in grape cultivation are use of training system, shoot orientation, pruning timing and types, bunch load management, berry thinning and use of plant growth regulators, etc. has great influence on grape quality. Light distribution is one of the major important parts in achieving eating quality in grapes. The modifications in canopy affects the microclimate through growth, yield, disease development, and fruit composition. Comparative quality grape production demands priority for its management practices in grape cultivation. It has been widely reported that trellis systems dividing uniform vine canopy on the trellis increase sunlight penetration which in turn increases yield and fruit quality. Canopy modifications mainly aimed at improving production potential, reduced disease incidence, and facilitate mechanization.

However, it has been observed that due to soil and water related problems (availability of calcareous soil, salt in the irrigation water) and weather-related problems (high temperature and sudden rainfall and cloudy weather during foundation pruning) in tropical viticulture poses a threat to produce grapes with improved yield and quality.

Role of weather prediction

Grape cultivation under tropical belt is highly vulnerable to weather-driven diseases due to frequent canopy flushes and prolonged periods of high temperature, relative humidity and intermittent rainfall. Under such conditions, weather prediction and agrometeorological advisories play a pivotal role in minimizing disease incidence by enabling timely, preventive, and need-based disease management practices.

Major grape diseases in the tropics particularly downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*) and anthracnose are strongly influenced by weather parameters such as temperature, relative humidity, rainfall, cloud cover, and leaf wetness duration. Weather forecasting helps in identifying the periods favourable for pathogen infection, sporulation and disease spread thereby allowing growers to act before visible symptoms appear. For instance, downy mildew outbreaks are closely associated with rainfall events followed by high relative humidity and moderate temperatures while powdery mildew development is favoured by warm temperatures and high humidity.

Short and medium range weather forecasts for a period of 3-7 days are particularly useful in tropical viticulture to predict the disease infection. Prediction of rainfall, prolonged leaf wetness or cloudy weather for a longer time alerts the grape growers to high-risk periods demanding prophylactic fungicide applications, canopy management practices. Timely sprays based on forecasted weather conditions are more effective than calendar-based schedules, as they target the most vulnerable stages of pathogen development and reduce unnecessary chemical applications.

Weather prediction also supports the use of disease forecasting models, which integrate temperature, humidity, rainfall, and leaf wetness data to predict disease onset and severity. In tropical regions where rapid disease progression is common, these models are particularly valuable for preventing epidemic development rather than attempting curative control. In addition to spray scheduling, weather-based advisories assist in cultural and canopy management decisions that influence disease incidence.

The weather prediction models used in grape cultivation has helped in minimising the pesticide residue meant for export to European countries. Using actual weather forecasts, growers could reduce the number of sprays during forward pruning period thereby maintaining pre-harvest intervals more effectively, ensuring compliance with maximum residue limits (MRLs). The work carried out at National Research Centre for Grapes,

Pune on use of weather forecast in minimizing the residue has resulted into sample failure from 24.5% in 2004 to less than 2% in the year 2024. The number of sprays also reduced from 37 to 18 in one fruiting season.

Moisture sensors

Efficient irrigation management is critical in grape cultivation, particularly under tropical and subtropical conditions where high evaporative demand and limited water resources are available. As compared to all other fruit crops, drip irrigation is being used in grape cultivation during the last three decades. However, in the recent years, the use of soil moisture sensors has emerged as an important precision viticulture tool for minimizing irrigation without compromising vine growth, yield, or fruit quality. Moisture sensors provide real-time information on soil water status, enabling need-based irrigation scheduling tailored to soil type, rootstock-scion combination and also phenological stage of the vine.

Soil moisture sensors function by measuring parameters such as volumetric water content, soil water tension, or dielectric properties of the soil. Commonly used sensors in grape vineyards include tensiometers, capacitance probes, frequency domain reflectometry (FDR), and time domain reflectometry (TDR) sensors. These sensors help determine when soil moisture approaches crop-specific threshold levels thereby avoiding both under as well as over irrigation. In grapevines, moderate soil moisture stress is required during fruit bud differentiation (after foundation pruning) while sufficient irrigation water is required to improve berry quality after forward pruning thereby sensor-based irrigation becomes valuable.

Majority of the grape vineyards are in light to murram type of soil. Under such type of soils, moisture sensors help in reducing irrigation water. In sandy soils with low water-holding capacity and excess drainage, moisture sensors help to prevent water loss and nutrient leaching. Moisture sensor guided irrigation ensures timely application of only required water, maintaining soil moisture within the optimal range thereby improving water use efficiency. In clayey soils the water holding capacity is very high but infiltration and aeration are limited. Under such soil condition, moisture sensors can help to avoid excessive irrigation thereby keeping good health of feeder roots.

Under calcareous and saline soils, common in many grape-growing regions, sensor-based irrigation is particularly beneficial for managing salt accumulation in the root zone. By monitoring soil moisture dynamics at different depths, irrigation can be optimized to meet vine water demand while minimizing excessive leaching or salt build-up. In such soils, moisture sensors assist in scheduling irrigation to maintain adequate soil moisture for nutrient uptake and root activity without inducing secondary salinity stress. In tropical grape production systems where drip irrigation and fertigation are widely adopted, the moisture sensors can help in enhancing the water and nutrient use efficiency.

Artificial intelligence

The grape being high input demanding crop need attention towards the application of artificial intelligence in grape cultivation to address the challenges of maintaining high fruit quality and reducing production costs.

In grape cultivation, the components of AI are soil and water testing, data procurement from weather station, use of moisture sensor to minimize the water use, use of drones and satellite images, etc. plays an important role. At present, the major important contribution of AI is judicious use of irrigation water. The AI model analyse soil moisture, evapotranspiration, vine water status, and short-term weather forecasts to recommend optimal irrigation requirement, its timing and quantity. This helps in preventing excess use of irrigation, minimizes nutrient leaching. Improved water-use efficiency directly reduces operational costs while stabilizing berry size and uniform ripening. In grape vineyard, drone or camera-based systems can identify early symptoms of disease infestation. The multispectral images obtained from the vineyard can help to identify the grey areas that can be attended location specific and thus the production cost can be reduced with improvement in grape quality.

Crop covers

In India, unexpected rains during forward pruning periods often result in heavy losses due to increased fungal diseases, inflorescence rot and berry cracking. The major grape area under cultivation is concentrated in Nashik district. In this district, early pruning practices are also being followed. However, unseasonal and erratic rainfall has become a major climatic constraint particularly during sensitive growth stages such as flowering, ripening and at harvest. Under these conditions, the use of crop covers has emerged as an effective climate-smart strategy to protect grapevines from rains.

Crop covers, typically made of UV-stabilized polyethylene or woven plastic sheets, are installed as overhead rain shelters over the vine canopy. They act as

a physical barrier, preventing direct wetting of leaves, shoots, and bunches. Using the plastic, the leaf wetness duration is reduced thereby the chances of fungal disease emergence are reduced to certain extent. This helps in reducing the use of frequent fungicidal applications.

The study conducted at National Research Centre for Grapes, Pune during 2015-2018 concluded that the crop covers play a vital role in maintaining fruit quality during ripening and harvesting. Protected vines experienced a more stable microclimate in the bunch zone, resulting in improved berry firmness, better colour development, higher total soluble solids, and superior market acceptability compared to uncovered vines. However, their success depends on proper design and ventilation to avoid excessive heat and humidity buildup under different climatic condition. Overall, crop covers offer a practical and sustainable adaptation strategy to mitigate the adverse effects of unseasonal rains in tropical viticulture.

Drones to improve Work Efficiency

Grape cultivation under tropical conditions involves intensive management across multiple phenological stages, requiring frequent interventions in canopy management, irrigation, nutrition, and disease control. In this context, unmanned aerial vehicles or drones have emerged as effective precision agriculture tools for improving operational efficiency and decision-making in grape vineyards.

Drones equipped with high-resolution RGB and multispectral sensors enable rapid monitoring of vine vigor, canopy density, and spatial variability within vineyards. This is particularly relevant under tropical conditions where rapid vegetative growth is common.

In grapes, drone-based multispectral imaging helps in detection of grey areas in the vineyard including pest and disease incidence, physiological stress, nutrient deficiency much before the appearance of visible symptoms. This is critical in tropical viticulture where diseases such as downy mildew and anthracnose also proliferate rapidly under high humidity and rainfall.

After forward pruning, tractor movement becomes difficult under heavy black soil conditions due to continuous and heavy rainfall. However, fungicidal sprays for effective disease management become essential during this period. Therefore, fungicide applications are carried out using drones to ensure timely and uniform coverage of the vineyard for the control of diseases.

The study conducted at National Research Centre for Grapes, Pune has also experienced the enhanced work efficiency using drones through rapid and uniform agrochemical application, particularly in large vineyards. When the tractor movements become difficult due to continuous rains, the drone-assisted spraying ensures timely interventions during narrow weather windows improving spray coverage and disease control while reducing labour dependency.

Biotechnological tools

Biotechnological tools strengthen by accelerating genetic improvement and enhancing precision in selection. Marker-assisted selection allows early identification of desirable traits such as disease resistance, seedlessness, and superior fruit quality thereby shortening breeding cycles. Advances in genomics, transcriptomics and proteomics have improved understanding of the molecular mechanisms governing yield, berry development and stress responses facilitating the development of targeted breeding strategies. Emerging genome-editing technologies, such as CRISPR/Cas-based approaches offer potential for precise modification of genes controlling fruit quality, stress tolerance and disease resistance.

Market Demand

The grape cultivation based on market demand can be the best option. Many of the international market demands thin skinned grape varieties. The varieties that are to be exported should also have better shelf life. Plant growth regulators at different berry development stages decides the berry quality. Efficient utilization of inputs including use of judicious use of plant growth regulators should be the priority to produce quality grapes. Establishing a strong market link for procurement of produce and distribution is necessary. Exploring the unexplored markets can supports to sell the produce and increase the area under cultivation. Standardization of package of practices and evaluation of grape varieties in a specific region can save the transport cost instead of grapes brought from other state.

During the period of glut in the market, the producer does not get sufficient price to the produce. Hence, exploration of other avenues like raisin production, juice and wine making can support the grape industry.

Future Strategy

India maintains its position as a major producer of table grapes. Production is currently much higher than demand in domestic market. There is a need to promote the export of grape and its products to sustain current

production trend. Till recently, export of grapes from India was primarily limited to neighbouring countries due to inadequate pre-cooling facilities and consciousness about quality. Development of pesticide residue laboratory at ICAR- National Research Centre for Grapes has helped to reduce the failure of grape samples from 24% to less than 4% and thus helped to increase the export. To increase exports, regular guidance is being given to the grape growers on different aspects (pre-harvest, proper use of pesticides, post-harvest, packaging, cold storage, and transportation). However, still there is a need to increase the share of Indian grape in the international market where higher prices can be fetched. Breeding the varieties based on the market demand can support the Indian grape industry to sustain with higher returns.

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Utilization of Systems for Hybrid Seed Production in Cucurbits

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Abstract

Major cultivated cucurbit species include cucumber (*Cucumis sativus*), bottle gourd (*Lagenaria siceraria*), bitter gourd (*Momordica charantia*), pumpkin (*Cucurbita moschata* and *C. maxima*), muskmelon (*Cucumis melo*), summer squash (*Cucurbita pepo*), and ridge gourd (*Luffa acutangula*). These crops are predominantly cross-pollinated and exhibit considerable genetic variability, making seed quality a critical determinant of crop performance. High-quality seed ensures uniform germination, vigorous seedling establishment, improved stress tolerance, and enhanced yield, whereas poor seed quality often results in weak plant stands, reduced productivity, and economic losses. Cucurbits constitute one of the most important groups of vegetable crops cultivated worldwide, particularly in tropical and subtropical regions, owing to their wide adaptability, high productivity, nutritional richness, and economic value (Ma *et al*., 2022). In India, cucurbit crops collectively occupy approximately 6.95% of the total vegetable cultivated area, underscoring their substantial contribution to national vegetable production despite being largely grown as short-duration and region-specific crops (MoAFW, 2024).The development and adoption of efficient seed production practices are essential for sustaining cucurbit cultivation and meeting the growing demand for quality seed in both open-pollinated varieties and hybrids (Cardarelli *et al*., 2022; Singh *et al*., 2023).

Understanding of breeding behaviour, sex expression, time of anthesis, stigma receptivity and pollinator play important role in hybrid seed production.

Breeding behaviour: Majority of cucurbits are cross-pollinated in nature and pollination takes place with the intervention of pollinating insects and flower remain open for a day and then collapse which is distinct behaviour from other vegetable crops.

***Sex expression*:** Cucurbits have eight different kind of sex expression *viz.,* hermaphrodite (Ridge gourd-Satputia), monoecious (bottle gourd, bitter gourd, pumpkin, cucumber), dioecious (pointed gourd, ivy gourd), andromonoecious (muskmelon), gynoecious (cucumber and bitter gourd) are major sex form present in the different cucurbits and some are trimonoecious & gynodioecious etc. which are generally available in genetic stock. However, monoecious and gynoecious have been exploited commercially for hybrid seed production.

***Time of anthesis*:** Refers to the opening of the flower by definition but it vary crop to crop and mostly the white flower cucurbits (bottle gourd, ivy gourd, pointed gourd etc.) open during night and close in the next morning. Whereas the yellow flower cucurbits such as bitter gourd, pumpkin, cucumber, long melon, muskmelon, watermelon, sponge gourd and ridge gourd anthesis occurs in early morning and remain open upto noon and there after close/withered. Stigma receptivity and pollen viability are two another aspect which determine the fruit set as well as seed set in most of the cucurbit hence knowledge on time of opening, pollen viability and stigma receptivity need to be understood properly. Stigma receptivity and pollen viability are maximum at the time of anthesis, however in some cases the stigma becomes receptivity even before the complete anthesis (bottle gourd).

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Hybrid seed production:

There are two pre-dominant systems which are commercially used for hybrid seed production in cucurbits, *viz.* hand pollination and gynoecious sex mechanism.

Protection of flower and hand pollination: In this system, the female and male flower in seed and pollen parent are protected by white butter paper bag before anthesis and next day the male flowers are removed and pollens are collected/dusted to the female flower of the seed parent. After pollination the female flower is again covered with the white butter paper bag with tagging containing the date of pollination mention over it. This system is commercially used in muskmelon, watermelon, bitter gourd, bottle gourd, pumpkin and cucumber etc.

***Gynoecious sex mechanism*:** This system is perfected, stable and exploit for hybrid seed production in cucumber and bitter gourd. In this system, seed parent and pollen parent are grown in a different planting ratio and pollination is carried out by locally available pollinators in the vicinity. The enhanced activity of pollinators helps to have more number of fruit as well as seed set in both the crop. Lack of pollinators also affect the seed yield and quality.

***Maintenance of parental lines of hybrids*:** In case of monoecious and other sex form the parental lines are either maintain and multiplied by growing in isolation or following the control pollination mechanism in one farm.

***In isolation*:** When small number of parental lines of different crops has to maintain and multiplied this approach works very well and ensures higher amount of good quality seed can be obtained.

***Through control pollination*:** In case of large number parental lines in one crop has to multiply and maintain then control pollination are effective method. Since growing large number of parental line isolation involved high expenditure and practically difficult to manage.

Maintenance and multiplication of gynoecious lines

The gynoecious lines used as seed parent in hybrid seed production are maintained and multiplied by spraying of Silver thiosulphate (500 ppm) at 2-4 true leaf stage and 2-3 sprays are required to induce the normal male flower. The pollen obtained from the plants are used for pollination to the other plants of the same line which are producing only female flowers. Two repeat pollination at 7 AM and 8 AM give higher number of fruit set and seed yield with better quality.

Management practices:

***Choice of season and location*:** The choice of season and location is critical for successful hybrid seed production in cucurbitaceous crops. Studies on pumpkin conducted at ICAR-IARI, New Delhi, indicate that the summer season (mid-February–mid-June) provides favorable thermal conditions for flowering, fruit set, and seed development (Singh et al., 2010). However, elevated temperatures during late summer can adversely affect fruit maturation, which can be effectively mitigated through protected cultivation systems such as insect-proof net houses, thereby ensuring stable seed yield and quality. The choice of season depends upon the location i.e. summer season in North India is ideal for muskmelon, watermelon and round melon seed production whereas winter season November to March is used for seed production of many cucurbits in Southern States especially Ranebennur.

***Synchrony in flowering*:** Flowering synchrony is crucial for successful hybrid seed production in cucurbitaceous crops, directly impacting pollination efficiency and seed yield. Evidence showed that misaligned flowering between parental lines can severely limit hybrid seed production. Padmini et al., (2007) demonstrated that delaying planting of pollinator lines by one week can synchronize peak flowering, resulting in significantly higher fruit set (80%) and hybrid seed yield (15g/plant) compared to simultaneous planting. A study by Campbell et al., (2012) showed that the OP varieties of summer squash showed more phenotypic variation and a greater increase in synchrony from individual to plot level.

***Method of planting*:** Regular planting is followed in parental line multiplication in isolation as well as in-case of gynoecious sytems is used for hybrid seed production in 2:1 planting ratio in cucumber and bitter gourd. *Block planting* (3:1) is recommended for hybrid seed production and seed parents/pollen parent are grown in block with some isolation.

Planting ratio

Planting ratio in cucurbit seed production refers to the proportion of male (pollen parent) to female (seed parent) plants maintained in a seed production field to ensure adequate pollination while maximizing seed yield. Since most cucurbits are insect-pollinated and produce separate male and female flowers, an optimum planting ratio is essential for efficient pollen transfer. Generally, male-to-female ratios ranging from 3:1 to 4:1 are recommended in crops such as cucumber, muskmelon, bottle gourd, bitter gourd and pumpkin, although the exact ratio may vary depending on species, floral biology, pollen production, vigour of parental lines and pollinator activity. A higher proportion of female plants increases seed yield potential, but insufficient male plants can lead to poor fruit set due to inadequate pollen availability. Conversely, excessive male plants reduce the effective area under seed-bearing female lines. Proper spatial arrangement of male rows within the female block, synchronization of flowering and effective pollinator management are therefore crucial to optimize the planting ratio and ensure high seed set, genetic purity and uniform seed quality in cucurbit seed production (Nerson, 2007).

