National Seed Association of India

Seed Times

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Recent Trends
in Vegetable Breeding, Seed Production and Opportunities in Vegetable Seed Trade

ABOUT US

National Seed Association of India (NSAI) is the apex organization representing the Indian seed industry. The vision of NSAI is to create a dynamic, innovative and internationally competitive, research based industry producing high performance, high quality seeds and planting materials which benefit farmers and significantly contribute to the sustainable growth of Indian Agriculture.

The mission of NSAI is to encourage investment in state of the art R&D to bring to the Indian farmer superior genetics and technologies, which are high performing and adapted to a wide range of agro-climatic zones. It actively contributes to the seed industry policy development, with the concerned governments, to ensure that policies and regulations create an enabling environment, including public acceptance, so that the industry is globally competitive.

NSAI promotes harmonization and adoption of best commercial practices in production, processing, quality control and distribution of seeds.

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Message

FROM THE DESK OF PRESIDENT

We all know that seed is universally recognized as one of the most vital inputs for enhancing agricultural production and productivity. High-quality seeds not only play a key role in ensuring food security for a growing population but also contribute significantly to nutritional security. To encourage farmers to adopt quality seeds, it is essential to ensure the availability of adequate quantities of seeds that meet established quality standards, are suitable for diverse agro-ecological conditions, and are accessible at affordable prices.

The vegetable seed industry is experiencing a dynamic transformation, driven by innovations in breeding technologies, advanced seed production practices, and evolving market opportunities.

Recent trends in vegetable breeding include the accelerated use of molecular markers, CRISPR gene editing, and precision phenotyping to develop high-yielding, disease-resistant, and climate-resilient varieties. Breeding efforts are increasingly aligned with consumer preferences such as nutritional quality, shelf life, and visual appeal, giving rise to value-added vegetable cultivars.

On the **seed production front**, there is a growing emphasis on maintaining genetic purity, uniformity, and quality through improved agronomic practices and stricter field standards. Technological integration in hybrid seed production, such as male sterility systems and controlled pollination techniques, has significantly enhanced efficiency and scalability.

The **vegetable seed trade** presents exciting opportunities both domestically and internationally. Rising demand for high-quality vegetables seeds, increasing adoption of protected cultivation, and a shift toward healthy diets are fueling seed market growth. Export potential is expanding, especially for countries with favorable agro-climatic conditions and robust quality assurance systems.

India, with its vast biodiversity and skilled manpower, stands well-positioned to become a global leader in vegetable seed production and trade. Strategic public-private partnerships, capacity building, and supportive regulatory frameworks will be key to unlocking this potential.

As the vegetable seed sector evolves, collaboration among breeders, seed producers, policymakers, and market players will be essential to address challenges and seize the emerging opportunities in the vegetable seed value chain.

I am happy to see that this edition of "Seed Times" has been brought out on the theme **"Recent trends in Vegetable Breeding, Seed Production and opportunities in Vegetable Seed Trade"**, which is need of the hour. I am sure, the readers will have opportunity to go through quality articles on vegetable seeds.

M Prabhakar Rao

Message

FROM THE DESK OF EXECUTIVE DIRECTOR

Dear Readers,

The most reputed NSAI quarterly magazine of the seed industry, the **Seed Times** covers scientific research papers/articles/review articles/information on various aspects related to seed industry. It is widely circulated to all the stakeholders of seed industries *viz*., ICAR, SAUs, Central Govt. Agriculture Departments, State Agriculture Departments, NSC, SSC, Private Seed Companies etc.

The theme of Sep-Dec, 2024 issue of the Seed Times is **"Recent trends in Vegetable Breeding, Seed Production and opportunities in Vegetable Seed Trade"** with the aim to disseminate the knowledge about the vegetable seeds by eminent scientists and professionals.

Recent trends in vegetable breeding and seed production are focused on developing high-yielding, climate-resilient, and nutritionally enriched varieties to meet the growing global demand for food and health. Advances in molecular breeding, marker-assisted selection, and genome editing technologies like CRISPR are accelerating the development of improved cultivars. Simultaneously, precision seed production practices, including controlled pollination, hybrid seed technology, and quality assurance protocols, are ensuring the availability of genetically pure, high-vigor seeds. These innovations are contributing to enhanced productivity, disease resistance, shelf life, and adaptability, thereby supporting sustainable vegetable cultivation and food security.

I appreciate NSAI team for focusing on Vegetable Seeds in this edition of Seed Times which is need of the hour for the growth of seed industry.

I hope the readers would greatly be benefited from the magazine.

Happy Reading!

Y R Meena

TABLE OF CONTENTS

SEEDS PROCESSING PLANT AND RESEARCH FARM

FOR SALE

NEAR MEDCHAL, HYDERABAD

1. Seeds processing plant in 8 Acres of land with 46,000 Sq.Ft. Plant built up area with fullfledged seed processing and packaging facility. Ready for operation, Licences in place, HMDA approved, RCC basement, 3 processing lines, HT line, 125 KV generator. Located near to Industrial Area - Non-Agriculture converted.