Planting Ratios

Below is General male: female planting ratios used in hybrid seed production:

Crop	Male: female ratio	Notes
Summer Squash	3:1	Standard practice with insect pollination.
Muskmelon	4:1	Improves cross-pollination efficiency.
Cucumber	4:1	Often used with gynoecious female lines.
Bottle Gourd	4:1	Depends on pollinator population and field layout.
Bitter Gourd	4:1	Standard in open field hybrid seed production.

***Trailing systems*:** This system along with crop geometry play a decisive role in cucurbit seed production. Traditional ground trailing systems, although widely practiced, often lead to excessive vine overlap, poor aeration, higher disease incidence and difficulties in pollination and fruit management. In contrast, vertical training or trellising systems have been shown to improve canopy architecture, light interception and air circulation, thereby enhancing flowering, fruit set and seed development. Studies conducted under Indian conditions, including those at ICAR-IARI, New Delhi, have demonstrated that vertical training in crops such as bottle gourd and cucumber results in increased seed yield per vine, improved seed size and higher germination and vigour compared to ground-grown plants.

***Supplementary pollination*:** Generally, hybrid seed production is carried out with the available population of the locally available pollinator but the density of pollinator matter and affect the seed yield. In the event of low pollinator density then supplementary pollination becomes important. Two to three medium sized honey bee hives are recommended for placement on the boundary of field with suitable protection.

Fruit load and post-harvest ripening

Fruit load management and fruit position on the vine have a pronounced effect on seed yield and quality in cucurbits. Research conducted at ICAR-IARI, New Delhi, has demonstrated that excessive fruit retention leads to competition for assimilates, resulting in reduced seed size, lower germination and poor vigour. Conversely, retaining an optimum number of fruits per vine enhances assimilate partitioning to developing seeds. In cucumber, retention of two fruits per vine has been found optimal for achieving higher seed yield and superior seed quality attributes. Harvesting and post-harvest handling of seed fruits play a vital role in determining final seed quality. Cucurbit fruits intended for seed extraction must be harvested at full physiological maturity, when seeds attain maximum dry weight and viability. Post-harvest curing of fruits under shaded or ambient conditions allows completion of seed maturation and improves germination potential. Seed extraction through fermentation, followed by washing and drying to safe moisture levels, is essential for maintaining seed longevity.

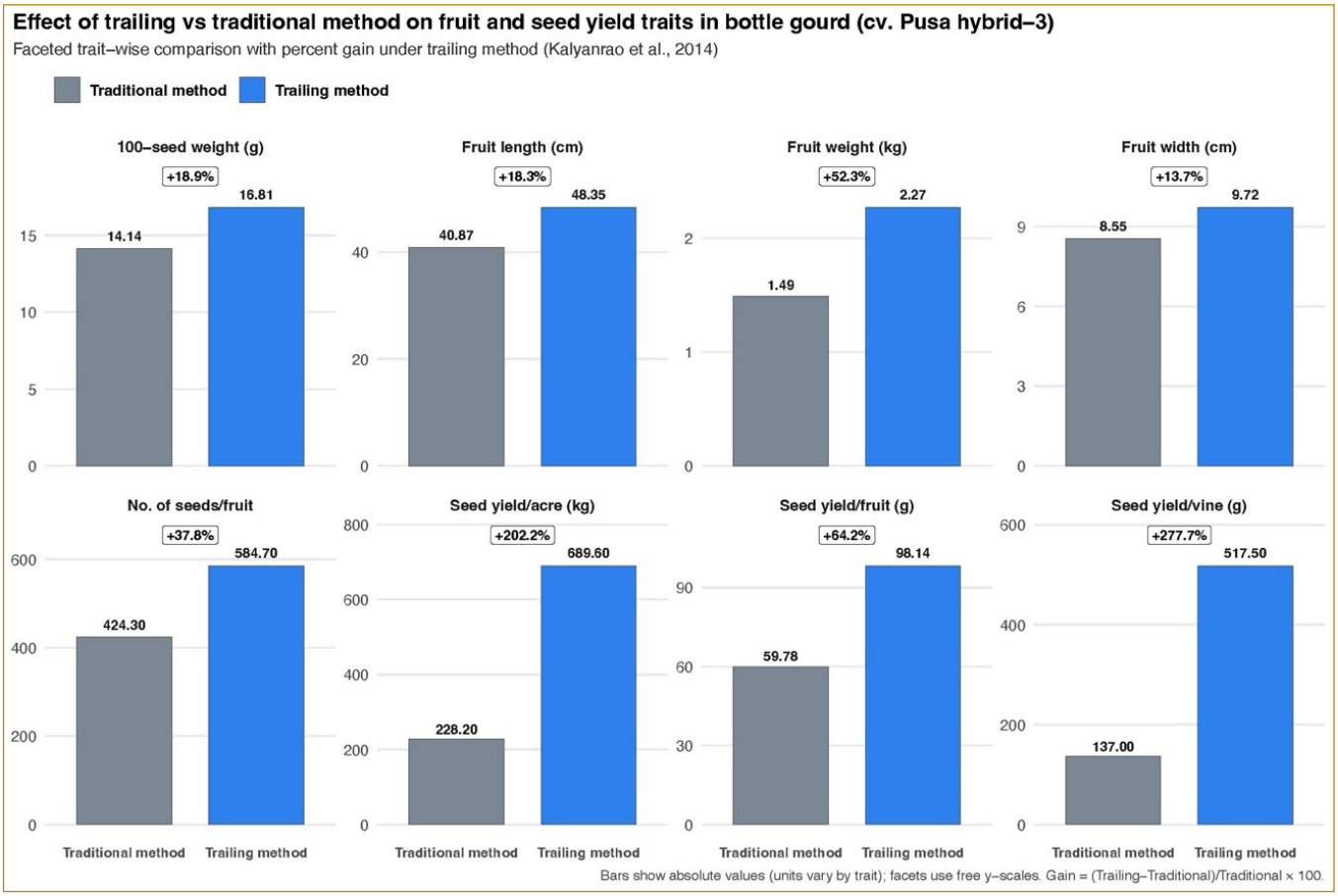


Fig.1: Effect of trailing and traditional methods on fruit and seed yield parameters in bottle gourd

Scope of protected cultivation

Protected cultivation has emerged as a promising approach for hybrid seed production in cucurbits, offering greater control over environment, pollination and pest pressure. Hybrid seed production under net houses and polyhouses results in higher seed purity and consistency compared to open-field conditions. Appropriate male-to-female planting ratios, commonly 3:1 or 4:1 depending on crop and pollinator availability, are followed to maximize seed yield.

Future prospect of hybrid seed production in Cucurbits

Future advancements in cucurbit seed production are expected to arise from integration of molecular tools, precision agriculture and climate-resilient practices. Molecular markers for rapid purity testing, automation of pollination processes, improved seed enhancement technologies and strengthened pollinator management strategies will contribute to sustainable cucurbit seed production systems.

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Climate-Smart Fruit Crops for Enhancing Livelihoods and Ecosystem Resilience in Rainfed Semi-Arid Regions

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Abstract

To ensure nutritional security and sustain fruit production under changing climatic conditions, there is an urgent need to promote climate-smart fruit crops. Crops such as bael (*Aegle marmelos*), jamun (*Syzygium cumini*), aonla (*Phyllanthus emblica*), manila tamarind (*Pithecellobium dulce*), and custard apple (*Annona squamosa*) can significantly contribute to nutritional security and enhance rural livelihoods and it well adapted to climatic stresses and can be successfully cultivated under adverse conditions. These fruit crops are nutritionally rich and offer viable alternatives for mitigating production losses caused by climate change. Research initiatives, have led to the development of improved fruit crop varieties possessing superior horticultural traits. India holds a prominent position in global horticulture due to its highly diverse agro-climatic conditions, which enable the cultivation of a wide array of fruit and vegetable crops. Climate change is largely driven by unsustainable anthropogenic activities, and its adverse consequences require urgent and effective mitigation and adaptation strategies. A promising strategy for ensuring nutritional security through continuous fruit availability is the identification and promotion of climate-smart fruit crops. These crops exhibit enhanced tolerance to heat stress and moisture stress and are therefore better suited to withstand the challenges posed by changing climatic conditions. Fruits constitute a vital component of Indian agriculture, the economy, and food systems, with fruit cultivation emerging as a profitable enterprise that significantly contributes to rural employment and income generation (Singh et al., 2025).

Environmental stresses represent major constraints to global fruit production, contributing to yield losses of up to 70%. Among these stresses, high temperature is responsible for approximately 40–50% of yield reduction, followed by salinity (20%), drought (17%), and low temperature stress (15%). Fruit crop establishment and productivity are particularly limited in arid and semi-arid regions, which are characterized by extreme temperatures, salinity, drought, and nutrient deficiencies (Singh et al., 2020; Singh *et al.*, 2025d). In this context, integration of underutilized arid-zone fruit species presents a sustainable strategy for maintaining productivity under adverse environmental conditions. These species possess inherent xerophytic adaptations encompassing morphological, physiological, and biochemical traits that confer stress tolerance without substantially compromising yield (Singh *et al.*, 2010). Adaptive mechanisms such as modified phenology, optimized root-to-shoot ratios, and specialized leaf morphology enable these genotypes to withstand environmental stresses while sustaining stable fruit and seed production. (Singh *et al.*, 2022; Singh *et al.*, 2025e).

Semi-arid fruit crops of arid and semi-arid regions such as bael, aonla, phalsa, wood apple, custard apple, wild noni, khirni, mahua, jamun, chironji, ber, and Manila tamarind exhibit a wide range of morpho-physiological adaptations that enable their survival and productivity under harsh abiotic conditions (Singh *et al.*, 2018). Adaptive traits such as deep root systems and high root-to-shoot ratios enhance water and nutrient acquisition, while deciduous behaviour and dormancy mechanisms reduce transpiration losses and improve stress tolerance (Singh *et al.*, 2024). Additional xerophytic characteristics, including spines or reduced foliage, mucilaginous sap, thick or pubescent leaves, waxy cuticles, sunken stomata, and selective ion uptake, further contribute to environmental resilience. These structural adaptations are complemented by biochemical and molecular responses, such as the accumulation of osmolytes (e.g., proline, sugars, and betaine), enhanced antioxidant activity, and the induction of heat-shock proteins and drought-responsive genes, which collectively maintain cellular homeostasis and confer adaptability in arid and semi-arid ecosystems (Singh *et al.*, 2023).

Such semi-arid fruit crops could emerge as climate-resilient alternatives for ensuring sustainable production and improving farmers' economic returns (Singh et al., 2025a). The key features and prospective uses of underexploited fruit crops of arid and semi-arid regions are described in detail below, with a summary of their key attributes presented in Tables 1.

Morphological and Economic Significance

Fruit crops such as bael, manila tamarind, aonla, chironji, phalsa, wood apple, karonda, mahua, jamun, khirni,

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custard apple, fig, lasoda, timru and capegooseberry, ber, mulberry and Palmyra Palm are characterized by relatively low moisture requirements and reduced transpiration rates. Their flowering and fruiting processes are also less sensitive to temperature fluctuations compared to conventional fruit crops. Consequently, these species represent promising candidates for next-generation climate-smart fruit crops suitable for cultivation under changing climatic conditions.

Bael

Bael (*Aegle marmelos* Correa), a member of the family Rutaceae, is a medicinally important indigenous fruit species extensively utilized in traditional Indian systems of medicine owing to its wide range of pharmacological properties (Singh et al., 2025c). The crop is known by various regional names, including Vilvam, *Billi*, and stone apple, and holds significant religious importance in Hindu culture, where it is considered sacred to Lord Shiva. Bael exhibits remarkable adaptability across diverse agro-climatic conditions and demonstrates high tolerance to heat, drought, low temperatures, poor soil fertility, saline–sodic soils, and several pests and diseases (Singh et al., 2015; Singh et al., 2006). Morphologically, it is a deciduous, medium-sized, gum-bearing tree characterized by cauliflorous flowering, a deep taproot system, thorny branches, and trifoliate leaves. The species is capable of thriving in a wide range of soil types, including swampy, alkaline, and rocky soils, with a pH tolerance ranging from 5 to 10. It is nutritionally rich, containing appreciable amounts of carbohydrates, proteins, fats, dietary fiber, essential minerals (Ca, P, K, and Fe), and vitamins such as A, B_1, C, nicotinic acid, and riboflavin. Due to its high riboflavin content, bael has been traditionally used in the management of beriberi, while the unripe fruit is commonly employed for the treatment of diarrhea and dysentery. The fruit pulp contains bioactive compounds such as marmelosin, which is effective against various gastrointestinal disorders. Additionally, all parts of the bael plant are rich sources of bioactive constituents including coumarins, alkaloids, sterols, and essential oils exhibiting diverse pharmacological activities such as analgesic, antipyretic, anti-inflammatory, antifungal, hypoglycemic, wound-healing, and antifertility effects (Singh et al., 2008a; Singh and Singh 2007a). In recent years, value-added bael products such as juice, powder, candies, preserves, nectar, toffees, and ice cream have gained substantial market demand, particularly during the COVID-19 pandemic (Singh et al., 2016). These attributes, combined with its stress tolerance and low input requirements, make bael a highly profitable and climate-resilient fruit crop suitable for cultivation in arid and semi-arid regions (Singh et al., 2016a).

Manila tamarind (*Pithecellobium dulce*), Also known as Madras thorn, Monkey pod, or Jungle jalebi, is a medium-sized, fast-growing, thorny tree belonging to the family Fabaceae. The species serves multiple purposes, including live fencing, fodder for livestock, hardwood timber production, windbreak establishment, and as a potential host for lac cultivation. Its fruit is sweet-acidic and nutritionally valuable, containing dietary fiber, proteins, essential minerals such as calcium, iron, and phosphorus, unsaturated fatty acids, and antioxidants. Traditionally, the fruit and other plant parts have been used in managing oral health issues (toothache, mouth ulcers, sore gums), gastrointestinal disorders (dysentery, chronic diarrhea), and age-related conditions, including oxidative stress, hyperpigmentation, and skin aging.

Chironji (*Buchanania lanzan* Spreng.), A member of the Anacardiaceae family, is indigenous to the Indian subcontinent and naturally occurs in the arid and semi-arid forests of Jharkhand, Chhattisgarh, Madhya Pradesh, Rajasthan, Gujarat, and Uttar Pradesh. It is a medium-sized, sub-deciduous to evergreen tree characterized by a straight trunk and coriaceous leaves. Chironji is highly heterozygous, cross-pollinated, and exhibits a pronounced tendency for alternate bearing (Singh et al., 2010a). Its fruits are edible both raw and roasted, while the kernels are nutritionally rich, containing approximately 59% fats, 19–21.6% proteins, 12.1% carbohydrates, 3.8% fiber, and significant amounts of minerals such as phosphorus (528 mg), calcium (279 mg), and iron (8.5 mg), along with essential vitamins. The species also possesses considerable medicinal potential; traditionally, various plant parts have been used to manage snakebite, dysentery, diarrhea, asthma, fever, ulcers, cold, and Alzheimer's disease, and modern studies indicate anti-diabetic and antihyperlipidemic activities (Singh and Singh, 2014).

Mahua, Jamun and Karonda

Mahua [*Madhuca longifolia* (Koenig)], A commonly known as the Indian Butter Tree, is a multipurpose and socio-economically significant tree widely distributed across central and northern India. Various parts of the tree including flowers, fruits, seeds, leaves, and wood have diverse applications. The flowers are rich in sugars, vitamins, and minerals, and are utilized for alcoholic fermentation, distilled liquor production, and livestock feed. The fruits are consumed raw or cooked, while the pulp serves as a natural sugar source for fermentation processes. The seeds are particularly oil-rich, containing higher oil content than many conventional oilseed crops. The edible oil, abundant in linoleic and other unsaturated

fatty acids, has cardiovascular benefits and is used in the production of vegetable oil, soaps, lubricants, fatty alcohols, and candles. The defatted seed flour has potential applications in bakery products, whereas saponins and oilcake serve industrial, manure, and insecticidal purposes (Singh et al., 2005). The leaves are used for making eco-friendly plates, and the wood provides quality timber. Collectively, these multiple products render Mahua a valuable resource for tribal communities and smallholder farmers (Singh and Singh, 2005).

Jamun (*Syzygium cumini* Skeels), A member of the Myrtaceae family, is an indigenous, evergreen, and highly resilient fruit tree commonly found in neglected, wasteland, or marshy areas. Among the 400–500 species within the genus *Syzygium*, only a few produce edible fruits (Singh et al., 2019). Traditionally, its fruits, leaves, seeds, and bark have been utilized in Ayurvedic medicine for their therapeutic properties. Jamun is a large evergreen tree characterized by dense foliage, greyish-brown exfoliating bark, and durable whitish wood that produces brown dyes and gum kino. The species thrives best in deep, well-drained loamy soils, with dry conditions during flowering and fruiting being optimal. Flower panicles emerge from the leaf axils between March and April, followed by clusters of 10–40 non-climacteric, single-seeded berries that exhibit sigmoid growth (Singh and Singh, 2005).

Karonda (*Carissa carandas*), A member of the Apocynaceae family and locally known as Christ's thorn, is a hardy, evergreen, spiny shrub native to India. It is widely cultivated as bio-fencing or live-fencing in Rajasthan, Gujarat, and Uttar Pradesh and thrives under arid and semi-arid conditions due to its xerophytic adaptations. Each plant produces 5–8 kg of fruit with minimal management. Karonda flowers during January–February and June–July, with fruits maturing 60–90 days after fruit set. Fruit color varies among genotypes, ranging from white, green, purple, to pinkish-red, making the species both edible and ornamental. Immature fruits are traditionally used for pickles, while mature fruits are processed into pickles, jellies, jams, squashes, syrups, chutneys, candies, and natural colorants. The fruits are nutritionally rich, particularly in iron (39 mg/100 g) and vitamin C, and are traditionally used to manage anemia and scurvy. They also provide calcium, magnesium, and phosphorus and exhibit high antioxidant activity. Additionally, their high pectin content makes them especially suitable for value-added products, which have strong market potential.

Khirni, It is an evergreen, medium-sized, slow-growing fruit tree native to India, characterized by a spreading canopy. The species is well adapted to arid to tropical climates and is also valued as an avenue or bonsai tree due to its dense evergreen foliage and compact growth habit. Flowering occurs from February to March, with fruits ripening between May and June. Khirni is commercially utilized as a rootstock for sapota (*Manilkara zapota*) because of its tolerance to salinity and drought (Singh and Singh, 2015). Its bark, seeds, and fruits are rich in tannins, oil, and vitamin A, respectively, and have been traditionally used in the management of fever, flatulence, digestive disorders, leprosy, ulcers, corneal opacity, dyspepsia, and bronchitis (Singh et al., 2016b).

Wood Apple (*Limonia acidissima*), It is an indigenous deciduous tree characterized by thorny branches, rough spiny bark, and moderate stature. It typically grows as a solitary tree in the plains of Southern Maharashtra, Uttar Pradesh, West Bengal, Madhya Pradesh, and Chhattisgarh, thriving on poor, saline, or neglected soils. Flowering occurs from February to May, with fruit maturation from October to December, depending on moisture availability. The fruit is a hard, woody berry containing sweet, aromatic pulp. Various plant parts possess medicinal properties: leaves exhibit diuretic, antimicrobial, and digestive effects; bark and roots have insecticidal and anti-snakebite activity; spines are used for liver disorders and menorrhagia; gum treats diarrhea and diabetes; and the pulp is employed in managing skin disorders, diarrhea, jaundice, and gastropathy. The fruit is also processed into powders, preserves, squashes, jams, beverages, candies, pickles, ready-to-serve (RTS) drinks, and capsules (Singh et al., 2016).

Custard Apple (*Annona squamosa*), It is drought-tolerant member of the Annonaceae family, is cultivated on a limited scale in the Indian Deccan Plateau and can grow on light, gravelly, or pebbly soils. It is a small, semi-deciduous shrub with simple leaves, cauliflorous, bisexual, and protogynous flowers, and superior ovaries. Flowering primarily occurs on new shoots after leaf shedding from March to August, peaking in April–May. The climacteric fruits are typically heart-shaped, lopsided, or irregular, with yellowish protuberances at maturity. Custard apple is valued for its sensory appeal, rich nutritional content including vitamins A, B, C, E, K1, and essential minerals and therapeutic properties, driving growing demand in domestic and international markets (Yadav et al., 2017).

Indian gooseberry (*Phyllanthus emblica*), It is exceptionally rich in vitamin C (500–1800 mg/100 g), proteins, polyphenols, pectin, iron, calcium, and phosphorus, making it a key component in Ayurvedic formulations such as *Triphala* and Chyavanprash (Singh et al., 2011; Singh et al., 2024a; Singh et al., 2014b). To date, thirty improved varieties have been developed, facilitating commercial cultivation in arid and semi-arid

regions (Singh et al., 2014a). Hardy and drought-tolerant, aonla thrives with minimal management even on saline soils (Singh and Singh, 2006). Due to its naturally acidic and astringent taste, the fruit is predominantly processed into preserves, candies, jellies, pickles, fruit leathers, juices, ready-to-serve (RTS) beverages, dried powders, and Ayurvedic tonics (Singh et al., 2010; Singh et al., 2009; Singh and Singh, 2007a).

Fig (*Ficus carica* L.), Fig is native to Southwest Asia and the eastern Mediterranean and is widely cultivated in warm, dry climates for its edible fruits. Varieties of fig differ in shape, color, taste, and functional properties, often being named based on their morphology or region of cultivation. Figs are nutritionally valuable, providing essential minerals, vitamins, dietary fiber, and amino acids, while being low in fat and free from cholesterol.

Tamarind (*Tamarindus indica*), It is a long-lived, semi-evergreen tree of the Leguminosae family, is highly adaptable and well-suited for avenue plantations, backyard gardens, and agroforestry systems (Singh *et al.*, 2010). The tree produces terminal and lateral drooping bisexual flowers in May–June, with pendulous pods maturing approximately ten months later (Singh *et al.*, 2008). Its fruit pulp and seeds are rich in tartaric acid, sugars, tannins, pectin, dietary fiber, and essential minerals such as potassium, calcium, phosphorus, sodium, iron, and zinc. Tamarind is extensively utilized in culinary applications, including sauces, chutneys, beverages, and natural food colorants, and also serves multiple industrial purposes in food, fodder, timber, fuel, textiles, and pharmaceuticals, including fluoride removal (Singh and Singh, 2005; Singh *et al.*, 2025b).

Cordia (*Cordia spp.*), It is a minor fruit also known as Indian Cherry, Sebesten, Lehsua, Lasoda, or Gunda, grows naturally on wastelands, farm boundaries, and roadsides across India (Gujarat, Rajasthan, Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, Maharashtra) and in countries such as Myanmar, Egypt, China, Sri Lanka, and Australia. The species thrives in warm climates but is sensitive to frost. The soft, red, edible fruits have sweet, sticky pulp that can be consumed fresh, juiced, or fermented. They exhibit notable medicinal properties, functioning as diuretics, demulcents, astringents, antidiarrheals, antiseptics, and carminatives, and are traditionally used in the management of urinary disorders, hypertension, and diabetes. The tree produces oblong-lanceolate leaves with a pubescent upper surface and scarious underside, while white tubular flowers emerge after rains, followed by fruiting approximately two months later. The fruit mucilage contains sugars and acids, including D-glucose, D-fructose, D-xylose, D-rhamnose, and galacturonic acids.

Phalsa (*Grewia subinaequalis* D.C.), Phalsa is one of the oldest fruit crops of India and is mentioned in Vedic literature for its medicinal properties. It is a hardy, drought-tolerant shrub capable of growing under neglected and water-scarce conditions, making it an important catch crop in commercial orchards and suitable for wastelands and sodic soils. The fruits are mildly acidic, rich in vitamins A and C, and minerals, but have a short shelf life, restricting their use mainly to local markets or immediate processing.

Timru/ Tendu (*Diospyros melanoxylon*), Timru is a dioecious tree of the Ebenaceae family (2n = 30), is native to India and also distributed in Nepal and Pakistan. It thrives in dry deciduous forests across central, western, and northern India, including Madhya Pradesh, Bihar, Jharkhand, Chhattisgarh, Rajasthan, Gujarat, Odisha, Andhra Pradesh, and Tamil Nadu. The species is multipurpose and medicinally valuable: its leaves serve as livestock fodder and are commercially used for bidi wrapping due to their flexibility and texture; the bark exhibits diuretic, carminative, laxative, styptic, and antimicrobial properties; and dried flowers are traditionally used to treat urinary, skin, and blood disorders. The bitter and acrid fruits are consumed by tribal communities and possess cooling, digestible, carminative, and astringent properties. Additionally, the wood has considerable economic importance for various uses.

The Indian jujube (*Ziziphus spp.*) It is one of the oldest cultivated fruit trees in the north Indian plains. It can thrive on marginal lands and poor soils where most other fruit trees fail or perform poorly, earning it the reputation of the "king of arid zone fruits" and the "poor man's apple." Three main species occur in India: *Z. mauritiana*, the principal species of commercial importance with numerous varieties; *Z. nummularia*, valued for its protein-rich leaves used as livestock fodder (pala); and *Z. rotundifolia*, which bears smaller edible fruits and is commonly used as rootstock for commercial jujube cultivation. The seeds contain bioactive compounds such as saponins, jujubogenin, and obelin lactone (Singh *et al.*,2010), while the fruits are rich in vitamin C, as well as vitamins A and B, protein, calcium, and phosphorus (Singh et al., 2007;Singh *et al.*, 2004). Indian jujube is a hardy, perennial fruit tree that provides multiple sources of income including fruits, fodder, and fuelwood even under severe drought conditions. Its physiological adaptations, including hairy leaves and branches specialized to reduce moisture loss through stomata, enable it to withstand prolonged dry spells and extreme drought, making it highly suitable for rainfed cultivation across sub-tropical to tropical regions.

Mulberry (*Morus spp.*), a member of the Moraceae family and native to Southwest Asia, is a fast-growing, deciduous tree cultivated across temperate to tropical regions. The main species used in commercial orchards include *M. alba*, *M. nigra*, and *M. rubra*. Although primarily grown for silk production and as shelterbelts, mulberry fruits are nutritionally rich, containing vitamins, minerals, dietary fiber, sugars, amino acids, carotenoids, flavonoids, and phytosterols. The fruits are utilized as functional foods including teas, juices, marmalades, smoothies, and capsules and as natural colorants. They also exhibit diverse pharmacological properties, such as anti-obesity, cardioprotective, antidiabetic, hypocholesterolemic, antioxidant, anti-aging, antifungal, anxiolytic, and hepatoprotective activities.

Palmyra palm (*Borassus flabellifer*), Also known as toddy, wine, or sugar palm, is widely cultivated across India in diverse soils and climatic conditions, including Karnataka, Kerala, Maharashtra, Madhya Pradesh, Andhra Pradesh, Chhattisgarh, West Bengal, Bihar, and Odisha. The species is multipurpose: its leaves are used for mats, baskets, fans, roofing, and fuel, while trunks provide poles and walking sticks. Young fruits (endocarp) are consumed raw, whereas the mature mesocarp is processed into various food products, palm jaggery, neera, wine, and vinegar. Neera, extracted from inflorescences, is nutritionally rich in iron, calcium, phosphorus, carotenoids, and B vitamins. The seeds and pulp are also nutritious, consumed fresh or dried, and incorporated into porridges and traditional preparations. Additionally, male inflorescence paste is a valuable source of pectin, cellulose, hemicellulose, polyphenols, and lignin.

Varietal wealth of semi-arid fruits

The selection of suitable plant species and varieties is crucial for successful cultivation, especially under marginal and challenging conditions. Ideal traits include deep root systems, summer dormancy, high tissue water retention, reduced leaf area, sunken stomata, thick cuticles, waxy or pubescent surfaces, latex production, and the ability to thrive on shallow, rocky, or undulating wastelands. Many semi-arid fruit crops remain regionally restricted and neglected by markets and breeders due to limited transportability or commercialization potential, which constrains the development of improved cultivars (Sharma et al., 2013; Singh *et al.*, 2013). The ICAR institutes and Agricultural Universities have facilitated the collection, characterization, evaluation, and conservation of these crops, supporting the development of high-yielding, quality varieties with the potential to address malnutrition and enhance climate resilience (Table. 2).

Conclusion

Orchard cultivation represents a long-term investment, necessitating the selection of crops and varieties capable of withstanding extreme climatic conditions such as prolonged drought or high temperatures. The accelerating pace of climate change poses a significant threat to fruit production. To ensure future fruit availability and maintain nutritional security, emphasis must be placed on drought-tolerant fruit trees that can not only survive under water-limited conditions but also produce economically viable yields.

Future Prospects

Despite their well-documented advantages, semi-arid fruit crops in India are still underrepresented in commercial orcharding systems. These species hold considerable potential to enhance food security, nutrition, and energy supply. Most indigenous fruits exist only as local varieties, often sourced from wild habitats or

Table 1. Other minor fruit crops introduced to India from various countries

Common name	Scientific name	Family	Flowering	Fruiting	Uses
Bay berry	*Myrica esculenta*	Myricaceae	Oct-Nov.	March-April	Fresh eaten, pickle, refresh drink
Water Apple	*Syzgiumaqueum*	Myrtaceae	March-April	July-August	Fresh
Star gooseberry	*Phyllanthus acidus*	Euphorbiaceae	March -April	Sept-Oct.	Culinary, Fresh
Pulasan	*Nephelium mutabile*	Spindaceae	March-May	Aug-Oct.	RTS, Fresh
Mangosteen	*Garcinia mangostana*	Clusiaceae	April -June	Oct -Nov.	Processed, Fresh
Rambutan	*Nephelium lappaceum*	Sapindaceae	March – April & June - July	June-Oct.	RTS, Fresh
Persiman	*Diospyros kaki*	Ebenaceae	Feb -March -April	Oct-Nov.	Dried product, Fresh
Kiwi fruit	*Actinidia deliciosa*	Actinidaceae	Feb-March	Oct-Nov.	Culinary, Fresh,beverages
Carambola	*Averrhoea carambola* L.	Oxalidaceae	June-July	Dec-Jan.	RTS, Fresh
Bhawa	*Garcinia cowa*	Clusiaceae	Feb-March	April-June	Juice, Squash, fresh,

Table 2. Varietal wealth of minor fruit crops

Crops	Varieties
Bael	Goma Yashi, Thar Divya, Thar Neelkanth, Thar Srishti, Thar Shivangi, Thar Prakriti, Thar Gauri, Thar Bhavya, NB-5, NB-7, NB-8 NB-9,NB-10, NB-16, NB-17 CISHB-1, CISHB-2, Pant Aparna, Pant Shivani, Pant Sujata and Pant Urvashi
Jamun	Goma Priyank, Thar Kranti, Konkan Bahadoli, Jamwant,Paras,Rajamun, Rajendra Jamun-1, Jamwant
Custard apple	Thar Amrit, Washington PI 98797, Washington PI 107005, British Guinea, Barbados seedling, Island Gem, Bullocks Heart, Pink Mammoth,Balanagar, Mammoth, Red Sitaphal, Yellow Sitaphal**,** Phule Janki and Sindhan
Mulberry	Thar Lohit, Thar Harit, Victoria-1, China White, Saharanpur Local-1, Saharanpur Local-2, S-13, S-34, S-146, S-7999, S-1635, Chak Majra
Karonda	Pant Manohar, Pant Sudarshn, Pant Suverna, Konkan Bold, Thar Kamal
Tamarind	Goma Prateek,Thar Rashmi, Prathisthan, PKM-1, T 263, Urigam, Ajanta, Yogeshwari, DTS 1 and DTS 2, Anant Rudhira
Lasoda	Thar Bold, Paras Gonda, Puskar Local, Maru Samridhi, Karn Lasoda
Khirni	Thar Rituraj
Phalsa	Thar Pragati
Chironj	Thar Priya
Mahua	Thar Madhu, NM-2, NM- 4, NM-7, NM- 9
Manila tamarind	PKM (MT) 1
Fig	Poona Fig, Dianna, Dinkar, Conadria, Excel, Chalisgaon
Wood apple	Thar Gaurav, Thar Prabha
Ber	Goma Kirti, Thar Malti, Thar Sevika, Thar Bhubhraj, Umran, Gola, Seb, BanarasiKadaka
Aonla	Goma Aishwarya, NA-4, NA-5, NA-6, NA-7, NA-10,NA-26, NA-27, Anand-1, Anand-2, BSR-1, BSR-2, Laxmi-52

home gardens, providing accessible and nutritious food. Promoting their cultivation and conservation is therefore essential.

Semi-arid fruits require minimal external inputs, are well-adapted to marginal and diverse ecosystems, and tolerate conditions unsuitable for highly bred cultivars, making them ideal for sustainable and organic production. Their integration into home gardens, agroforestry systems, terraces, and mixed cropping systems enhances agro-biodiversity and climate resilience. Furthermore, value addition through processing such as jams, jellies, fermented products, resins, gums, or cosmetics can increase economic returns and create niche market opportunities for growers.

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Advances in Grape Processing

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Abstract

Grapes (*Vitis vinifera* L.) are among the oldest cultivated fruit crops playing a significant role in global fruit processing industry. With rising consumer demand for healthy, natural, and functional foods, grape processing has undergone substantial technological advancements aimed at improving product quality, sustainability, and value-addition. Recent advances in grape processing with emphasis on byproduct valorization, innovative drying technologies, and green extraction techniques have own importance as futuristic approaches are more efficient and able to satisfy consumer demands. Grape pomace, a major by-product of wine and juice industries, has emerged as a valuable source of polyphenols, dietary fiber, and bioactive compounds, finding applications in functional foods, nutraceuticals, and active packaging. Novel abrasive pre-treatment system for grape drying offers an eco-friendly alternative to available pretreatment method for grape drying with reduced drying duration. Furthermore, green extraction technologies such as supercritical fluid extraction, ultrasound- and microwave-assisted extraction enable efficient recovery of thermolabile bioactive from grape residues, aligning with circular economy principles. Overall, these advancements demonstrate the potential of modern grape processing technologies to enhance economic returns, promote sustainability, and support the development of high-value functional products.

Grape is one of the very old fruit crops known to human. It is believed domestication of the grapevines began 6,000–8,000 years ago in the Transcaucasian region, between the Black Sea and Iran, from populations of *V. vinifera* subsp. *sylvestris* (Zohary and Hopf, 1993). The domesticated grapevine (*Vitis vinifera* L.) belongs together with about another 70 species to the *Vitis* genus (Wen *et al.*, 2018) and being one of the oldest and extensively cultivated fruit crops. The grapevines are commercially grown in all continents except Antarctica. In 2024, grapevines covered an area of 7.1 mha and production was 77.7 mt (OIV 2025). China, Italy, USA, Spain and France are major grape producing countries. As per available data, 33.3 mt of grapes (47%) is pressed to produce wines (30.5 mt) and juices (2.8 mt). The out of remaining grapes, 33.3 mt are consumed as table grapes (46%) and 5.2 mt (7%) is utilized for raisin making. According to an estimate, an area of 172.27 thousand ha was covered by vineyards and production was 3522.86 thousand tons during 2024-25. Maharashtra is major grape producer followed by Karnataka and Andhra Pradesh (Anonymous 2025). The grape utilization pattern in India is different than major grape producing countries. About 71% of total grape production is utilized for table purpose and about 2% for wine and juice while 27% is processed in the form of raisins (Sharma et al., 2018).

The grape processing is vibrating sector and experiencing robust growth, driven by increasing demand for grape-based products like wines, dried grapes, juices, concentrates, etc. It being affected by several factors like rising global consumption of processed foods and beverages, a growing preference for convenient and healthy options, and the increasing popularity of functional foods and beverages enriched with antioxidants and other beneficial compounds available in grapes. On the global arena, consumer preferences and technological advancements are main drivers of the grape processing industry. Now consumers are demanding healthier, more natural products, desiring innovation in processing methodologies, leading to reduced sugar content, increased use of natural preservatives, and focusing on sustainable approaches. The market demand for functional foods and beverages has background of health benefits beyond basic nutrition, is driving interest in grape-based products with enhanced antioxidants or other beneficial properties.

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Technological advancements

Valorization of grape pomace:

The grape pomace is byproduct from wine and juice industries. The large-scale production of wine increases the pressure of grape pomace disposal. According to an estimate, production of 6 L of wines generates 1 kg of grape pomace and globally about 10.5–13.1 million tons of grape pomace is generated globally (Dávila *et al.* 2017). The diverse nutritional or bioactive ingredients in grape pomace offer rich possibilities in utilization of different food materials or creating new products. However, a wide range in nutraceutical properties of grape pomace powder were observed by Sharma et al., (2018). The pomace can be utilized as food fortifies in traditional foods like bakery products (Sharma et al. 2023 and Maner *et al.*, 2017). Extracted polyphenols from pomace powder can be utilized into antioxidant ingredients, natural colorants, and preservatives. Recent studies demonstrated stabilized extracts with promising antioxidant and antimicrobial activity for incorporation into functional foods, dietary

supplements, and active packaging.