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Optimizing Seed Production Technology of High Value Vegetable Crops Under Protected Conditions

BALRAJ SINGH[1], DHANESHVARI ARYA[2] AND RAJU YADAV[2]
[1]Vice-Chancellor, S.K.N. Agriculture University, Jobner, Rajasthan, India
[2]Research Scholars, Department of Horticulture, S.K.N. Agriculture University, Jobner, Rajasthan, India
Email: drbsingh2000@yahoo.com

Lead Author

DR. BALRAJ SINGH

Vice- Chancellor, S.K.N. Agriculture University, Jobner, Rajasthan, India

Prof. (Dr.) Balraj Singh was born on 15th July, 1963, graduated in Agriculture with Honors, in 1984 and obtained his M. Sc. (Hort.) in 1986 from CCS University, Meerut, (UP). He earned his Ph.D. in Vegetable Science from CCSHAU, Hisar, Haryana in 1991. Dr. Singh started his career as Asstt. Professor (Hort.) at KVK, Kumher, Bharatpur in April 1989, thereafter he worked at AICRP on Vegetable crops, ARS Durgapura, Jaipur, from 1991 to Nov 1998. He joined at ICAR-CAZRI Jodhpur (Rajasthan) in 1998 as Senior Scientist, subsequently, after transfer to IARI he served Indo-Israel Project (Presently CPCT) as Senior Scientist, **Principal Scientist** and thereafter occupied the position of **Head,** CPCT, ICAR-IARI, New Delhi. On 1st September 2012 he was appointed as Director, ICAR-NRCSS, Ajmer (Rajasthan). In year 2016, he was selected as Horticulture Commissioner by GOI and as well as **Vice Chancellor, Agriculture University, Jodhpur** He preferred to provide leadership as Vice Chancellor of Agriculture University, Jodhpur, Rajasthan. After successful completion of his three years term of vice chancellor he joined back ICAR and worked as **Project Coordinator**, Honey Bees and Pollinators at ICAR - IARI, New Delhi, w.e.f. 26.03.2019 to 14.10. 2022. Dr Singh is presently working as **Vice Chancellor,** SKNAU, Jobner, Jaipur w.e.f. 15th October 2022. Dr. Singh has total more than 36 years of research, teaching, extension and experience RMP positions.

Achievements: He is initiated R&D work on protected cultivation and precision farming in the country under the Indo-Israel Collaborative Project at IARI, New Delhi and has standardized numerous cost effective and energy efficient protected cultivation technologies suitable for different agro-climatic conditions for vegetable production. As a resource person, he has been the member of Working Groups formed in many Indian States for implementation of Protected Cultivation. Dr. Singh has intensively worked for development of hybrid seed production technology of high value vegetable crops under protected conditions.

Awards and Recognitions: Dr. Singh has been awarded with Dr. Kirti Singh Gold Medal for the year 2015 by Horticulture Society of India for his outstanding contributions in the field of horticulture (Vegetable Sciences). Dr. Singh has been awarded with highest Marwar Award i.e. "Veer Durga Das Award" for doing outstanding work in Research and Development in field of Agriculture at AU, Jodhpur by H.H. Maharaja Gaj Singh - II of Jodhpur during 2018. Dr Balraj Singh has been awarded **DSc (Honoris causa) by VGU, Jaipur in year 2025.** Dr. Singh is the founder Secretary of the Indian Society for Protected Cultivation and President of the Indian Society of Seed Spices, Ajmer. He has been the Vice President of Indian Society of Seed Technology and Fellow member of Academy of Sciences, Engineering and Technology; Indian Society of Seed Technology; Horticulture Society of India, Indian Society of Seed Spices and he is presently President Society for Horticultural Cultural Research & Development (SHRD). He had training in Leadership and Decision Making at Harvard Kennedy School, Cambridge, USA and has also represented India at various international forums as oral/lead speakers in conferences and seminars & training programs, as part of delegation.

Research Publications: He has published 165 research papers, 50 book chapters 120 technical and popular articles, 8 books, 15 bulletins, vision documents & policy papers.

Abstract

Protected cultivation has become a vital component of modern agriculture, significantly contributing to global food security and vegetable seed production. The wide variety of structures and vegetables cultivated under these protected environments highlights the adaptability and versatility of such systems. As the

world faces the increasing challenge of growing high-value, low-volume crops, protected cultivation is poised to play a positive role in the future of vegetable seed production by offering solutions to issues such as climate change, resource scarcity and seed quality. To fully utilize the potential of protected cultivation for hybrids and quality seed production, collaboration between governments, agricultural institutions and the private sector is essential to support and promote sustainable practices, ensure training and knowledge dissemination and establish favorable policies for its continued expansion. Looking ahead, the potential of protected cultivation is substantial. With global population growth and climate change placing increasing pressure on traditional vegetable seed production, protected cultivation hence offers a sustainable approach to enhance food production, ensure seed vigor and reduce dependence on seasonal variations. Furthermore, technological advancements in seed production systems and the adoption of new methods such as INM (Integrated Nutrient Management), IPM (Integrated Pest Management), IWM (Integrated Weed Management) and IDM (Integrated Disease Management), along with renewable energy, are expected to make protected cultivation even more sustainable and economically viable.