Grape drying: new approaches:

Grape drying is an oldest method of grape processing. Grape drying under natural conditions require longer duration, affect quality attributes also. The major hurdle for the natural drying of grapes to produce the raisins, is the presence of the waxy cuticle layer on the surface of the berry. Generally, the waxy layer is damaged by dipping of grape bunches in the solution of ethyl oleate and potassium carbonate. In this process a lot of chemicals is utilized along with water. The used chemicals can lead to soil and water pollution with unacceptability of raisins as organic product also. A novel industrial-scale abrasive pre-treatment system was developed, and its operating parameters were optimized. The physical pre-treatment system consists of the rotating drum with its inner surface of specific abrasive protrusions. The optimized abrasive pre-treatment taken less drying time (27.77%) in comparison to chemical pre-treatment of grapes (Pawar et al. 2021).

Green extraction techniques for grape valorization:

The valorization of grapes and their by-products through green extraction techniques have emerged as a sustainable strategy to enhance the economic and environmental value in modern grape industry. Grapes are rich in bioactive compounds such as polyphenols, flavonoids, anthocyanins, stilbenes (resveratrol), and dietary fibers, which exhibit various nutraceutical properties such as general antioxidant, antimicrobial, anti-cancerous, radio-protective, anti-aging and cardio protective properties etc. Traditional extraction methods often rely on organic solvents and energy-intensive processes following liquid-liquid extraction, raising concerns about low recovery of target bio-active compounds, environmental impact, safety, and regulatory compliance concerned with organic solvents etc. In contrast, green extraction approaches—such as supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme assisted extraction, natural deep eutectic solvents (NADES) extraction etc. offers eco-friendly alternatives that minimize solvent use, reduce energy consumption, and preserve thermolabile compounds enhancing the recovery of active substances. These techniques not only improve yield and selectivity but also align with circular economy principles by enabling the recovery of valuable compounds from grape pomace, seeds, and skins, which are typically discarded as agro-industrial waste ensuring additional income to the growers. The integration of green extraction into grape valorization supports the development of functional foods, nutraceuticals, cosmetics, and pharmaceutical formulations, thereby expanding market opportunities while reducing environmental burdens. Challenges in terms of cost-effectiveness, regulatory acceptance, and optimization for diverse grape matrices restrict their industrial adoption but ongoing research demonstrates promising pathways for sustainable exploitation. Overall, green extraction techniques represent a pivotal tool in transforming grape residues into high-value bioactive ingredients, contributing to resource efficiency, consumer safety, and the global transition toward sustainable food systems through a circular economy.

Grape seed oil: nutraceutical potential

The grape seed oil, containing the desired bioactive compounds, is then extracted from the seeds using a supercritical fluid extraction technique optimized by Response Surface Methodology. This extraction method employs a pressure ranging from 100 to 400 bar, a duration of 1 to 8 hours, and a solvent percentage ranging from 1 to 15%. It is noteworthy that ethanol, comprising 15% of the solvent, is the preferred choice for the extraction process (Anonymous 2023). The extracted grape seed oil contains various bioactive compounds, such as total Vitamin E, γ-tocotrienol, fatty acids, and polyphenols. Within the grape seed oil, the total Vitamin E content typically ranges from 1200 to 1500 mg/kg, while the γ-tocotrienol content falls between 890 and 1070 mg/kg. The presence of Vitamin E and phenolic compound present in oil make it as an ideal oil to use in nutraceutical products (Vitamin E supplement) and a cosmetic oil in dermatological therapy. The oil has proven to be beneficial for the treatment of hepatic inflammation related disorders in animal bodies. The polyphenolic constituents provide antioxidant properties on oral ingestion or dermal supplementation.

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Youth Dynamics in Agriculture and Horticulture Sector

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Abstract

Youth represent the most dynamic and innovative segment of our society. Their energy, adaptability, and openness to innovation make them crucial agents of transformation in agriculture and horticulture. The concept of **youth dynamics** refers to the changing roles, aspirations, capacities, and participation patterns of young people in Agri-food systems. Understanding these dynamics is essential for designing policies and interventions that can attract, retain, and empower youth in agriculture and horticulture. This lead paper explores the evolving role of youth in agriculture and horticulture, examines opportunities and constraints, highlights emerging trends and success stories, and suggests policy and institutional measures to harness youth potential for sustainable agricultural development.

Agriculture and horticulture continue to play a pivotal role in ensuring food and nutritional security, rural employment, and economic stability, particularly in developing countries like India. Despite structural changes in the economy, agriculture remains the largest source of livelihood for rural populations. However, the sector is currently facing a generational challenge, as a significant proportion of rural youth are gradually distancing themselves from traditional farming activities. At the same time, rapid advancements in technology, market integration, and value-chain development are creating new opportunities for youth engagement.

Demographic and Socio-Economic Context of Youth

Youth in agriculture largely come from rural households, facing limited land access and financial constraints. Their socio-economic context is shaped by high unemployment, migration pressures, and aspirations for modern, technology-driven farming. India is one of the youngest nations in the world, with nearly two-thirds of its population below the age of 35. This demographic dividend offers immense potential for economic growth if appropriately harnessed. A significant proportion of this youth population resides in rural areas and is directly or indirectly dependent on agriculture and allied sectors.

However, data trends indicate a gradual decline in youth participation in agriculture due to urban migration, limited profitability, land fragmentation, and changing career aspirations. The challenge lies not in the absence of youth but in making agriculture an attractive and viable livelihood option.

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Youth aspirations and changing perceptions

Youth aspirations in agriculture and horticulture are undergoing a significant transformation, driven by changing perceptions of farming as a modern, technology-enabled, and globally connected sector. Unlike earlier generations who often viewed agriculture as subsistence and low prestige, today's youth increasingly see it as a platform for innovation, entrepreneurship, and social impact. Their aspirations are shaped by opportunities in precision agriculture, digital platforms, startups, and export-oriented horticulture, each redefining the image of farming and making it more attractive to educated and ambitious young people.

Precision agriculture reflects this shift by appealing to youth who value efficiency, sustainability, and scientific innovation. With tools such as drones, GPS-guided machinery, and soil sensors, farming is no longer about guesswork but about data-driven decision-making. Young farmers aspire to use these technologies to maximize productivity while conserving resources, aligning their goals with both profitability and environmental stewardship.

Digital farming platforms have further changed perceptions by positioning agriculture as a knowledge-driven sector. Mobile apps and online portals provide real-time advisory, weather forecasts, and transparent market access, empowering youth with information and connectivity. For many young people, these platforms represent a way to bridge rural and urban divides, making farming more professional, transparent, and rewarding.

Start-ups and agripreneurship embody the entrepreneurial aspirations of youth, who increasingly view agriculture not just as cultivation but as a business ecosystem. Young entrepreneurs are building ventures in hydroponics, polyhouse farming, organic horticulture,

and Agri-tech solutions, tapping into niche markets and consumer trends. Their perception of agriculture is shaped by innovation, scalability, and impact, making it a sector where creativity and business acumen can thrive.

Export-oriented horticulture has redefined youth aspirations by connecting local production to global markets. High-value crops such as fruits, vegetables, and floriculture are cultivated with international standards, certifications, and post-harvest technologies. For youth, this represents an opportunity to engage in global trade, earn premium returns, and contribute to national economic growth. Their perception of horticulture is no longer limited to local consumption but extends to international competitiveness and global recognition.

Technical opportunities

Mobile-based advisory services

Mobile-based advisory services have become one of the most accessible technical opportunities for youth in agriculture. In India, platforms like **Kisan Suvidha**, **AgroStar**, and **DeHaat** provide real-time crop advisory, weather forecasts, pest alerts, and market price updates directly to farmers' phones. DeHaat, for example, has expanded to serve over **2 million farmers across 11 states**, offering end-to-end solutions from input supply to market linkages. Youth entrepreneurs are increasingly developing mobile apps that bridge the information gap between rural producers and urban consumers, making farming more knowledge-driven and profitable. With smartphone penetration in rural India exceeding **60% by 2025**, mobile advisory services represent a scalable and youth-friendly business model.

GIS and remote sensing

Geographic Information Systems (GIS) and remote sensing technologies provide youth with advanced tools to monitor and manage agricultural landscapes. These technologies enable mapping of soil types, crop health, water resources, and land use patterns, helping farmers optimize resource allocation. In India, the **National Remote Sensing Centre (NRSC)** has partnered with agricultural universities to train youth in satellite-based crop monitoring. Remote sensing applications are already being used in states like Maharashtra for sugarcane monitoring and Andhra Pradesh for paddy crop assessment. Youth-led consultancies offering GIS-based services are emerging, creating opportunities for precision farming and sustainable land management.

Artificial intelligence and data analytics

Artificial intelligence (AI) and data analytics are redefining agriculture by enabling predictive insights and smart decision-making. AI-powered platforms are being used to forecast crop yields, detect diseases, and recommend optimal input usage. Startups such as **CropIn** and **Intello Labs** are leveraging AI to provide farm-level intelligence and quality assessment of produce. CropIn, for instance, has digitized over **16 million acres of farmland** and works with thousands of farmers across India. For youth, AI offers opportunities to innovate in crop advisory systems, supply chain optimization, and smart irrigation solutions. With India's push toward **Digital Agriculture Mission 2021–2025**, young entrepreneurs are well-positioned to lead AI-driven innovations in farming.

Drones and IoT-enabled farm equipment

Drones and IoT-enabled farm equipment represent cutting-edge opportunities for youth to modernize agriculture and horticulture. Drones are increasingly used for aerial mapping, crop monitoring, and spraying fertilizers and pesticides. In 2022, the Government of India launched the **Drone Rules** and provided subsidies for drone adoption in agriculture, encouraging youth to establish drone service businesses. IoT devices such as soil moisture sensors and automated irrigation systems are being deployed in polyhouses and orchards, allowing real-time monitoring and control of farm operations. Startups like **Fasal** are using IoT-enabled devices to provide precision irrigation and crop advisory, helping farmers save up to **30% water and increase yields by 20%**. For youth, these technologies open avenues to create service-based enterprises offering drone mapping, IoT installations, and smart farm management solutions.

Horticulture as a youth-friendly sector

Horticulture has increasingly emerged as a youth-friendly sector in India, offering diverse technical opportunities that combine profitability, innovation, and sustainability. One of the most attractive avenues is **protected cultivation through polyhouses and greenhouses**, which enables year-round production under controlled environments. Case studies from Uttar Pradesh and Haryana show that polyhouse farming allows small-scale farmers to grow vegetables and flowers profitably despite climate variability. Youth-led ventures in protected cultivation are particularly successful in producing high-value crops such as capsicum, cucumbers, and roses, which fetch premium prices in urban and export markets. Government subsidies under the National Horticulture Mission (NHM) and state-level programs further encourage young entrepreneurs to adopt this model. Another promising area is **floriculture and ornamental plants**, which cater to growing domestic and international demand. India has over **285,000 hectares under floriculture cultivation**, producing more than **3.2**

million metric tonnes of flowers annually, making it the second-largest producer globally. Youth-led initiatives in states like Karnataka, Tamil Nadu, and Mizoram have tapped into export markets for roses, orchids, and anthuriums. The **CSIR Floriculture Mission**, launched in 2020, has supported entrepreneurship development by providing training, improved varieties, and market linkages. For young entrepreneurs, floriculture combines creativity with profitability, offering opportunities in nurseries, landscaping, and exports.

Equally important are **fruit orchards and vegetable clusters**, which provide long-term income and collective strength. The **Cluster Development Programme (CDP)** launched by the National Horticulture Board in 2024 aims to make horticulture clusters globally competitive by leveraging geographical specializations. Youth participation in mango clusters in Andhra Pradesh, grape clusters in Maharashtra, and vegetable clusters in Uttar Pradesh has improved supply chain efficiency, reduced post-harvest losses, and enhanced bargaining power. These initiatives also align with nutritional security goals, making them socially impactful as well as economically viable.

Finally, **medicinal and aromatic plants** present youth with opportunities to enter specialized markets linked to wellness, pharmaceuticals, and cosmetics. India is gifted with over **8,000 medicinal and 2,500 aromatic herbs**, many of which are in high demand globally. Youth-led ventures cultivating aloe vera, tulsi, lemongrass, and lavender have successfully tapped into value-added markets by producing oils, extracts, and herbal products. The **National Medicinal Plants Board (NMPB)** supports training and entrepreneurship in this sector, while case studies from Punjab and Bihar highlight how youth entrepreneurs are building profitable businesses around medicinal crops. With rising consumer preference for natural and organic products, this niche sector offers sustainable and lucrative opportunities for young farmers.

Agripreneurship and startups

Youth-led Agri-startups are emerging across the value chain, including:

Agripreneurship as a pathway for youth

Agripreneurship represents a paradigm shift in how young people engage with agriculture and horticulture. Instead of viewing farming as subsistence, youth increasingly see it as a business opportunity that combines innovation, sustainability, and profitability. Agripreneurship allows them to reimagine agriculture as a modern enterprise, integrating production, processing, logistics, and marketing into cohesive value chains. This entrepreneurial approach not only generates income but also creates employment opportunities for peers, thereby reducing ruralto-urban migration. By positioning agriculture as a sector of innovation and growth, Agripreneurship makes farming attractive to educated youth who might otherwise seek careers outside rural economies.

Technology-driven start-ups

Youth-led startups are harnessing cutting-edge technologies to address long-standing challenges in agriculture and horticulture. Mobile applications provide advisory services, weather forecasts, and market linkages, empowering farmers with real-time information. IoT-based solutions enable precision farming by monitoring soil moisture, nutrient levels, and crop health. Blockchain platforms ensure transparency and traceability in value chains, enhancing consumer trust. Artificial intelligence and machine learning are being applied to predictive analytics for crop yields, pest management, and resource optimization. In horticulture, startups focusing on hydroponics, vertical farming, and polyhouse cultivation are redefining production systems, making them more resilient and resource-efficient. These ventures demonstrate how technology can transform agriculture into a dynamic, youth-driven sector.

Horticulture-specific ventures

Horticulture offers unique opportunities for youth agripreneurs due to its high-value crops and diverse market potential. Startups in floriculture, organic fruits and vegetables, and exotic plant cultivation are tapping into urban and global demand. Protected cultivation models such as polyhouses and greenhouses allow year-round production, ensuring consistent supply and profitability. Youth-led ventures in urban horticulture, including rooftop gardens and vertical farming, are addressing food insecurity in cities while promoting sustainability. By focusing on horticulture, young entrepreneurs can create niche markets, diversify income streams, and contribute to nutritional security.

Government support and policy framework

Government initiatives have played a crucial role in fostering Agripreneurship among youth. Programs such as **Start-up India**, **Agri-Infra Fund**, and incubation centers in agricultural universities provide financial support, mentorship, and training. Schemes like **PM-Kisan** and

Skill India further enhance youth participation by offering direct benefits and skill development opportunities. These policies aim to reduce barriers to entry, encourage innovation, and create an enabling environment for youth-led startups. However, effective implementation and awareness are essential to ensure

that young entrepreneurs can fully leverage these opportunities. **4.3.5 Case Studies of youth-led start-ups**

Several successful startups illustrate the potential of youth Agripreneurship. **DeHaat**, founded by young entrepreneurs, provides end-to-end services including input supply, advisory, and market linkages, benefiting thousands of farmers across India. **AgroStar** empowers smallholders through digital platforms that deliver crop solutions directly to their phones. In horticulture, ventures like **Farm2Fam** and **Kheyti** have pioneered organic production and greenhouse farming models, showcasing how youth can combine innovation with sustainability. These case studies highlight that Agripreneurship is not limited to farming but extends to building scalable businesses that integrate technology, logistics, and consumer engagement.

Agripreneurship as social impact

Beyond profitability, Agripreneurship enables youth to create social impact by addressing rural unemployment, food insecurity, and environmental sustainability. Youth-led startups often prioritize eco-friendly practices such as organic farming, waste recycling, and renewable energy integration. They also foster inclusivity by involving women and marginalized groups in entrepreneurial ventures. By combining innovation with social responsibility, Agripreneurship ensures that agriculture and horticulture evolve into resilient sectors capable of meeting future demands while contributing to equitable development.

5. Government incubator support programs

Government-backed incubator support plays a crucial role in empowering aspiring graduates in agriculture and horticulture by providing them with funding, mentorship, and infrastructure to transform innovative ideas into successful ventures. One of the most prominent initiatives is the

Agri-Business Incubators (ABIs), established under ICAR, State Agricultural Universities

(SAUs), and the RKVY-RAFTAAR scheme. These incubators offer seed funding of up to ₹25 lakhs, along with expert mentoring and access to facilities. They focus on areas such as crop protection, seed production, irrigation, post-harvest handling, and value chain management, making them highly relevant for graduates entering the Agri-sector.

In addition to ABIs, **Rural Business Incubators (RBIs)** are designed to promote entrepreneurship in rural areas. They provide training, infrastructure, and market linkages to graduates who want to establish ventures in processing, packaging, cold chain logistics, and

Agri-based services. These incubators are often connected with state agricultural universities and Krishi Vigyan Kendras (KVKs), ensuring that rural youth and graduates have access to localized support systems.

Another major pillar of support comes from **NABARD**, which has launched several initiatives to strengthen agribusiness incubation. NABARD provides grant funding and credit support through programs such as the Agri-Business Incubation Fund and the Rural Innovation Fund. These schemes help graduates with early-stage ideas and encourage innovation in rural enterprises. NABARD also collaborates with universities, NGOs, and state-level institutions to build incubation ecosystems that are inclusive and accessible.

The **Atal Innovation Mission (AIM)**, spearheaded by NITI Aayog, further expands opportunities for graduates by supporting Atal Incubation Centres (AICs) and Atal Community Innovation Centres (ACICs). AIM provides grants of up to ₹10 crores to establish incubation centres and offers structured mentorship for startups. It emphasizes the integration of modern technologies such as IoT, AI, blockchain, and precision farming into agriculture, enabling graduates to adopt cutting-edge solutions for sustainable growth.

Together, these initiatives create a comprehensive ecosystem for aspiring graduates in agriculture and horticulture. They not only provide financial assistance but also mentorship, networking opportunities, and skill development in areas like packaging, cold chain logistics, and technology integration. However, challenges remain, including competitive selection processes, scalability hurdles, inclusivity gaps for women and rural youth, and the need for stronger market linkages. Addressing these challenges will be key to ensuring that graduates can successfully move from idea to incubation, funding, and eventually scaling their ventures.

Role of ICAR-NAARM in shaping youth towards agriculture and horticulture sectors

The NAARM plays a pivotal role in shaping youth for leadership in agriculture and horticulture through its flagship PGDM-ABM programme and its incubation arm a-IDEA, combining academic excellence with entrepreneurial support.

PGDM-ABM Programme

The **Post Graduate Diploma in Management – Agri Business Management (PGDM-ABM)** is a premier AICTE-approved programme offered by ICAR-NAARM, Hyderabad. It is designed to prepare graduates for careers in agribusiness, horticulture, and allied sectors. The curriculum blends management principles

with agricultural sciences, covering areas such as supply chain management, rural marketing, food processing, and Agri-finance. The programme emphasizes **experiential learning**, case studies, and industry internships. It has a strong record of **placements in leading agribusiness firms, banks, and startups**, ensuring youth are industry-ready. Alumni have contributed significantly to **agribusiness job creation and entrepreneurship**, strengthening India's agricultural economy

a-IDEA: NAARM's Agribusiness Incubator: The NAARM also houses a-IDEA (Association for Innovation Development of Entrepreneurship in Agriculture), it's Technology Business Incubator. The a-IDEA supports startups in agriculture, horticulture, and food processing through incubation, mentoring, and seed funding. It has nurtured ventures in precision farming, Agri-tech platforms, organic inputs, and value chain innovations. The incubator collaborates with NABARD, RKVY-RAFTAAR, and Atal Innovation Mission, giving youth access to national-level funding and networks. Events like Agri-Eureka and Startup Days provide platforms for young entrepreneurs to pitch ideas and connect with investors.

NAARM's broader role in youth empowerment

Beyond PGDM-ABM and a-IDEA, NAARM contributes to youth development by: Offering **capacity-building programs** in agricultural research and education management. Providing **policy and consultancy support** to strengthen agricultural innovation ecosystems. Acting as a hub for entrepreneurship, skill development, and technology transfer in agriculture and horticulture Together, the PGDM-ABM programme and a-IDEA incubator create a **dual pathway for youth**: Academic and managerial training for careers in agribusiness. Entrepreneurial incubation for those who want to launch startups in agriculture and horticulture.

This synergy ensures that graduates are not only employable but also capable of becoming **job creators, innovators, and leaders** in the Agri-sector.

Challenges faced by youth in agriculture and horticulture

Youth in agriculture and horticulture face barriers such as limited land access, financial constraints, and skill gaps. Market volatility, climate risks, and low social prestige further discourage sustained youth participation in the sector.

Limited access to land and resources

One of the most pressing challenges faced by youth in agriculture and horticulture is limited access to land. In many rural areas, land ownership is concentrated among older generations, leaving young people dependent on family holdings or unable to acquire land for independent ventures. This lack of ownership restricts their ability to experiment with modern practices, secure loans, or invest in long-term projects such as orchards and polyhouses. Alongside land, access to resources such as quality seeds, irrigation facilities, and mechanization remains uneven, creating barriers for youth who aspire to modernize farming.

Financial constraints and credit barriers

Youth often struggle to access credit and financial support due to institutional hesitancy and perceived risks. Banks and financial institutions are reluctant to lend to young farmers who lack collateral or established track records. Even when schemes exist, bureaucratic hurdles and lack of awareness prevent youth from benefiting fully. This financial exclusion limits their ability to invest in high-value horticulture, adopt advanced technologies, or establish Agripreneurship ventures. As a result, many young people are discouraged from pursuing agriculture as a viable career option.

Skill gaps and knowledge limitations: Another major challenge is the gap in skills and knowledge. While traditional farming practices are passed down through generations, modern agriculture requires expertise in areas such as precision farming, digital platforms, supply chain management, and export standards. Many youth lack exposure to these advanced practices due to inadequate training facilities, limited extension services, and weak linkages between universities and rural communities. Without proper capacity building, young farmers find it difficult to compete in increasingly globalized and technology-driven markets.

Market volatility and infrastructure deficits: Youth engaged in agriculture and horticulture also face challenges related to market volatility and poor infrastructure. Prices of fruits, vegetables, and flowers fluctuate widely, often leaving farmers vulnerable to losses. Inadequate cold chain facilities, storage systems, and transportation networks exacerbate post-harvest losses, particularly in horticulture where perishability is high. Young entrepreneurs attempting to build businesses around horticulture often struggle to maintain consistent supply and quality due to these systemic gaps.

Social perceptions and migration pressures: Agriculture continues to be perceived by many youth as a low-prestige occupation compared to urban employment opportunities. This perception drives rural-to-urban migration, leaving behind an aging farming population. Young people often aspire to careers in technology, services, or industry, viewing agriculture

as less rewarding. Changing these perceptions requires showcasing agriculture as a modern, entrepreneurial, and innovation-driven sector. Without this shift, youth participation will remain limited, and the sector risks losing its most dynamic workforce.

Climate change and environmental risks: Finally, climate change poses a significant challenge for youth in agriculture and horticulture. Increasingly unpredictable rainfall, rising temperatures, and frequent pest outbreaks threaten productivity and profitability. Young farmers, who often lack financial buffers and insurance coverage, are particularly vulnerable to these risks. Climate-smart practices and resilient technologies are essential, but adoption remains slow due to cost and knowledge barriers. This environmental uncertainty discourages youth from investing in long-term agricultural ventures.

Institutional and Policy Support for Youth Engagement

Government schemes and programs

Institutional support for youth in agriculture and horticulture is anchored in government schemes that provide financial assistance, training, and infrastructure. Initiatives such as **PM-Kisan Samman Nidhi**, **Agri-Infra Fund**, and the **National Horticulture Mission (NHM)** offer direct benefits to farmers, subsidies for protected cultivation, and credit support for agribusiness ventures. These programs reduce entry barriers for youth, enabling them to adopt modern technologies, establish horticulture clusters, and participate in value-added activities. By targeting young farmers, these schemes encourage innovation and entrepreneurship in agriculture.

Skill development and capacitybuilding

Skill development programs play a critical role in empowering youth to engage with modern farming practices. The **Skill India Mission**, agricultural universities, and Krishi Vigyan Kendras (KVKs) provide training in areas such as precision farming, polyhouse cultivation, floriculture, and Agripreneurship. Specialized incubation centres in agricultural institutions further support youth-led startups by offering mentorship, technical guidance, and business development services. These capacity-building initiatives ensure that young farmers are equipped with the knowledge and skills required to compete in globalized and technology-driven markets.

Institutional credit and financial inclusion

Access to affordable credit is essential for youth participation in agriculture and horticulture. Institutions such as **NABARD** and cooperative banks provide loans and financial products tailored to young farmers and entrepreneurs. The **Stand-Up India** and **MUDRA Yojana** schemes encourage youth to establish agribusinesses by offering collateral-free loans and financial support. These measures address one of the biggest challenges faced by youth—lack of capital—and enable them to invest in high-value horticulture, modern equipment, and exportoriented ventures.

Market linkages and infrastructure support

Institutional support also extends to market linkages and infrastructure development. Platforms like **e-NAM (Electronic National Agriculture Market)** provide transparent and accessible markets for youth farmers, while government investments in cold chains, pack houses, and logistics strengthen horticulture supply chains. Cluster development programs initiated by the National Horticulture Board (NHB) aim to make horticulture globally competitive by leveraging geographical specializations. These initiatives ensure that youth-led ventures can access markets efficiently, reduce post-harvest losses, and enhance profitability.

Policy frameworks for youth engagement

Policy frameworks increasingly recognize the importance of youth in driving agricultural transformation. Programs such as **Start-up India**, **Digital Agriculture Mission**, and state-level horticulture policies encourage youth to adopt technology, build startups, and engage in exportoriented production. By integrating youth into national agricultural strategies, these policies position them as key stakeholders in achieving food security, sustainability, and rural development.

Youth-led innovations and case illustrations

Technology-driven innovations

Youth-led innovations are reshaping agriculture and horticulture by integrating modern technologies into traditional practices. Startups founded by young entrepreneurs are leveraging mobile apps, artificial intelligence, and IoT devices to provide real-time advisory services, precision farming solutions, and supply chain management tools. For instance, platforms like **DeHaat** and **AgroStar**, created by young innovators, deliver end-to-end services including input supply, crop advisory, and market linkages. These ventures demonstrate how youth are using digital tools to bridge information gaps, improve productivity, and empower smallholder farmers.

Protected cultivation and smart farming models

Young entrepreneurs are pioneering protected cultivation models such as polyhouses, hydroponics, and vertical farming. These innovations allow year-

round production of high-value crops with controlled environments, ensuring better quality and higher yields. Case illustrations include **Kheyti**, a youth-led startup that developed affordable greenhouse solutions for small farmers, enabling them to increase incomes while reducing climate risks. Such models highlight how youth are combining technology with sustainability to make horticulture more resilient and profitable.

Value addition and agribusiness ventures

Youth are also driving innovations in value addition and agribusiness. Ventures like **Farm2Fam** focus on organic horticulture and direct-to-consumer models, ensuring traceability and quality assurance. Others are exploring food processing, packaging, and cold chain logistics to reduce post-harvest losses and enhance market competitiveness. These case illustrations show that youth are not limiting themselves to production but are building integrated businesses that span the entire value chain, from farm to fork.

Export-oriented horticulture

Another area where youth-led innovations are making an impact is export-oriented horticulture. Young entrepreneurs are adopting international standards, certifications, and post-harvest technologies to meet global market requirements. For example, grape clusters in Maharashtra and mango exporters in Andhra Pradesh have seen significant youth participation, with startups facilitating quality control and logistics for international shipments. These ventures illustrate how youth are positioning horticulture as a globally competitive sector, contributing to foreign exchange earnings and national economic growth.

Social impact and inclusivity

Beyond profitability, youth-led innovations often emphasize social impact and inclusivity. Many startups involve women and marginalized groups in horticulture ventures, promoting equitable participation. Initiatives in medicinal and aromatic plants, such as aloe vera and tulsi cultivation, have created opportunities for rural youth to engage in wellness and herbal product markets.

These case illustrations highlight that youth are not only innovators but also change-makers, ensuring agriculture evolves into a sector that is sustainable, inclusive, and socially responsible.

Policy recommendations

Enhancing access to land and finance

A key policy recommendation is to improve youth access to land and affordable finance. Land leasing reforms, cooperative ownership models, and youth-focused land banks can help overcome barriers to entry. Financial institutions should design tailored credit products for young farmers, including collateral-free loans, flexible repayment schedules, and startup grants. Expanding schemes like **MUDRA Yojana**, **Agri-Infra Fund**, and youth-targeted subsidies will encourage investment in horticulture ventures such as polyhouses, orchards, and floriculture.

Strengthening skill development and capacity building

Policies must prioritize skill development to equip youth with modern agricultural knowledge. Expanding training programs under **Skill India**, Krishi Vigyan Kendras (KVKs), and agricultural universities can provide hands-on exposure to precision farming, digital platforms, and export standards. Establishing dedicated incubation centres for Agripreneurship will foster innovation and mentorship. These measures ensure that youth are not only producers but also innovators capable of building scalable agribusinesses.

Promoting technology adoption and innovation

Youth-friendly policies should incentivize the adoption of advanced technologies such as drones, IoT-enabled equipment, GIS mapping, and AI-driven advisory systems. Subsidies for protected cultivation, digital farming platforms, and smart irrigation systems can accelerate modernization. Encouraging public-private partnerships in Agri-tech will create opportunities for youth-led startups to thrive. By embedding technology into policy frameworks, agriculture becomes more attractive to digitally literate youth.

Building market linkages and infrastructure

Policies must strengthen market linkages and infrastructure to reduce post-harvest losses and improve profitability. Expanding platforms like **e-NAM** and supporting Farmer Producer Organizations (FPOs) will enhance youth participation in transparent markets. Investments in cold chains, pack houses, and logistics hubs are essential for horticulture, where perishability is high. Cluster-based development programs should be scaled up to make fruit, vegetable, and floriculture clusters globally competitive, providing youth with sustainable income opportunities.

Encouraging export-oriented horticulture

Export promotion policies should focus on youth-led horticulture ventures by supporting international certifications, quality assurance systems, and trade facilitation. Incentives for medicinal and aromatic

plants, floriculture, and exotic fruits can help young entrepreneurs tap into global wellness and lifestyle markets. Strengthening linkages with export promotion councils and providing training in global standards will position youth as key players in international agri-trade.

Fostering inclusivity and social impact

Finally, policies must ensure inclusivity by encouraging youth participation across gender and marginalized communities. Special incentives for women-led horticulture startups, cooperative models, and social enterprises can broaden representation. Integrating sustainability goals—such as organic farming, renewable energy use, and climate-smart practices—into youth-focused policies ensures that agriculture evolves as both profitable and socially responsible.

Future trends

Technology-enabled farming

The future of youth in agriculture and horticulture will be shaped by rapid adoption of advanced technologies. Precision Farming, Drones, IoT-enabled equipment, and artificial intelligence will become mainstream, allowing young farmers to optimize resource use, reduce costs, and increase productivity. Digital platforms will continue to expand, offering advisory services, market linkages, and real-time data, making agriculture more knowledge-driven and attractive to techsavvy youth.

Diversification into high-value crops

Youth participation will increasingly focus on horticulture and high-value crops such as fruits, vegetables, floriculture, and medicinal plants. Protected cultivation models like polyhouses, hydroponics, and vertical farming will gain prominence, enabling year-round production and premium quality outputs. This diversification will not only enhance profitability but also align with consumer demand for organic, exotic, and nutritionally rich produce.

Agripreneurship and start-ups

The rise of Agripreneurship will continue to redefine youth dynamics in agriculture. Startups focusing on farm-to-fork models, value addition, packaging, and cold chain logistics will expand, creating new business opportunities beyond traditional farming. Youth-led ventures will integrate technology, sustainability, and social impact, positioning agriculture as a modern entrepreneurial sector. Government incubation centres and funding schemes will further accelerate this trend, encouraging risk-taking and innovation among young entrepreneurs.

Global market integration

Export-oriented horticulture will become a major avenue for youth, with increasing demand for Indian fruits, vegetables, spices, and floriculture in international markets. Young entrepreneurs will adopt global certifications, traceability systems, and post-harvest technologies to meet international standards. This integration into global value chains will not only generate foreign exchange but also elevate the profile of youth-led ventures as globally competitive businesses.

Sustainability and climate-smart practices

Future youth dynamics will also be shaped by sustainability and climate resilience. Young farmers are expected to adopt eco-friendly practices such as organic farming, renewable energy integration, and waste recycling. Climate-smart agriculture will be critical to mitigate risks from unpredictable weather and environmental challenges. Youth-led innovations in sustainable horticulture will ensure that agriculture evolves as both profitable and environmentally responsible.

Conclusion

Youth dynamics hold the key to the future of agriculture and horticulture. By transforming agriculture into a modern, technology-driven, and profitable sector, youth can become central actors in ensuring food security, sustainability, and rural prosperity. With enabling policies, institutional support, and innovation-driven ecosystems, agriculture can evolve into a preferred career choice for youth rather than a last resort. Investing in youth today is essential for building resilient and future-ready Agri-food systems.

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Development of Phytonutrient and Mineral-rich Potatoes in India

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Abstract

Potato is an important food crop for providing nutritional security in our daily diet. It is the most consumed and produced crop after wheat, rice, and maize. The potato provides food security for billions of people worldwide. Potatoes are a crucial food source globally due to their high yield per unit area and rich nutrient content, including carbohydrates, proteins, fiber, vitamin C (ascorbic acid), vitamin B6 and minerals like potassium and manganese. Compared with other food crops, potato provides the highest yield per unit area and time. Potato has largely been considered a carbohydrate-rich food; however, in the recent past, introgression of nutrient-rich germplasm to the modern potato varieties helped to enhance the bioavailability of important phytonutrients (anthocyanins and carotenoids) and minerals (iron and zinc) in the potato crop. Fresh potatoes and their processed products are rich sources of various bioactive compounds, including carotenoids, anthocyanins, and phenolics. Carotenoids, a class of phytochemicals responsible for the pigmentation of many foods, play a crucial role in disease prevention and overall health maintenance. They contribute to immune system enhancement, provide provitamin 'A' activity, and exhibit potent antioxidant properties. Ascorbic acid (vitamin C) functions primarily as an antioxidant and electron donor, supporting collagen synthesis and facilitating iron absorption. Anthocyanins possess a broad spectrum of pharmacological properties, including anti-obesity and cardioprotective effects, as well as strong antioxidant activity. Zinc, an essential trace element, supports wound healing, cell division, growth, and immune function, and serves as a structural and catalytic component in numerous enzymes and proteins. Iron deficiency, or anaemia, is a major public health concern in India, affecting 50–70% of the population across all demographic groups. It is particularly prevalent among infants, young children, adolescent girls, women of reproductive age, and pregnant women. Both rural and urban populations are affected equally; however, gender disparities emerge around adolescence, with females becoming increasingly vulnerable to iron deficiency (Dalamu *et al.* 2023).