Keywords: - Protected cultivation, food security, seed production, climate change

Introduction

India ranks as the second-largest global producer of vegetables after China, with production reaching 212.91 million tonnes from 10.25 million hectares in 2024–25. A major constraint is the limited availability and high cost of quality seeds particularly hybrids of high-value crops like cherry tomato, tomato, sweet pepper with different colours, chilli, summer squash and cucurbits. This high cost is primarily driven by low seed yields in open-field conditions, limited availability of suitable seed production zones and increasing biotic and abiotic stresses resulting from climate change. Frequent extreme weather events, pest outbreaks and pollination challenges in open-field systems further reduce seed yield, compromise seed quality and affect genetic purity. Moreover, pesticide overuse affects pollinator activity and raises residue levels in seeds. These factors contribute to reduced profitability and unstable seed supply. Protected cultivation offers a sustainable alternative by providing a controlled environment that minimizes climatic risks and biological stresses. Structures such as greenhouses, shade nets, insect-proof net houses, low tunnels and walk-in tunnels enable precise regulation of temperature, humidity and light. They also facilitate controlled pollination, reduce pesticide use and improve genetic purity. The global success of protected cultivation particularly in countries like China demonstrates its potential in enhancing seed yield, quality and land productivity. Though research comparing seed production under open versus protected systems is limited, available studies confirm superior outcomes in controlled environments. Adopting climate-resilient, techno-economically viable protected structures according to crop type, location and season is crucial. This transition will ensure consistent, high-quality seed production, secure the supply chain for high-value vegetables and enhance the profitability and resilience of India's vegetable seed sector.

Scope of protected cultivation

India, with its vast agro-climatic diversity, is embracing protected cultivation technologies—such as greenhouses, net-houses, high and low tunnels to enhance vegetable production and meet the rising food demands driven by population growth and dietary changes. Despite initial challenges, particularly in harsh northern plains, success in mild regions like Bengaluru and Pune has been encouraging. Government schemes under MIDH, NHM, TM, NHB and RKVY have promoted adoption, though early implementation lacked region-specific technical support. Over time, public sector research and international collaboration improved design and adaptability of protected structures. Now, suitable varieties and hybrids are developed for protected cultivation. Successful cluster models, such as in Bassi-Jhajhra (Jaipur), showcase scalability potential. While current coverage is around 2.0 lakh ha, projections estimate expansion up to 15–17 lakh ha by 2050. With vegetable demand expected to rise from 214 to 750 million tonnes by 2050, protected cultivation is crucial for securing India's horticultural future.

Crop Requirements for optimal seed production

Optimal vegetable seed production under protected cultivation in India necessitates careful management of environmental factors well-cut to the specific needs of each vegetable crop. Key parameters include temperature, humidity, light, soil conditions and carbon dioxide levels. Temperature is critical throughout the lifecycle, with tomatoes favoring warm (15-27°C day), capsicum cooler (21-24°C day, 16-18°C night) and cucumbers (18-32°C average). Humidity affects pollination and disease, requiring 80-90%/65-75% (day/night) for tomatoes, 50-60% for capsicum and around 85% for cucumbers, managed through ventilation. Adequate light intensity (e.g., 50,000 lux for cucumbers) is vital for photosynthesis, potentially requiring supplementation. Well-drained, fertile soil with specific pH ranges is minimal, necessitating regular testing and amendments. Finally, enriched carbon dioxide levels in greenhouses can boost photosynthesis and overall seed production, contributing to higher yields for farmers in the region.

Methods and Techniques Employed in Vegetable Seed Production under Protected Cultivation.

A. Protected structure for vegetable seed production

1) **Low-cost playhouses** (50–250 m²) are increasingly being adopted for vegetable seed production in regions prone to frost, pests and viruses. These structures provide a basic level of environmental control, improving seed quality and purity by minimizing biotic stress. States such as Uttarakhand, Himachal Pradesh, Tamil Nadu, Jammu and Kashmir and North Eastern regions are expected to witness 8–10% annual growth in the use of this technology.

2) **Plasticlowtunnels** areextensivelyusedforoff-seasonseedproductionofcucurbits during the winter months. These tunnels create a favorable microclimate for flowering and seed development, leading to better synchronization and higher seed yield. They are gaining popularity in Punjab, Haryana, Rajasthan and Uttar Pradesh, with a projected 15–20% growth covering 20,000–22,000 acres.

3) **Naturally ventilated greenhouses** offer the most suitable environment for large-scale and round-the-year vegetable seed production, especially for high-value crops like tomato, cherry tomato, capsicum, seedless cucumber and eggplant. These structures allow effective isolation and quality assurance, with an expected 15–20% expansion covering 1.2–1.3 lakh hectares in Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, Maharashtra and other major states.

4) **Semi-climate-controlled greenhouses** are essential for producing nursery transplants and high-value vegetable seeds under regulated conditions. These structures improve seedling health and support early hybrid seed production, particularly in Rajasthan, Gujarat, Madhya Pradesh, Maharashtra and semi-arid areas, with 8–10% growth anticipated over 1,500–2,000 hectares.

5) **Shade net houses** facilitate seed production of leafy vegetables and herbs during high-temperature months by reducing heat stress and ensuring better pollen viability and seed formation. These are gaining traction in arid and semi-arid zones of Madhya Pradesh, Rajasthan, Gujarat, Maharashtra andhra Pradesh and Tamil Nadu, with 10–12% expansion projected across 12,000–14,000 hectares.

6) **High tunnels** are suited for off-season seed production of cucurbits and support drying of seed materials like chilli and fenugreek (methi). These are beneficial in managing temperature and humidity during critical reproductive stages, with 8–10% growth expected in Rajasthan, Madhya Pradesh, Gujarat and other arid regions.