Traditionally, potatoes with white or yellow pulp have been the most preferred varieties across the country. Apart from this, consumer demand is gradually shifting towards coloured potatoes due to their enhanced nutritional value. These preferences also vary by region. Traditionally, certain geographical areas of our country preferred red peel varieties like Kufri Red, Kufri Sindhuri, Kufri Lalima, Kufri Kanchan, Kufri Arun, Kufri Lohit, Kufri Uday, having superior consumer preference texture. For instance, red-skinned potatoes are commonly favoured in the eastern plains, north eastern region, north Bengal hills, Himachal Pradesh and parts of Jammu and Kashmir have special preference for red/purple/black peel varieties and locally maintained clones. Similarly, in **Bareilly district (Uttar Pradesh)**, the local cultivar **'Bareilly Red'** is highly valued among regional consumers due to its **dark red tubers**, **variegated flesh colour**, and **waxy texture** (Luthra *et al.* . 2020). Institute has developed a number of varieties with red peel varieties and among these Kufri Sindhuri and Kufri Lalima are largely been cultivated in the eastern plains of India. Looking at the rising demand of nutrient dense varieties ICAR-CPRI has recently developed several colourful genotypes featuring red and purple skin (peel) and pulp, rich in these health-promoting nutrients viz; Kufri Manik, Kufri Neelkanth, Kufri Jamunia and Kufri Ratan. The detailed information (Fig-1) on each variety is given below:

***Kufri Neelkanth*:** Kufri Neelkanth first ever purple skin specialty potato variety with yellow flesh colour was released in 2018. This variety is developed and released by ICAR-CPRI for planting in the main crop in the plains. Its tubers are beautiful purple, oval with shallow eyes and yellow flesh. Antioxidants (anthocyanin and carotenoids) in this variety are higher than other red colored varieties. It is a medium-duration variety and can yield up to about 35-38 tons per hectare. The dry matter content in this variety is 17-18 percent. It has moderate resistance to late blight disease and has good storage capacity. Antioxidant levels in the variety are as under:

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Antioxidant status in specialty purple coloured Kufri Neelkanth

Genotypes	Anthocyanin in flesh ug/100 g FW	Carotenoids in flesh ug/100 g FW	Ascorbic acid in flesh mg/100g FW
Kufri Neelkanth*	108	292	26.00
Kufri Lalima	34.0	30.0	21.83
Kufri Sindhuri	37.0	32.0	21.12
Kufri Lalit	80.0	41.0	50.64

***Anthocyanin in peel 410 ug/100 g FW,** Luthra *et al.* 2020

***Kufri Manik*:** Kufri Manik was released in 2021. This variety is suitable for growing in the eastern plains. The tubers of this variety are red, round, medium-deep with eyes and the pulp is yellow . It is a medium-duration variety (90-100 days). The yield capacity is about 25-30 tons per hectare. It has a good storage capacity and has a dry matter content of 18-19 percent. This variety is resistant to blight disease. This variety is high in iron and zinc and is good for our health. Antioxidant levels, zinc and iron contents in the variety are as under:

Antioxidants, zinc and iron status in specialty purple coloured variety Kufri Manik

Genotypes	Anthocyanin in flesh ug/100 g FW	Zinc mg/100 g DW	Iron mg/100 g DW	Phenols in flesh mg/100g FW
Kufri Manik	68	33	30	71

Shambhu Kumar *et al.* 2023

Kufri Jamunia: It was released in 2024. This variety is suitable for growing in the plains. The tubers of this variety are dark purple, long oval, shallow-eyed and the pulp is purple. It is a medium-duration variety (90-100 days). Its yield potential is about 32-35 tons per hectare. It has a good storage capacity and has a dry matter content of 19 percent. Antioxidants (anthocyanins and carotenoids) and vitamin C in this variety is higher than other red colored varieties which are known to have beneficial effects on human health. It possesses higher levels of anti-oxidants as under:

Antioxidant status in specialty purple coloured variety Kufri Jamunia

Genotypes	Anthocyanin in flesh ug/100 g FW	Carotenoids in flesh ug/100 g FW	Ascorbic acid in flesh mg/100g FW
Kufri Jamunia	32.0	163	52.00

Luthra *et al.* 2025

***Kufri Ratan*:** Kufri Ratan was released in 2024. This variety is suitable for growing in plains and plateau areas. The tubers of this variety are dark red, oval, shallow to medium-eyed and with yellow pulp. It is a medium-duration variety (90-100 days). It has a yield potential of 36-38 tons per hectare. It has a good storage capacity and has tuber dry matter content of 17-18 percent. This variety has a moderate level of resistance to late blight disease.

Nutritional values: Kufri Ratan is nutrient-dense variety by virtue of high anthocyanin (632 ug/100g FW), Zinc (273.7 ppm), Iron (41.8 ppm) and vitamin C (33.3mg) as compared to red skin control varieties like Kufri Lalima and Kufri Lalit.

Antioxidants, zinc and iron status in specialty red coloured (peel) variety Kufri Ratan

Genotypes	Anthocyanin in flesh ug/100 g FW	Carotenoids in flesh ug/100 g FW	Ascorbic acid in flesh mg/100g FW	Zinc in flesh ug/100 g FW	Iron in flesh ug/100 g FW
Kufri Ratan	632.0	26.1	33.3	27.7	41.8
Kufri Lalima	336.0	17.2	21.9	22.0	35.29
Kufri Lalit	135.0	68.3	31.7	28.8	43.9

Luthra *et al.* 2025

Conclusion

Thus, looking at the importance of phytonutrients, minerals and dietary habits of common Indians promoting nutrient rich potatoes would not only fulfil the economic advantage of its cultivation but this will also provide excellent source of nutrients to the deficient population of our country. In line with growing consumer interest in nutrient-rich foods, efforts to develop bio-fortified coloured potato varieties are continued. Farmers are



encouraged to select varieties that are best suited to their local climate and specific agricultural needs. By cultivating improved, high-yielding varieties with desirable colour and nutritional traits, farmers can enhance both their productivity and profitability. Export potential can also be harnessed in the coming time for destinations like Bangladesh, Bhutan, Nepal, Pakistan, and Philippines, where red-skinned tubers are traditionally preferred.

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Pre-breeding and Introgression: Bridging Genetic Diversity to Crop Improvement in Horticulture

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Abstract

Pre-breeding has emerged as a strategic and promising approach for effectively linking plant genetic resources (PGRs) with mainstream crop improvement programmes. It serves as a critical interface between conserved germplasm and applied breeding by facilitating the identification, transfer, and utilization of valuable traits from unadopted or under-utilized genetic resources into breeding-ready materials. The scope of pre-breeding encompasses its conceptual framework, objectives, applications, importance, and diverse methodologies aimed at broadening the genetic base of cultivated crops. Crop wild relatives (CWRs) represent an invaluable reservoir of genetic diversity, having evolved under diverse ecological conditions and natural selection pressures that enabled their survival and adaptation to a wide range of biotic and abiotic stresses. The importance of CWRs was first systematically recognized by the Russian botanist N. I. Vavilov, who, during the 1920s, identified the geographical centres of origin and diversity of cultivated crops. Since then, CWRs have been increasingly acknowledged as vital genetic resources for enhancing crop adaptability, particularly for improving resistance to diseases and insect pests.

In horticultural crops, breeding efforts extend beyond yield and yield-contributing traits to include quality attributes, nutritional value, and adaptive traits essential for performance in marginal habitats and stress-prone environments. The impacts of global climate change—manifested through increased frequency and intensity of droughts, floods, temperature extremes, and the emergence of new pest and pathogen races—pose serious challenges to sustainable horticultural production. In this context, the effective utilization of conserved genetic diversity has become increasingly important, reinforcing the renewed global emphasis on PGR-related activities. The pre-breeding and introgression work in several vegetable crops have been done across globe is presented in (Table,1,).

Table 1. Important traits improved in vegetable crops through pre breeding approach

Crop	Findings
Tomato	Genetic enhancement of popular tomato varieties for introgression of tomato leaf curl disease (ToLCD) resistance utilizing LA1777 an accession of Solanum habrochaites in India
	Divergent genes resistant to infections have been backcrossed and included in commercial hybrids produced with various natural resources. These genes are found on distinct tiny chromosomal regions that derive from various donor species. Fruit with an important gene introduced from a wild tomato species (Lycopersicon pennellii B.) raised by a factor of fifteen in pro-vitamin A.
	Demonstrated that diploid plants from the offspring of monosomic alien addition lines (MAALs) of S. lycopersicoides may be identified for use as donors in tomato breeding to improve characteristics that are wanted. novel characteristics in the MDILs associated with drought tolerance that are not present in the fields of parents.
Brinjal	It has been tried to pre-breed for bacterial wilt resistance.
Potato	In the genetically incompatibility species S. bulbocastanum, four cloned wide-spectrum genes (Rpi) resistant to the infection of Phytophthora infestans were discovered. Plants having each of the four-leaf blight-resistant genes had been chosen in trials performed in both greenhouse and outside environments. Somatic hybridization combined with gene-specific markers along with associated Avr effectors offers a successful approach of discovering and delivering late blight genes for resistance through the potato gene pool.
Cauliflower	Interspecific asymmetric somatic hybrids of Brassica oleracea var. botrytis (cauliflower) and Brassica nigra (black mustard) were created by protoplast fusion, and the backcrossed (BC3) and selfed (S3) offspring were seen.
Asparagus	Using crop wild relatives (CWR) such as A. maritimus, A. pseudoscaber, A. brachyphyllus, and A. macrorrhizus to produce novel plant material has widened the genetic base. The results demonstrate an increase in genetic variability, presenting new opportunities for improving asparagus.
French bean	Wild relatives are a valuable source of novel alleles that can be utilized to enhance yield and other quantitative traits

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There are some very peculiar examples of pre-breeding and trait introgression in India which are as follows:

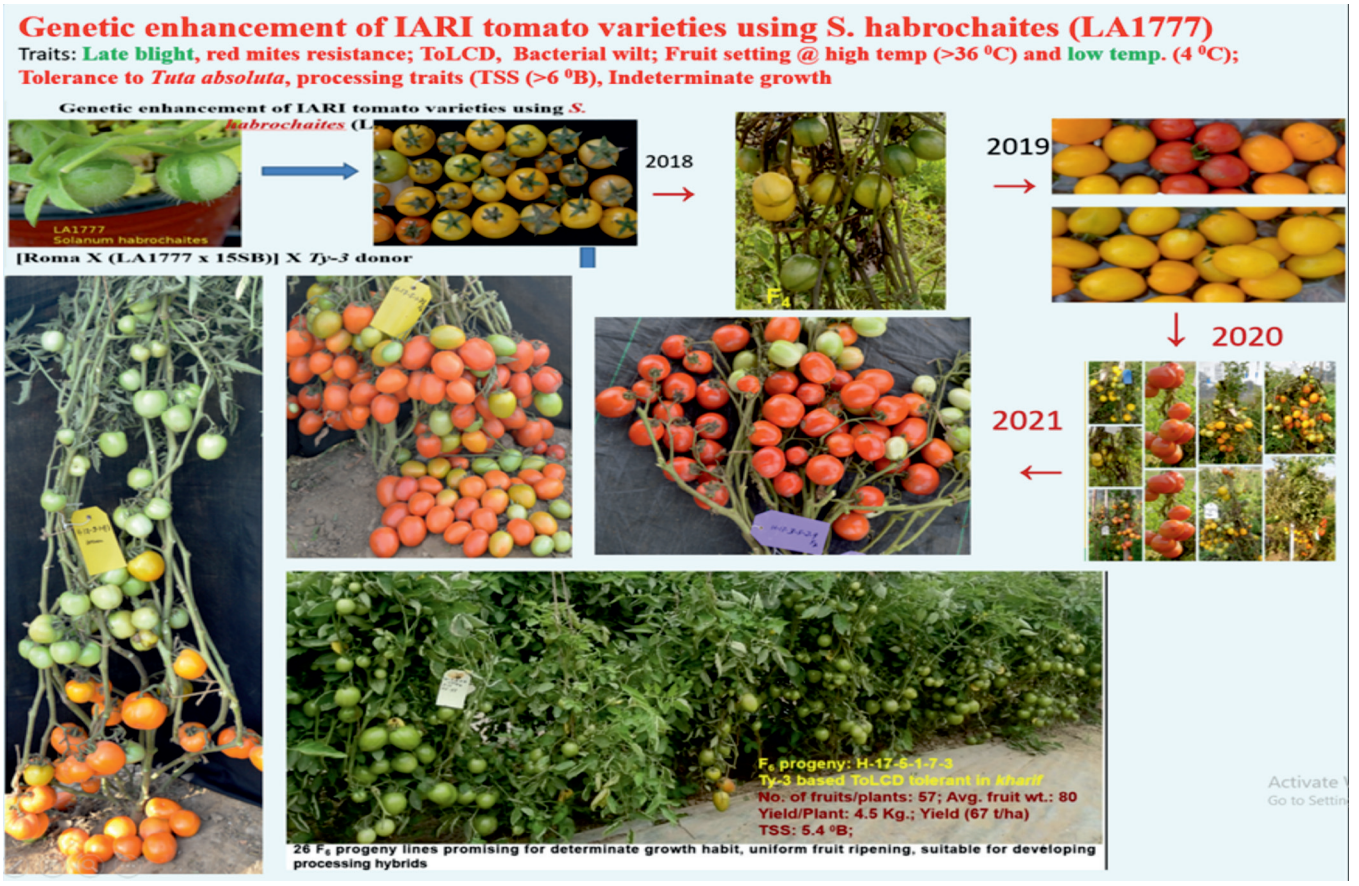
Exploitation of crop wild relatives in crop improvement programmes: -

Pre-breeding and Introgression work in tomato

Tomato (*Solanum lycopersicum* L.) is the second most-produced and consumed vegetable crop after potato and a rich source of vital minerals and antioxidants. Besides its global nutritional and economic value as a vegetable crop, tomato is a suitable model for studying the pre-breeding challenges in economically important crops. In India, tomato leaf curl disease (ToLCD) is one of the most devastating diseases of tomato with symptoms similar to those caused by tomato yellow leaf curl virus (TYLCV). Symptoms of ToLCD infections include stunting, yellowing, leaf curling and flower abortion which results in significant yield loss (Chakraborty et al. 2009). ToLCV is a begomovirus of family Geminiviridae causes tomato leaf curl disease (ToLCD). The virus has a broad host range and is transmitted by the whitefly Bemisia tabaci.

Most of tomato cultivars in India are susceptible to ToLCD. However, several wild species of tomato including *Solanum chilense, Solanum habrochaites* and *Solanum peruvianum* (Ji et al. 2007) have been found promising for ToLCD resistance. Currently, six resistance genes i.e. (Ty-1and Ty-3 on chromosome 6, Ty-2 on chromosome 11, Ty-4 on ch. 3, ty-5 on ch 4 and Ty-6 on ch 10) are available for commercial breeding against ToLCD (Zamir et al. 1994; Ji et al. 2007).

In view of low genetic variability in tomato (less than 5 %) of total genetic variability existed in tomato and its wild relatives (Ref) there is urgent need to develop pre-breeding strategies utilizing tomato wild relatives in primary secondary as well as tertiary gene pool. The programme was aimed at genetic enhancement of popular tomato varieties for introgression of tomato leaf curl disease (ToLCD) resistance utilizing LA1777 an accession of Solanum habrochaites. However, in advanced generations (F4:5) ToLCD resistance breakdown indicating that LA1777 is not carrying the resistance. Based on results on various ToLCD resistant lines carrying Ty genes alone or in combination Ty-3 gene was found to most suitable for resistance against ToLCD caused by more virulent bi-partite begomoviruses including Tomato leaf-curl New Delhi virus (ToLCNDV). The studies were undertaken using an interspecific hybrid 15SB x LA1777 Pusa Early dwarf and a Ty-3 carrying breeding line of tomato. Signification recombinants were



obtained including ToLCD late blight and bacterial-wilt resistance high TSS (>6 0 B) fruit set at high (40 0 C) and low (4 0 C) temperatures. The overall genetic diversity in the advanced breeding lines was increased by 30 %. Gene-linked markers for resistance to various diseases including Ty gens for ToLCD Ph genes for late blight BW genes for bacterial wilt ovate gene for fruit shape were found helpful introgression of multiple biotic abiotic and superior quality traits in popular cultivars. The approach was found promising for genetic enhancement of tomato utilizing its wild relatives for making tomato with more adaptability in multiple environments with multiple biotic and abiotic stresses.

Pre-breeding in okra

Abelmoschus is one of the major vegetable genera under family Malvaceae. *Abelmoschus* with 14 species reported so far (Misra *et al*., 2023), has two major species under cultivation, viz. *A. esculentus* (L.) Moench (okra) and *A. caillei* (A.Chev.) J.M.C.Stevels (Guinean okra). In South Pacific Islands, Papua New Guinea, and eastern Indonesia, *A. manihot* (L.) Medik. is also popular as leafy vegetable (Prabawardani *et al*., 2016; Rubiang-Yalambing *et al*., 2016). Apart from the cultivated genepool, wild *Abelmoschus* spp. has many desirable traits like perennation tendency, extended bearing, biotic and abiotic stress tolerance (Suma *et al*., 2023). Among biotic stresses, Yellow Vein Mosaic Virus (YVMV) and Enation Leaf Curl Virus (ELCV) diseases are the two major ones causing significant yield losses. Though Pusa Sawani (a derivative of a cross between IC1542 and Pusa Makhmali) was the first ever YVMV resistant variety of okra to be released at national level in India, Parbhani Kranti, Arka Anamika and Arka Abhay were the ones released as a result of interspecific hybridization between *A. esculentus* and *A. manihot* for the former (Jambhale and Nerkar, 1986), and *A. manihot* subsp. *tetraphyllus* (Roxb. Ex Hornem.) Borss. Waalk. for the latter two (Dutta, 1991). Further, *A. manihot* was used for developing a variety Anjitha, by exploiting interspecific hybridization followed by mutation breeding by Kerala Agricultural University (KAU) for transferring YVMV resistance and tolerance to shoot and fruit borer. Susthira was another variety belonging to *A. caillei* reported as resistant to YVMV, released by KAU. Gangopadhyay *et al.* (2016) reported resistance to YVMV disease in accessions belonging to three wild species viz. *A. caillei, A. manihot* and *A. moschatus* Medik., while resistance to shoot and fruit borer and leaf hopper was found in all the three above besides *A. tuberculatus* Pal and Har B. Singh.

It was also been noted that *A. manihot* subsp. *tetraphyllus* is one of the most widely used species worldwide for transferring genes responsible for resistance or tolerance to YVMV, jassids, and fruit borer (Badiger and Yadav, 2019; Patel *et al*., 2021). Promising accessions of *A. moschatus* (IC141055), *A. tetraphyllus* (IC90476-1), and *A. caillei* (Sikkim) were also reported by Santhiya *et al.* (2022) under natural epiphytotic screening, where the above accessions demonstrated a very low prevalence of YVMV and no incidence of ELCV diseases. Singh *et al.* (2023a) revealed that *A. angulosus* accessions IC203833 and IC470751 were extremely resistant to YVMV disease under artificial screening conditions employing mass inoculation mediated by viruliferous whiteflies.