7) **Retractable greenhouses**, though still limited in adoption, are gaining attention for the specialized seed production of temperate crops. These structures provide seasonal flexibility and climate resilience and are expected to grow by 5–8% over 20–30 hectares in Uttarakhand, Uttar Pradesh and Madhya Pradesh.

8) **Climate-controlled greenhouses or glasshouses** offer the highest level of environmental control and are suitable for precision seed production systems, including hydroponics and aeroponics. They are particularly beneficial for crops like potato and are expanding gradually (3–5%) in Haryana, Punjab, Uttar Pradesh and Rajasthan.

B. Cultural Practices:

- **Healthy nursery raising of vegetables for quality seed production**: Healthy nursery raising is principal for quality vegetable seed production, ensuring healthy and virus-free seedlings for open-pollinated (OP) varieties and parental lines for hybrids. Standardized plug tray technology under greenhouse conditions is crucial, as each seed's value necessitates 100% germination and quality seedlings for successful establishment. Off-season nursery raising in cucurbits has also been advanced. Studies on tomato plug cell size and shape demonstrate that round cells with a 68.2 cm^3 volume yield the highest shoot fresh weight, indicating the importance of optimizing these parameters for robust seedling development.

- **Soil Management:** Includes solarization to reduce soil-borne pathogens and the use of raised or sunken beds.

- **Irrigation and Fertigation:** Primarily managed via drip irrigation for efficient and precise water and nutrient delivery based on soil testing and crop needs.

- **Plant Density and Spacing:** Carefully determined to optimize seed yields, varying by vegetable species.

- **Pruning and Training:** Employed to improve light penetration, air circulation and ease of harvesting (e.g., vertical tying, single-stem training in tomatoes, branch pruning in capsicum).

- **INM (Integrated Nutrient Management):** In protected cultivation, INM focuses on precise nutrient delivery through methods like fertigation, optimizing plant health and seed quality while minimizing fertilizer runoff within the enclosed system.
- **IWM (Integrated Weed Management):** Weed control in protected environments emphasizes preventative measures such as using weed-free growing media and physical barriers like mulching.
- **IPM (Integrated Pest Management):** IPM under protected cultivation is crucial due to the confined environment potentially favoring rapid pest build-up. Strategies include exclusion (insect-proof netting), biological control (introducing beneficial insects), sticky traps for monitoring and the judicious use of targeted biopesticides or selective chemicals as a last resort.
- **IDM (Integrated Disease Management):** Disease management in protected cultivation prioritizes hygien, using disease-resistant varieties and controlling environmental factors like humidity and ventilation to discourage pathogen development. Biological control agents and targeted fungicides may be used preventatively or curatively based on monitoring.

Pollination management under protected cultivation

Effective pollination at the right time plays a crucial role in ensuring high seed quality, seed vigour and overall profitability in seed production. However, in open-field conditions, several challenges can hinder successful pollination. Environmental factors such as wind, rain, temperature fluctuations and pest infestations can disrupt the pollination process, leading to poor seed set, reduced yields and uneven seed maturity. Moreover, the excessive use of pesticides not only decreases the attractiveness of flowers but also harms pollinators by reducing their efficiency and population. These issues collectively impact the success of seed production and the quality of the final product. Conversely, protected environments like polyhouses and net houses offer significant advantages. They shield crops from harsh conditions and pests, resulting in well-filled, mature and uniformly developed seeds of superior quality. Pesticide use is minimized, protecting pollinators. Furthermore, alternative pollinators such as bumblebees, carpenter bees and stingless bees thrive in these enclosed spaces. These pollinators are more active and efficient, being less affected by external environmental stressors and resource competition, making them ideal for ensuring better pollination, higher yields and improved fruit and seed quality in protected cultivation systems.

Vegetable Varieties Suitable for Protected Cultivation

Sl. No.	Crops	Variety / Hybrids
1	Tomato	Pusa tomato protected-1, Pusa Rakshit, Rakshita, Himsona, Himsikhar, Snehlata, Naveen,
2	Cherry tomato	Pusa Golden Cherry Tomato -2, Pusa Cherry Tomato -1
3	Coloured Capsicum	Natasha, Swarna, Indra, Bombi, Orobelle, Bachata, Inspiration
4	Parthenocarpic Cucumber	Pant Parthenocarpic Cucumber-2, Punjab Cucumber-1, Pusa Parthenocarpic Cucumber-2, Pusa Parthenocarpic Cucumber-6 and Pusa Parthenocarpic Cucumber Hybrid-1, Kian, Hilton, Sun Star, Multistar, Mini Angel
5	Summer Squash	Pusa Alankar, Pusa Pasand, Australian Green, Seoul Green, Kora, Yellow Zucchini, Himanshu
6	Bitter Gourd	Pusa Rasdar

Economic Feasibility and Cost-Benefit Analysis of Protected Vegetable Seed Production

The economic viability of protected vegetable seed production in India balances higher initial and operational costs against increased returns. Constructing structures and installing equipment demands more investment than open fields and ongoing expenses for specialized inputs and controlled environments can be substantial. However, protected cultivation often yields significantly more high-quality produce, fetching premium off-season prices. Doubled net returns from polyhouses and positive cost-benefit ratios for crops like cucumber and capsicum are common. Government subsidies are crucial for easing the initial financial burden. Profitability depends on selecting high-demand crops, efficient resource use, modern practices, accessing support and minimizing losses. While some crops thrive, others need price advantages or lower costs. Careful planning and management are vital for realizing the economic benefits in the Indian context.

Entrepreneurial opportunities

For farmers seeking gratifying and sustainable business, protected vegetable seed production is ideal. Modern techniques like polyhouses ensure high-quality, high-germination, genetically pure and disease-resistant seeds. Year-round cultivation allows multiple harvests, enhancing production and profits. Controlled environments minimize pests and diseases, improving plant and seed quality. This opens doors to specialized farming, meeting consumer demand for organic, unique, or region-specific varieties popular in urban and export markets. Farmers can become experts in these niche seeds. Partnering with private companies or public sectors (ICAR, SAUs) for contract production offers stable income and market access, professionalizing their agribusiness. Example, IARI provides excellent initial seeds and offers technical guidance and best growing practices. Farmers cultivate the seeds following specific instructions and after harvesting, IARI or their authorized partners buy the seeds. This collaboration not only ensures a market for the seeds and a reliable income but also introduces farmers to the latest and most effective seed production methods. By taking advantage of these institutional partnerships, using protected cultivation and focusing on specialized farming that aligns with what consumers desire, entrepreneurs can build a dependable, market-focused and growing agribusiness in vegetable seed production.

SWOT analysis of vegetable seed production under protected cultivation

Strengths: Protected cultivation enhances vegetable seed quality by providing controlled environments that improve germination, genetic purity and disease resistance. Year-round production capabilities increase seed yield and income. Reduced pest and disease pressure minimize losses and the need for chemical treatments. The method supports niche farming for high-demand specialized seeds and facilitates contract production with guaranteed income. Collaborations with institutions offer access to quality seeds, technical support and markets. Efficient resource use is also a key advantage.

Weaknesses: High initial investment and ongoing operational costs are significant drawbacks. Specialized technical expertise is required for successful implementation. Reliance on technology can lead to vulnerabilities. Establishing market access for specialized seeds may be challenging. Specific pests and diseases can still thrive in protected environments if not properly managed.

Opportunities: Growing demand for high-quality seeds and expanding niche markets present significant opportunities. Government support and collaborations with research institutions offer valuable resources. The potential for export markets and advancements in protected cultivation technology can further enhance profitability and efficiency.

Threats: Market price fluctuations and competition from established seed companies pose economic threats. Climate change impacts and a lack of skilled labor could hinder progress. Changes in government policies and the emergence of new pests and diseases also present potential challenges.

Conclusion

In essence, protected cultivation offers a clear advantage over open fields for vegetable seed production. It ensures superior seed quality, year-round harvests and reduced risks from pests and weather. While requiring initial investment and expertise, it unlocks opportunities in niche markets and stable contract farming. Compared to the vulnerabilities and seasonal limitations of open fields, protected cultivation provides a more reliable, productive and sustainable approach to meet the growing demand for high-quality vegetable see.

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Hybrid Seed Production Techniques Involved in Vegetables

BHOOPAL SINGH TOMAR[1*], VISHWANATH YALAMALLE[2] AND PARESH CHAUKHANDE[3]
[1*]Head, Division of Vegetable Science, ICAR-IARI, New Delhi -110012
[2]Division of Seed Science & Technology, ICAR-IARI, New Delhi-110012
[3]Division of Vegetable Science, ICAR-IARI, New Delhi-110012
Email: bst_spu_iari@rediffmail.com

Lead Author

DR. B. S. TOMAR

Head, Division of Vegetable Science,
ICAR-IARI, New Delhi -110012

Dr. B. S. Tomar obtained B.Sc. Ag. and M.Sc. Agricultural Botany degree from Meerut University and Ph.D. degree in Horticulture with specialization in Vegetable Crop from ICAR-IARI, New Delhi.

He started his career as Technical Assistant (T-III) and joined the Division of Vegetable Science in 25/11/1985 with Dr. V S Seshadri, PC (VC) and continued till 1996. He joined Agricultural Research Service in NAARM, Hyderabad on 23rd March, 1996 and later posted in Division of Seed Science and Technology, IARI, Pusa, New Delhi. He served as In-charge, Seed Production Unit and promoted to the level of Principal Scientist (Seed Technology) on 22/03/2021. He joined as Head, Division of Vegetable Science, ICAR-IARI, New Delhi on 05/04/2016 and continuing till date. He also served as Professor, Division of Vegetable Science for a short period of eight months and served as Joint Director (Extn.) -Additional Charge from 5th March 2021 to 25th November, 2022. He is associated with AICRP (VC) as PI since April, 2016 and AINRPOG since November, 2018 onward.

He has been associated in the development of 24 vegetable crop varieties/hybrids and signed 23 MoU,s with seed companies and generated revenue of Rs. 55 lakhs and involved in eleven externally funded projects in vegetable improvement. He has been involved in registration of four new germplasm at NBPGR and two copy rights. He guided 21 (M.Sc. & Ph.D.) students in Seed Science Technology and Vegetable Science. He organized production of breeder & IARI seed of more than Rs. 84 lakh since last six years in the Division of Vegetable Science. He has created facility of molecular lab-III, pathology lab and strengthened the bio-chemistry lab to boost the resistance breeding and quality improvement programme in vegetable crops. He strengthened the maintenance of wild relatives and use in pre-breeding programs. He has also organized tomato field day in 2018, vegetable field day in 2017. He planned and organized the live vegetable demonstration at UVRD and Krishi Vigyan Mela site of vegetable crop varieties and their technologies. I delivered more than 300 TV & radio talks on vegetable and allied field.