With the implementation of National Agriculture Innovation Project (NAIP) during 2009-13 by the Indian council of Agricultural Research (ICAR), the biosystematics and crossability studies among various *Abelmoschus* species caught momentum, which were further progressed under the ICAR-Extramural Project of the ICAR, Horticultural Sciences Division (2015-17) and later under the ICAR-Emeritus Scientist Programme (2018–2021) for transferring genes tolerant/ resistant to YVMV and ELCV diseases. The tolerant species (*A. pungens* var. *mizoramensis, A. enbeepeegeearensis, A. tetraphyllus*, and *A. angulosus* var. *grandiflorus, A. crinitus, A. ficulneus*) were also identified through the field screening of wild *Abelmoschus* species germplasm (John *et al*., 2013a). These species were then employed in a wide hybridization program to produce interspecific hybrids with the cultivated okra. A total of 113 amphidiploids generated were extensively characterized for the important morphological characters by Suma *et al.* (2023). The promising amphidiploids identified are currently being advanced through back crossing and selfing. Among them, 13 selfed derivatives (involving crosses between *A. esculentus* and *A. pungens* var. *mizoramensis*, and a multi-cross combinations of *A. esculentus, A. angulosus* var. *grandiflorus*, *A. tetraphyllus* and *A. pungens* var. *mizoramensis*), one back cross derivative (involving *A. esculentus* and a multi-cross combination of *A. esculentus, A. angulosus* var. *grandiflorus*, and *A. pungens* var. *mizoramensis*) and nine open pollinated bulked amphidiploid derivatives (involving *A. esculentus* with *A. angulosus* var. *grandiflorus*, and *A. pungens* var. *mizoramensis*) exhibited field resistance in three locations namely Varanasi, Ludhiana and New Delhi (not published). In addition, *A. manihot* and newly described species *A. odishae* are also being currently utilized in wide hybridization programmes. Venkataravanappa *et al.* (2022) also identified cultivated, wild as well as advanced lines resistant to both YVMV and ELCV diseases. Embryo rescue was employed for successful production of F_1 hybrid for crosses involving *A. esculentus* and *A. moschatus* subsp.

tuberosus (Zaman and Parihar, 2023) and *A. esculentus* and *A. tetraphyllus* (Rattan and Kumar, 2020).

Besides employing the wild species for transferring genes tolerant to biotic stresses, crosses were attempted to exploit the ornamental potential of hybrids of the cross between *A. moschatus* and *A. sagittifolius* as reported by John *et al.* (2013a and 2013b). All the plants derived from both direct and reciprocal crosses were yielding plants with bright red flowers. The F_2 plants showed segregation for the flower colour with various shades ranging from pink, yellow, light red, dark red and with combinations of these colors, including contrasting dark veins on petals with lighter shades (Suma et al., 2024).

Genetic enhancement in teasel gourd

Teasel gourd (*Momordica subangulata* subsp. *renigera*) is an emerging high value vegetable worth promotion in humid tropics. Its superior nutritional value, non-bitter taste, unique flavor, adaptability to tropical climate, export potential, propagation efficiency and ease of developing recombinants etc. make it an excellent candidate for widening the vegetable diversity in Kerala. However, requirement of hand pollination outside its home range is a constraint to wider adoption. To overcome this, an attempt was made to transfer the natural insect pollination traits and cue mechanism of related *M. dioica* Roxb. and *M. sahyadrica* Kattuk. & V.T. Antony (both 2n=2x=28), to the teasel gourd genome (2n=4x=56), thus combining high vegetative propagation efficiency, bigger fruit size, prolificacy, extended harvest period and entomophily. Earlier attempts on interspecific hybridization resulted in developing F_1 (4n X 2n= 3n) with malformed fruits. Hence the dioecious pollen parents, *viz. M. dioica* and *M. sahyadrica* (diploid) were subjected to tetraploidization by treating tuber sprouts with 1% colchicine at 15 minutes interval from 7 am to 11 am on the growth primordia at two leaf stage for three days. Bulged collar region of survived plants was taken as an indication of polyploidization and such plants were used as pollinizers of teasel gourd. There was reduction in fruit size and seed number per fruits in crossed plants (11 to 35g; 4.67 to 15.33 seeds in *M. subangulata* subsp. *renigera* x *M. dioica* and 20 to 40g; 10 to 19 seeds in *M. subangulata* susp. *renigera* x *M. sahyadrica*) compared to the maternal parent (60 to 75g; 28 to 40 seeds). Results of the preliminary characterization of the amphidiploids revealed the transfer of traits of the naturally pollinating species viz., *M. dioica* and *M. sahyadrica*, into the amphidiploids. The leaves, flowers and fruits exhibited intermediate morphology of the parents. The lobing of leaves, increased intensity of yellow colour of petals, and increase in fruit rostrum.

Genetic enhancement through pre-breeding enables the systematic exploitation of unadapted and under-utilized germplasm by broadening the genetic base of cultivated crops and generating novel variability. This process supports the development of high-yielding, climate-resilient cultivars and hybrids with enhanced tolerance to biotic and abiotic stresses. Crop wild relatives are being increasingly utilized as sources of resistance and adaptability in horticultural crops such as tomato, okra, cucumber, teasel gourd, apple, asparagus, grape, and mulberry.

Throughout their evolutionary history, wild progenitors have retained traits conferring resilience under harsh and fluctuating environments. In contrast, modern breeding strategies focused on high productivity and broad adaptability have often resulted in genetic uniformity, leading to erosion of genetic diversity and increased vulnerability to emerging stresses. This scenario underscores a critical opportunity to harness the rich and adaptive genetic diversity of CWRs through targeted pre-breeding and genetic enhancement efforts. Leveraging this diversity offers a sustainable pathway for developing crop varieties better suited to marginal environments and future climatic uncertainties.

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Prospects of Date Palm Cultivation in Rajasthan

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Abstract

In India, it is believed that date palm has been introduced by the soldiers of Alexander in the 4th century B.C in the Indus valley. Grooves of seedling date palm are found on the coastal belt from Ajar to Mandvi in Kutch district of Gujarat. In Rajasthan, date cultivation was first introduced by then ruler Sri Ganga Singh Ji of the erstwhile Bikaner state through the plantation of few suckers of Halawy, Khadrawy and Zahidi at Shriganganagar, a part of *Thar* Desert after development of Gang canal in the state. (Rathore *et al.*, 2021). Its cultivation has great potential in western districts of Rajasthan viz. Bikaner, Jaisalmer, Barmer, Jodhpur, Sriganganagar, Hanumangarh, Jalore, Sirohi, Churu, etc. Vast areas of above-mentioned districts can effectively utilize for date palm cultivation including area where irrigation water is also saline. The plantation of date palm in western Rajasthan can also help in checking desertification and economic upliftment of rural masses by generation of employment besides giving net monitory income to the farmers.

Date palm (*Phoenix dactylifera* L) is one of the world's oldest cultivated fruit trees. Archaeological evidences suggest that the date palm was domesticated some 6000 years ago in the Mesopotamian region. As far as Indian concerned, *P. sylvestris* appears to be older than the *P. dactylifera*. It is believed that date palm is indigenous to countries around Persian Gulf but exact geographic origin has not yet been established. The date palm (*P. dactylifera*) evolved from *P. reclinata* native to tropical Africa or *P. sylvestris* in India, or a hybrid between the latter two species. The date palm was known to ancient people as the "Tree of Life". Commercial cultivation of dates in the world lies 20' and 35' and S latitude. Iraq, Saudi Arabia, Iran, UAE and Algeria are the main date palm producing countries in the world. Besides these countries Pakistan, Morocco, Libya, Tunisia, Sudan, Muscat, Oman, USA, Israel and Baharin also produce dates in substantial quantities. In Islam, date palm is cited 21 times in the Quran, similarly date palm is praised in Christian and Judaism faith and has been linked to numerous religious ceremonies such as Passover and Palm Sunday.

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Nutritive value

Date is a highly nutritious and favorite fruit throughout India. Fruits of date cultivars viz. Halawy,

Table 1. Area under date palm cultivation in Rajasthan (2024-25)*

District	Area (ha)	Varieties
Bikaner	350	Barhee, Khadrawy, Khuneizi, Khalas, Medjool, Saggai, Zamali
Jaisalmer	208	Barhee, Khadrawy, Khuneizi, Khalas, Medjool, Saggai, Zamali
Sriganganagar	250	Barhee, Khuneizi, Khalas, Medjool
Hanumangarh	150	Barhee, Medjool
Barmer	200	Barhee, Khuneizi, Medjool
Jhunjhunu	12	Barhee, Khuneizi, Medjool
Nagaur	50	Barhee, Khuneizi, Medjool
Jodhpur	120	Barhee, Khuneizi, Medjool
Pali	30	Barhee, Khuneizi
Sirohi	50	Barhee
Jalore	50	Barhee, Khuneizi
Churu	30	Barhee
	1500	

Source: Department of Horticulture and through personal communication

Khalas, Khuneizi and Barhee are eaten as fresh (doka stage). Besides fresh consumption, several value added products are prepared from date fruits. This fruit can supplement the dietary needs of the desert people where very less nutritious food is available. Dates are cured as dry dates (*chhuhara*) and soft dates (*pind khajoor*) which has great demand and market in the country. In fact, it was the only staple food available to the desert people in the Near East and North African region till oil was discovered there. Even today, it forms a prominent component of daily diet of people in these countries. Date fruits provide abundant quantities of sugar, iron, potassium, calcium and nicotinic acid. Small amounts of protein, copper, magnesium, chlorine, sulphur, Vitamins A, B_1 and B_2 are also present in date pulp. The flesh of dates with a moisture content of 20 per cent contains 60-65 per cent sugar, about 2.5 per cent fiber, 2 per cent protein and somewhat less than 2 per cent fat, mineral matter and pectic substances, giving about 3,550 calories per kg. Fresh 100g date fruit contains 59.2g moisture, 1.2g protein, 0.4g fat, 1.7g minerals, 3.7g fibre, 33.8g carbohydrates, 22.0 mg calcium, 38.0 mg phosphorus while 100g dry dates (chhuhara) provides 2.5 g protein, 2.1g minerals, 3.9g fibers, 75.8g carbohydrates, 120mg calcium, 50mg phosphorus, 7.30mg iron, 0.02 mg riboflavin, 0.9 mg Niacin, 3.0mg vitamin C (Gopalan *et al.*,1985). Date palm leaves are used for making handicrafts, mats, temporary huts, broom, etc. Its seed kernel is used in the preparation of cattle feed. In Gulf countries, several value added products are made from date palm plant parts as well as fruits.

Varieties

Date varieties have been developed by thousands of years of selection of seedlings. More than 1000 varieties of date palm are found all around the world. There are about 400 varieties in Iran followed by Iraq (370) and Tunisia (250). However, in India, about 50 cultivars have been introduced for evaluation at different research stations. The descriptions of some important varieties are as follows:

Halawy: An early maturing, high yielding and suitable variety to grow in large areas for fresh fruit and processing. Its fruits are yellow and sweet in taste at doka stage with average weight 9.6g; size 3.56 x 2.10 cm and TSS 31.0%. It produces about 80-100 kg doka fruits/tree per year.

Barhee: Its origin is Basrah, Iraq. A medium to late maturing cultivar and good for fresh consumption. The fruit at khalal stage (doka) has excellent flavour, yellow and attractive fruit colour and sweet in taste. The stone is very small in size with high pulp: stone ratio It has high market potential in the world's market. The yield potential of this variety is 80-120 kg per plant.

Medjool: The origin of this variety is Morocco from where it was introduced to the other countries of the world. It is avery high yielding cultivar due to its bigger attractive colour berries (size 4.5x3.2 cm). It also matures in late and it is highly suitable for dry dates preparation. Its doka fruits are astringent in taste. The colour of berry is yellow-orange at doka stage. It has high commercial value and very important variety for export. Average yield is 80-100 kg/palm.

Khalas: It is a medium maturing type cultivar. Its berry is big in size at doka stage and sweet in taste The yellow colour doka fruit is suitable for fresh eating and processing. This variety is medium to heavy yielder.

Khuneizi: It is an early to mid season maturing variety. The colour of berry is red and suitable for fresh consumption at doka stage. The doka fruits are very sweet in taste.

Zahidi: It is a late maturing variety and suitable for pind preparation. Its doka fruits are astringent in taste and solid with haard skin. The size of berry is small, attractive yellow colour but it is a heavy yielder (125 kg doka fruits/tree). The bunch of this variety is compact with 18 to 24 berries per strand.

Shamran: It is a mid season to late maturing and high yielding variety. The average fruit weight is 6.5 g and fruit size of 3.50 x 2.18 cm. The colour of berry is light yellowish red and astringent at doka stage. This variety is grown commercially. It is suitable for processing in to dry dates and other products. It is a prolific bearer as fully grown tree of Shamran has average yield potential of 100 kg doka fruits per tree.

Constraints in Date Palm Production

***Quality planting materials*:** The major constraint in the expansion of date palm cultivation in the country is the non-availability of quality planting material. Date palm is commercially propagated through suckers/offshoots or tissue culture plants. However, the availability of suckers is very limited, making large-scale area expansion impractical. On the other hand, the production of tissue culture plants is a complex and technically difficult process, and only a few public or private organizations have been successful in producing quality plants.

In Rajasthan, a joint venture agreement was executed between the Rajasthan Horticulture Development Society (RHDS), Atul Limited, and Atul Rajasthan Date Palm Limited for the supply of tissue culture plants. Secondary hardened tissue culture plants of varieties such as Barhee, Khuneizi, Khalas, Medjool, Khadrawy, Zamli, Saggai, along with male plants, were imported. These plants were supplied through the Jodhpur nursery

and, after secondary hardening, distributed to farmers in districts including Bikaner, Jaisalmer, Barmer, Jodhpur, Sri Ganganagar, Hanumangarh, Churu, and Nagaur.

The planting material was provided with substantial government support, offering a subsidy to the farmers for establishing date palm orchard, However, subsequently, quality issues were reported in the supplied planting material, and several court cases were filed by farmers. It was observed that the planting material supplied was not of the desired quality. Consequently, despite farmers' keen interest in establishing date palm orchards, the availability of assured quality planting material remains a major bottleneck. (Rathore *et al*., 2021)

***High irrigation requirements*:** Generally, date palm is cultivated in arid and semi-arid regions where water availability is a major limiting factor. The crop requires a relatively high amount of irrigation water, particularly during the peak summer months from April to June, when groundwater levels also decline significantly.

Rainfall during the fruit maturity period poses another major constraint. The *pind* stage of date fruit, which fetches a higher market price, is highly preferred by farmers and consumers. However, under Rajasthan conditions, the onset of the monsoon during June–July coincides with the fruit development and maturity period. As a result, farmers are compelled to harvest fruits at the *doka* stage, as the *pind* stage is rarely attained due to adverse weather conditions caused by monsoon rains. (Rathore *et al*., 2021)

***Non-availability of quality pollen-grains*:** Sometimes, female inflorescences emerge earlier than male inflorescences; consequently, farmers face difficulties in obtaining quality pollen grains at the appropriate time for effective pollination.

***Damage by birds*:** The fruits are damaged by birds like parrot, etc. Therefore, the use of fruit-covering non-woven bags or iron mesh guards to protect the fruit bunches becomes necessary, which significantly increases the cost of cultivation.

***Marketing of fruits*:** Farmers also face significant challenges in the marketing of date palm fruits due to the lack of organized markets, processing facilities, and assured price mechanisms.

Propagation

Date palm is propagated both by seeds as well as vegetative methods but it commercially multiplied through offshoot/suckers and also by tissue culture techniques. Seeds in date palm, variability and sex ratio are the main problem by seed propagation because half of the progeny will be males and half will be females, with no certain way to determine at an early stage the sex of the progeny. The germination of seeds indate palm have been observed about 80-90 per cent when seed sowing take place in the month of July- August. Moreover, growth in seedlings is very slow at initial stages. It has been observed that seeds soaked in cow dung solution for 24 hours enhanced germination and growth of seedlings in Phoenix species. Seedlings varied considerably with respect to vegetative and reproductive characteristics (Al-Ghamdi *et al*., 1988). However, date palm propagation through seedlings can provide an ideal material as some times seedlings palms are outstanding in performance (Chandra *et al*., 1992). In Kachchh region, seedlings are used for planting due to lack of planting material. Presently, date palm is mainly multiplied through suckers/offshoots. Offshoot plants are true-to-type to the parent palm. The offshoots develop from axillary buds on trunk of mother plant and consequently fruit will be the same quality as the mother palm and ensures uniformity to produce. Offshoots bear fruits 2-3year earlier than seedlings. But production of suckers is a limiting factor because a palm tree produces about 15-20 suckers in whole life. Out of them, some are aerial offshoots and have no roots and fail to establish after detachment from mother palm. It is main constraints in increasing area under date palm cultivation. Survival of offshoots is about 40-50% under field conditions. Work on initiation of roots in sucker's and better survival is also very important for increasing the area of cultivation in date palm. Sodagar *et al* (1996) observed that the best time of planting is April – May for higher survival and rapid growth in *Kachchh* region. In date palm, basal as well as aerial offshoot suckers are produced. Basal offshoot generally has well developed root system compared to poorly developed roots in aerial suckers. After 4-6 years of plantation, suckering starts and 2-3 suckers can be removed every year from each mother palm tree for a period of 8-10 years as per observations made at Abohar. The offshoot must be well rooted and of proper weight for better survival in the field. Well rooted offshoot of medium weight (range 10-15 kg) is better in survival performance in the field compared to poorly rooted small sized or bigger sized offshoots.

Tissue culture

The application of tissue culture techniques for date palm also called *in–vitro* propagation has many advantages that include propagation of elite cultivars, large scale multiplication, absence of seasonal effects, production of genetically uniform plants, and fast exchange of plants materials. In a commercial plantation, any two to three per cent male palm are sufficient to meet the pollination, hence the main emphasis should

be on increasing production of female plants. There are many reports on *in-vitro* multiplication of date palm, using various explants viz. shoot tips, inflorescence, immature fruits, leaf segments, stem and root section. The area under date palm cultivation is stagnant due to non-availability of planting materials, thus depriving the country to achieve the production potential. The tissue culture technology has potential to produce maximum number of plants in limited time and space that are true to type and ergonomically superior to conventionally propagated plants.