He has published 112 research papers comprising 94 research papers > 6 NAAS rating including 14 in reputed foreign journals. He also published 12 bulletins, 2 practical manuals, 250 popular articles & edited 4 books having ISBN with more than 100 pages.

He received Jawaharlal Nehru Award for outstanding contribution in Ph.D Research – 1995, IARI Best Teachers Award-2014, Dr. Gautam Kalloo Award for Excellence in Horticulture Research -2017 by SHRD, Dr. Kirti Singh Medal for outstanding contribution in vegetable science and 7th NHRDF Award for outstanding research work in onion 2021, fellow of IAHS, ISVS, ISST & ISSS and served Executive Councilor in IAHS (2019 &2020) and serving Executive Councilor in ISVS and International Society for Noni Science-2022 onwards. He is also serving member of Editorial Board of Indian Horticulture, Editor, Current Horticulture and member Scientific Advisory Committee NHRDF (since 2018 onwards). He also served as TCDC consultant in FAO in Uzbekistan for development of vegetable seed program during 2009 (15 days)

Abstract

India is a major vegetable producer that contributes significantly to the global food supply and the country's economy. The demand for hybrid vegetable seeds has grown because of their high yield, quality, and resilience to biotic and abiotic stresses. Hybrid seed production involves techniques, such as using gynoecious lines, male sterility, and self-incompatibility systems. Protected cultivation methods have also enhanced seed quality and production efficiency, ensuring better yields

and reducing pest impacts. These methods are labor-intensive, creating job opportunities in rural areas and improving farmers' incomes. Advancements in hybrid seed technology are helping India strengthen its position on vegetable seed exports, promote nutritional security, and support sustainable farming practices. Investment in this sector can drive rural prosperity and long-term agricultural success.

Keywords: *Cross-Pollination, Gynoecious lines, Hybrid seed production, Male sterility, Protected cultivation, Self-incompatibility and Yield improvement*

Introduction

India is the second-largest vegetable producer in the world. Its diverse soil and climate conditions provide ample opportunities to grow a variety of crops (tropical, semi-temperate, or temperate). Vegetables constitute a significant part of the country's total agricultural production. India's annual vegetable production was 200.45 million tonnes from 10.86 million ha area under cultivation (Anonymous, 2021). Vegetables alone contributed to 66.97 % of the total horticultural production (341.63 million tonnes). Its vast production base offers India tremendous opportunities for export. According to APEDA (2023-24), India exported fresh vegetables worth Rs. 6,861.05 crores (828.26 USD Millions). The growth in vegetable production is largely due to an increase in productivity; the average productivity of vegetables in India is 18.18 tonnes per hectare, and an increase in productivity has led to an improvement in per capita availability of over 250 g. This impressive improvement was attributed to the development of improved varieties and hybrids, along with the availability of high-quality seeds, production, and protection technologies through systematic research and large-scale adoption by farmers.

According to an estimate, the total vegetable seed requirement in India is 51,000 tons, but the actual availability is around 40,000 tons, and a large chuck of seeds is still being multiplied by the farmers themselves (Dutta, 2004). Vegetables play an important role in India's rural economy by improving farmers' incomes. The cultivation of vegetables is labor-intensive and generates many employment opportunities throughout the year. They fit well in the cropping system, either as a main crop, intercrop, or catch crop between the growing seasons. Vegetables are also rich sources of vitamins, minerals, proteins, and antioxidants that are deficient in cereals. Hence, they are referred to as protective foods and are of great importance to people's nutritional security. Thus, the cultivation of vegetables plays a vital role in the prosperity of a nation and is directly linked to people's health and happiness. Vegetables play an important role in providing a base for the growing agro-processing industry, as well as helping to obtain foreign exchange.

Most farmlands in India are small with an average size of 1.08 ha. For small and marginal farmers with assured irrigation facilities, vegetable production is productive. Vegetable crops have the potential to provide nutritional security for both urban and rural populations, and are more productive than other crops. Among vegetables, hybrid cultivars are preferred because of their higher yield, uniformity, biotic and abiotic stress tolerance, and high shelf life. A consistent increase in productivity can be achieved using high-quality seeds with built-in inbred and hybrid vigor, along with modern vegetable cultivation technologies and effective government policies. Therefore, the adoption of hybrid vegetable technology is a better option (Fig 1).

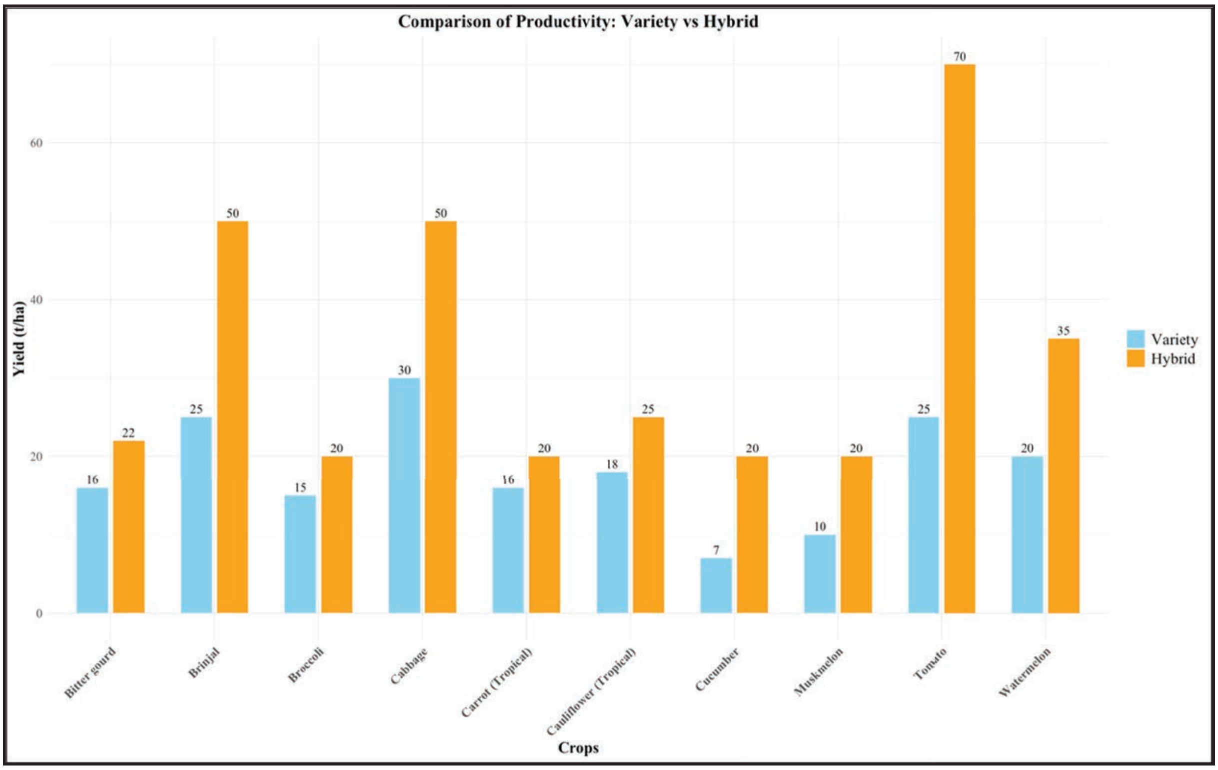

Fig 1: Comparison of productivity in variety vs hybrid

Vegetable seed production involves two processes: pollination and fertilization. The former involves the transfer of pollen from the male part of the flower, known as the androecium, to the female part, known as the gynoecium. There are two main types of pollination: self-pollination, which occurs when pollen is transferred from an anther to the stigma of the same plant. Self-pollination increases homozygosity. Self-pollination in some species causes inbreeding depression, and these species have evolved into cross-pollinated species. Cross-pollination refers to the transfer of pollen between different plants. Cross-pollination leads to heterozygosity.

Species that rely on outbreeding typically develop a balance of heterozygosity but may exhibit significant inbreeding depression if self-pollinated. In addition to self-pollination and cross-pollination, there is another type of species known as often cross-pollinated species, which are basically self-pollinated but outcrossing to an extent of 5%–30% occurs. Certain mechanisms such as bisexuality, homogamy, cleistogamy, and the position of anthers promote self-pollination, whereas others such as dicliny (including monoecy and dioecy), dichogamy, heterostyly, herkogamy, self-incompatibility, and male sterility promote cross-pollination (Singh et al., 2020).

Hybrid Seed Production Methods

In recent decades, the availability of an affordable technique for mass-producing F_1 seeds has gained momentum, which has increased the availability and affordability of seeds of hybrid varieties. Many techniques have been developed to create hybrid vegetable crops, but because of their practicality and economic viability, only a few are used to produce commercial hybrids in vegetables. The most commonly used mechanisms and methods for hybrid seed production in commercial vegetables are shown in Fig. 2.