The physiological performance of these plants is at par with those of sucker plants (Bhargava *et al.*, 2003). Thus, it seems apparent that this may provide a method for mass multiplication of date palm mother plants. In addition to this, supply of genuine plant material to farmers is another responsibility of scientists. Therefore, there is need to standardize the biochemical markers for identification of superior plant lets produced from tissue culture. Tissue culture is the only way to produce a large number of plantlets in date palm to meet out the requirement.

Future prospects

Date palm cultivation has considerable potential in India, particularly in arid and semi-arid regions where limited crop options are available. With increasing climate variability, date palm emerges as a promising perennial crop due to its tolerance to high temperatures and salinity. The crop can play a vital role in enhancing farmers' income, ensuring nutritional security, and promoting sustainable use of marginal lands.

Growing domestic demand for fresh and processed dates offers significant scope for expansion. At present, India is one of the largest importers of dates, indicating a strong market opportunity for domestic production to reduce import dependency. Expansion of date palm cultivation in suitable regions such as western Rajasthan, Gujarat, parts of Haryana, Punjab, and arid zones of other states can substantially contribute to meeting domestic demand.

Advances in propagation technologies, particularly standardization of tissue culture protocols and development of quality planting material, are expected to address the current bottleneck of plant availability. Strengthening public–private partnerships and establishing certified nurseries will ensure the supply of true-to-type and disease-free planting material.

There is also immense potential for value addition and processing of date palm fruits into products such as dry dates, date syrup, paste, jaggery substitutes, confectionery items, and health foods. Development of processing infrastructure, cold chain facilities, and organized marketing systems will enhance farmers' profitability and employment opportunities, especially for rural youth and women.

Strategies

Strengthening planting material supply

Establish certified public-sector and public–private tissue culture laboratories and nurseries to ensure the availability of true-to-type, disease-free, and quality planting material. A robust quality control and certification mechanism should be enforced to prevent supply of substandard plants.

Research and development support

Prioritize research on region-specific high-yielding varieties, pollen management and storage, synchronization of flowering, fruit maturity regulation, and climate-resilient production technologies under national and state research programs.

Efficient water management

Promote micro-irrigation, fertigation, rainwater harvesting, and conjunctive use of saline and fresh water through enhanced subsidies and technical support, particularly during critical growth stages.

Production and post-harvest infrastructur

Support establishment of fruit protection systems, harvesting tools, grading, storage, and processing units for value-added products such as dry dates, syrup, paste, and health foods at the cluster level.

Market development and value chain strengthening

Develop organized markets, farmer producer organizations (FPOs), and assured procurement mechanisms. Encourage branding, quality standards, and export-oriented production to improve market access and price realization.

Capacity building and extension

Strengthen farmer training, field demonstrations, and skill development programs focusing on orchard management, pollination techniques, water-use efficiency, and post-harvest handling.

Risk Mitigation and Farmer Confidence

Introduce crop insurance, quality assurance mechanisms, and grievance redressal systems to restore farmers' confidence and encourage adoption of date palm cultivation.

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Floriculture for Holistic Health: Nurturing Body, Mind and Emotions

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Abstract

Active engagement with flowers, either in flower cultivation, gardening or flower arranging as well as passive interaction with plants and flowers in one's surroundings stimulate psychological influence and positive emotions. Simultaneously, floral extracts from species such as rose, calendula, butterfly pea, marigold, lavender, chrysanthemum, etc. offer significant nutraceutical and anti-inflammatory benefits with antioxidant, anxiolytic and antimicrobial properties that contribute to immune modulation, skin health and general physiological resilience. Thus, flowers are recognized for edible purposes. There is emerging trend for floral-based herbal teas and phytonutrient-rich supplements as well as floral-based culinary dishes. Further, floral based skin and haircare products as well as cosmetics are the upcoming commerce. Flowers exert immediate and measurable influence on cognition and mental wellbeing. Studies demonstrate that ornamental plants positively affect alertness, elevate mood, reduce stress and increase dopamine and serotonin levels as well as regulating cortisol; thereby restoring the emotional equilibrium. Floriculture emerges as a powerful, holistic health practice tool that integrates physical vitality, mental clarity, emotional balance and ecological wellbeing. This article advocates for the inclusion of floriculture in wellness programs, healthcare settings and lifestyle strategies to promote comprehensive human flourishing.

Flowers and ornamental plants have been an indispensable part of human rituals, cultures, medicines and spirituals since the very beginning. The ancient Egyptians, Persians, Indians, Chinese, Greeks and Romans, among others, not only appreciated flowers for their beauty but also considered them as a source of healing, harmony and uplifting of the human spirit. The symbolic and practical use of flowers gradually transformed and became widespread in medicine, cosmetics, aromatics, religious offerings and emotional communication. They are known to be incredibly complex biological systems harboring a variety of naturally occurring chemicals, pigments, volatile oils and antioxidants that all work to affect the human body physiology.

The floriculture industry of today has a much wider scope than simply beautifying the home and gardens. This field of study incorporates areas such as horticultural therapy, eco-landscaping, aromatherapy, edible floral nutrition, floristry, recreational gardening and natural cosmetology. Studies in environmental psychology and neurobiology have shown that one can get less stressed, think better and have more social interactions and be more mentally clear simply by being around flowering and foliage plants. This wide-ranging impact makes floriculture a holistic science of wellness connecting environment.

Human interaction with ornamental plants takes place in two main forms: active and passive engagement. Active engagement includes all the activities that require direct human intervention such as planting flowers, taking care of gardens, making flower decorations or getting involved in gardening therapy. These activities lead to the mixing of different body movements, hand and eye coordination, creative thinking and mindfulness. They allow the person to participate in the natural rhythms of the earth, which in turn reduces anxiety and sharpens mental concentration. For example, gardening involves close watching, making plans, having the right attitude and being caring, all of which help the person to be emotionally stable and mentally active. In contrast, passive engagement with ornamental plants happens when people are not directly involved with flowers but still use them as a visual element in their surroundings. Just looking at ornamental plants in living rooms, hospitals, parks, offices or public areas can trigger reactions to relaxation, lessen stress and stimulate positive emotions.

Flowers and ornamental plants affect immune pathways as they minimize the levels of inflammation and oxidative stress; thus, the body can heal itself more effectively. Hospitals have already included healing gardens, floral landscapes, aromatic corridors and indoor flowering plants as part of their schemes to cut down patient anxiety, hassles and time wasted in recovery. Patients who are either in garden spaces or rooms decorated with flowers are reported to have less pain perception, lower stress levels and higher satisfaction with care. In rehabilitation centers, flower therapy and horticulture activities not only help the patients regain but also coordinate functions and skills in performing tasks plus the ability to manage emotions. For patients who are-about-to undergo-treatments flowers act as a barrier against anxiety and help them feel secure. The combined pathways are what give floriculture its power as a natural remedy for holistic therapy. Therapeutic

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programs are gradually making use of horticultural activities as a means for mental health improvement. Horticultural therapy invites the person to interact with plants through the various methods of planting, pruning, watering and arranging flowers, which promotes a sense of responsibility, success and mindfulness. Such therapeutic approaches are particularly helpful with dementia patients, children with autism, people recovering from trauma, elderly people suffering from isolation and people with depression or anxiety. Thus, in general, flowers and ornamental plants have shown immune modulatory effects on human health.

Nutraceutical and phytochemical content in flowers

A variety of flowers have been identified as the sources of phytochemicals that contain significant medicinal and nutritional value. Scientific studies conducted on flowers have shown the presence of various groups of phytochemicals including flavonoids, polyphenols, carotenoids, anthocyanins, terpenoids and volatile aromatic compounds. These major constituents have been attributing their beneficial actions to the activities, namely, scavenging free radicals, reducing inflammation, enhancing immune defense and supporting cellular repair. Floral extracts and essential oils derived from species such as jasmine, lavender, rose, calendula and butterfly pea provide anti-inflammatory, antioxidant and antimicrobial benefits that support skin health, immunity and natural healing. The growing use of flower-based nutraceuticals and cosmetic formulations further demonstrates the physiological relevance of floriculture.

Rose is full of soothing and antioxidant properties. Marigold have lutein content which is associated with eye health and antioxidant limiting the damage done in the eye by the light. Calendula is known for its strong antiseptic and healing of wound powers; thus, it is frequently found in herbal preparations of skincare. Butterfly pea flowers are studied for their content of anthocyanins which are connected to the enhancement of memory and thinking capacity. Lavender, as a source of linalool and linalyl acetate, is associated with relaxation and sleep-inducing properties. Pigments present in flowers play a major role in boosting immunity, scavenging free radicals and toxins from the body and helping us in combating major diseases.

As people take turns towards healthier and more natural food options, the global market for edible flowers has been increasingly fast. The use of edible flowers has now spread from teas, salads and confectionery all the way to syrups and health supplements and to even such famous cuisines as gourmet. Floral extracts and powders find their way into wellness drinks, antioxidant supplements, detox formulations and beauty-from-within products. Their application is not only in culinary arts for the purpose of enhancing flavor and presentation but also for the purpose of adding health benefits of functional denomination. This new trend reflects the changing attitude towards flowers in general, as more people now view them as nutraceutical resources that play a part in everyday wellness.

Chrysanthemum has been used in traditional medicines for its fever-reducing and detoxifying properties for quite a long time. Rose petals are an excellent source of polyphenols which are known for enhancing immune resilience and for imparting better skin health. Butterfly pea flowers are loaded with anthocyanins which have been reported to possess among their effects, the enhancement of memory and the demonstration of neuroprotection. Lavender is a flower which has antimicrobial, anti-inflammatory and sedative properties and hence is of great help to those suffering from respiratory sensitivity, insomnia or nervous tension. In this way, flower extracts and decoctions emerge as the natural therapeutics that help and support diverse physiological functions.

The use of edible flowers has been recognized for their health benefits. They are sprinkled over herbal teas, green drinks, salads, sweets and nutraceutical products. Among the most famous herbal teas are rose, lavender, chrysanthemum, chamomile and butterfly pea. The flowers' biochemical richness is responsible for improved digestion, better sleep and detoxification. Besides, it is

Table 1: Flower pigments and their health benefits

Pigments	Example of flower crops	Health Benefit
Carotenoids	Marigold, Calendula, Rose, Nasturtium, Palash	Protect immune system, heart diseases, macular degeneration, cancer *etc.*
Anthocyanins	Snapdragon, Geranium, Tulip, Camellia, Begonia, Verbena, Rose, Hibiscus, Poppy, Cornflower, Butterfly pea, *Gulmohar*, Bauhinia	Improve night vision, promote wound healing, high free radical scavenging capacity, prevention of cardiovascular disease, obesity, cancer, anti-allergic, anti-inflammatory, diabetes and other diseases
Betalains	Bougainvillea, Portulaca, *Butea monosperma*	Decreases oxidative damage to lipids and improves antioxidant status in healthy humans

Table 1: Flowers and their consumption method with their functional benefits

Flower	Consumption Method	Functions / Benefits
Saffron	Infused in warm milk, tea, or rice dishes	Antidepressant, antioxidant, memory enhance
Clitoria	Dried petals brewed as tea	Antioxidant, brain tonic, mood-enhancing, memory enhance
Chamomile	Tea, infused honey, supplements	Sleep aid, digestive relief, anti-inflammation
Rose	Petals in jams, desserts, tea, rose water	Antioxidant, mood-enhancing, skin care
Calendula	Petals in salads, stews, oil infusions	Wound healing, digestive support
Hibiscus	Dried petals brewed as tea	Lowers blood pressure, antioxidant
Lavender	Culinary buds in baked goods, tea, lemon	Stress buster and anti-anxiety
Elder flower	Cordials, syrups, teas	Immune boosting, anti-viral
Dandelion	Fresh petals in salads, wine; roots in tea	Liver support, diuretic, digestive tonic
Nasturtium	Fresh in salads, pickled flower buds	High in vitamin C, anti-bacterial
Viola/Pansy	Raw in salads or as cake decoration	Mild anti-inflammatory, diuretic

said that flowers are now part of the diet of many health-conscious consumers who consider the aesthetic and culinary aspects as well. Floral nutraceuticals are already promising with powders, capsules, extracts and tonics gaining popularity in the world health market.

Ornamental plants improve indoor AQI

A variety of foliage plants with ornamental foliage can be grown indoors. Foliage plants are valued for their foliar variegation in different combinations of colors and patterns, overall plant forms and styles. Most of them have a capacity to tolerate shade or thrive under indoor conditions. Indoor plants can purify and revitalize air in our homes and offices, protecting us from the negative effects of such common toxins as ammonia, formaldehyde and benzene. Plants remove VOCs (Volatile Organic Compounds) from indoor air through stomatal uptake, absorption, and adsorption to plant surfaces. Several indoor species have been screened for their ability to remove benzene, in addition to other VOCs (Toluene, TCE, m-xylene, hexane). The efficiency of VOC removal varies substantially among species and with the molecular characteristics of each compound. Research has also revealed significant decrease in the levels of CO_2 and CO in indoor environment under AC as well as non-AC conditions with the placement of potted indoor plants. Plants like *Aglaonema brevispathum, Pachira aquatic* and *Ficus benjamina* reduced the levels of VOC's like methane, toluene, ethyl benzene and formaldehyde. Many indoor plants species are *viz., Asplenium nidus, Ficus elastica, Hedera helix, Nephrolepis obliterata, Sinningia speciosa, Ocimum basilicum, Yucca massengena, Spathiphyllum wallisi, Diffenbachia* spp., *Rhapis excelsa* can effectively reduce the VOCs (HCHO, Toluene, Xylene, Acetaldehyde *etc*.) and CO_2 from indoor air and increase aesthetic value. Further, succulents like *Sansevieria, Crassula, Haworthia, etc* having CAM metabolism are highly efficient in improving indoor air quality with the added benefit of requiring less water. Thus, plants in the home or office can filter out toxins, stale air, pollutants, harmful viruses and mold spores. Plants act as filters because they absorb the toxins through their leaves, especially those with the largest leaves.

Effect of flowers and plants on human psyche

Sensory elements of flowers and ornamental plants like fragrance, colour, texture, softness, freshness, *etc.* in all directly influence human psyche and thereby awakening senses, enhancing sensitivity and awareness of the existing wonderful nature. Similarly, scent has also been shown to have deep psychological influence. Smell can evoke strong emotional reactions as our olfactory receptors are directly connected to the limbic system, the most ancient and primitive part of the brain, which is thought to be the seat of emotion. Pleasant fragrances have been found to have positive effects on moods in all age groups. Experiments have shown that exposure to pleasant fragrances significantly enhances performance on work-related tasks and relieves stress and anxiety. Sight and fragrance of flowers and plants combine to influence brain chemistry and stimulate more positive feelings, as reported by Dr. Jeannette Haviland-Jones, New Jersey, US. The interaction of color, form and pattern in flowers results in a multisensory experience that subtly changes the emotional states. The different colors of flowers cause different emotions in people

because they activate different neural pathways in the brain. Red (*Delonix regia*), orange (*Butea monosperma*) and yellow (*Calendula officinale*) flowers are considered warm-colored and are linked to life, energy and excitement. They usually cheer up the people, help the artists and make the listeners sharper. Moreover, cool-colored flowers such as blue (*Clitoria ternatea*), lavender (*Lavandula angustifolia*) and violet (*Viola tricolor*) give a restful feeling and make the body cool and calm by lowering the heart rate and the stress. Thus, flowers can be used to influence and change the thought process in a significant way that can be exploited for enhancing personal as well as even business relationships. Thus, flowers with sweet fragrance, colour and soft texture stimulate and awaken all the five senses in humans and thus significantly influence psychology to greater extent that serve as mood enhancer and stress buster.

Flowers and foliage plants emotions and stress management

The power of flowers and foliage plants emotionally heal people that reach the areas of stress management and mood regulation. Besides, numerous psychological studies have proved that the presence of ornamental plants can lower cortisol levels, which is the primary hormone involved in stress. An ornamental plant decorated room is likely to be relaxing and inviting, which will lead to emotional stability and comforting symptoms of anxiety and depression. Flowers help people to build their emotional resilience by putting them in the supportive and comforting atmosphere that helps them to cope with their grief, trauma or emotional exhaustion.

Flowers and foliage plants stimulate various mental powers, one of which is memory retention, attention span and problem-solving and creativity. According to the studies on learning environments, the presence of flowering plants in classrooms has a positive effect on the way students focus, improve the duration of their attention and draw them into more cognitive engagement. Staff working in an office environment decorated with flowers and plants usually feel less tired, concentrate more and have better mood and overall productivity is higher too. Ornamental plants contribute positively to urban microclimates by cooling, humidifying and purifying the air. Plants in the surroundings increase happiness, provide comport dealing with customers , improve work efficiency, and mood state along with improving working ambience as opined by different social gathered peoples from survey based case study conducted at different sites by Navsari Agricultural University. The use of ornamental plants seems to produce a mentally stimulating yet emotionally calming environment that is conducive to the highest level of cognitive functioning.

Conclusion

Floriculture is a science that is very much in line with nature and provides a mixture of good health for mankind and environment. Psychologically, flowers largely determine people's moods to the extent of using them in therapy and stress relief. Physiologically, they are a source of health and their main activities in this regard are antioxidants, anti-inflammatory and immune modulation. Their ecological role in having a positive impact on the environment and conservation of biodiversity directly contributes to human health creation of cleaner and more colorful and harmonious living spaces. In addition, flowers have a role in shaping the emotional experiences of people, connecting them socially and giving them comfort in times of stress or loss. As research continues to confirm these various benefits, the role of floriculture in the health sector is already being projected as a significant one in the future.

Flowers in the house not only provide an aesthetic look but also help define the lifestyle of the people living there by promoting relaxation, socializing and emotional bonding. It has been observed that households which grow flowers in their gardens or place them in their living rooms are happier and have less stress. On the contrary, being involved in the gardening process either as a family or alone provides one with benefits like physical fitness, mental awareness and more involvement with nature. The smell of flowers coming from different parts of the house provides relaxing environments that make one sleep better, less irritation and more emotionally in harmony with others. Biophilic design in architecture is among the floriculture future trends which allow the construction of buildings to include a garden for flowers, green walls and roof tops, thus providing the community with a natural habitat that is soothing and health promoting. The use of flowers in healthcare, education, urban development and daily lifestyle practices not only offers a beautiful and pleasant way but also a natural, sustainable and transformative avenue towards comprehensive human flourishing.

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