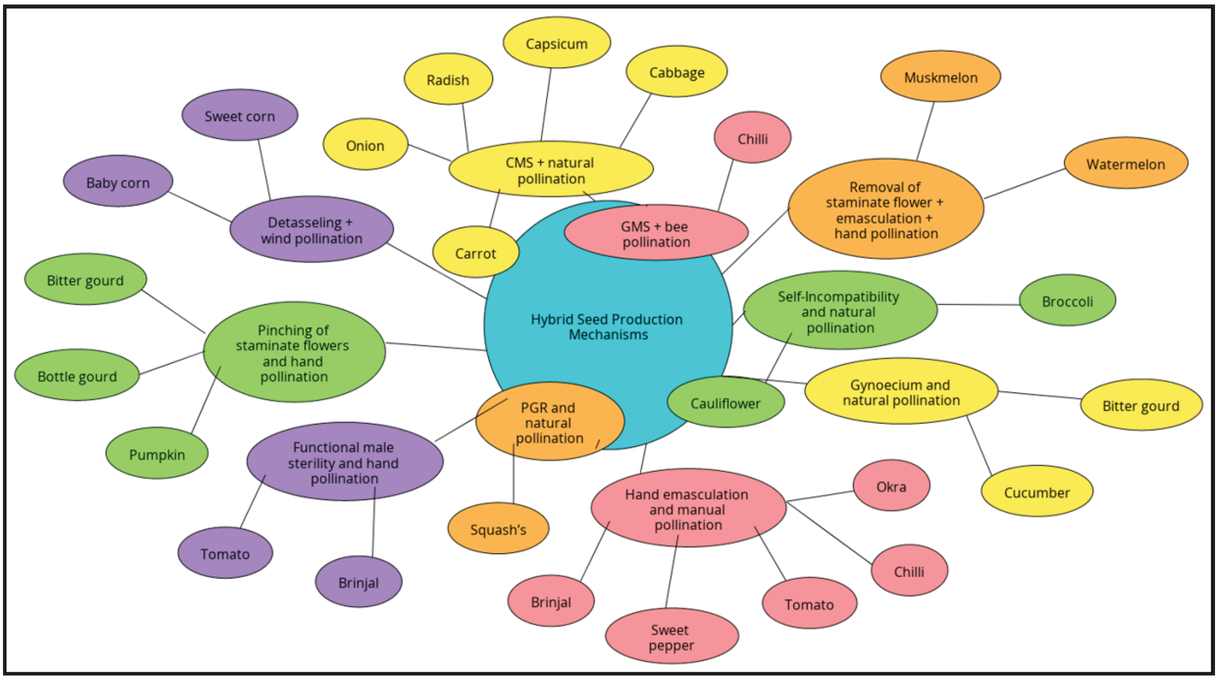

Fig. 2: Mechanisms of hybrid seed production commercially exploited in vegetable crops ***Source: Tomar et al., (2015)***

Use of Gynoecious lines

Gynoecious sex form: The majority of cucumber hybrids are produced by crossing gynoecious and monoecious cucumber lines. Other systems for producing gynoecious hybrid seeds are gynoecious × gynoecious, but gynoecious × monoecious hybrids are still widely grown because they offer advantages such as earliness (Jat et al., 2016b), a high degree of female sex expression (Jat et al., 2016a; Jat et al., 2017), and uniform and concentrated fruit formation, which is especially advantageous for mechanical harvesting (Robinson, 2000). Several institutes have released gynoecious hybrids; IARI, New Delhi has released a cucumber hybrid, Pusa Sanyog, and PAU Ludhiana has released the muskmelon hybrid (MH-10). Gynoecious hybrids employ honey bees for crossing in seed blocks; ideally, 4:2 (female: male) is maintained when the seed is produced under open field conditions, and isolation of 1000 m is recommended. Male parents were maintained by selfing. Since female plants only produce female flowers, male flowers are induced by spraying 200 ppm silver nitrate at 2-4 true to induce staminate flowers and plants are selfed. One of the major drawbacks of gynoecious lines is the stability of lines under varying photo-thermal regimes, particularly in tropical countries such as India. Efforts have been made in IARI, New Delhi, to develop stable gynoecious lines for cucumber and muskmelon. Consequently, the F_1 hybrid, Pusa Rasraj (Monoecious-3 × Durgapura Madhu), was developed and released by IARI.

Use of growth regulators for maintenance of gynoecious lines in cucurbitaceous crops

Gynoecy is the most important sex form that has led to phenomenal exploitation of hybrid vigor in cucumber, bitter gourd, and muskmelon (Munshi *et al*., 2017). Gynoecious inbreds can self-reproduce if a growth regulator is used to induce male flowering (Robinson 2000). Gibberellic acid (1500-2000 ppm) has been used to induce male flowers in cucumber (Peterson and Anhder (1960), but different gynoecious lines vary in response to GA application, and the number of induced male flowers is not sufficient for hybrid seed production, causing excessive stem elongation or malformed male flowers. Therefore, silver compounds, such as silver nitrate (250-400 ppm), are used to induce male flowers. These ions inhibit ethylene action and promote male flower induction in gynoecious cucumber lines (Beyer, 1976). However, because of the phytotoxic effects of silver nitrate, such as plant burning, silver thiosulfate (400 ppm) is now widely used by seed producers to maintain gynoecious and parthenocarpic cucumber and bitter gourd lines. It induces male flowering in cucumber plants over a longer period of time and is less phytotoxic than silver nitrate (Fig.3).

Fig. 3: Induction of male flowers in gynoecious lines

Hand Emasculation and Hand Pollination

Hand pollination and emasculation are the common techniques used to produce hybrid seeds. This technique is only economically viable for crops such as brinjal, tomatoes, chilli, capsicum and cucurbits, where more seeds are produced per pollination and less quantity of seeds per hectare for sowing (Vishwanath et al. 2008). As pinching, pollen collection, and hand pollination require a lot of trained labor, this method is only appropriate for small-scale production (Fig.4).

Fig. 4: Protection of female & male flower and hand pollination

Use of male sterile lines

Male sterility refers to the inability of a plant to create or release functional pollen as a result of failure to form or grow functional gametes, microspores, or stamens. Male sterility is consequently sometimes subdivided into the following categories: (a) "Pollen sterility," in which male sterile individuals differ from normal only in the absence or extreme scarcity of functional pollen grains; (b) "Structural or staminal male sterility,". in which male flowers or stamens are deformed, non-functional, or entirely absent; and (c) "Functional male sterility," in which perfectly good and viable pollen is present but fails to dehisce (Lasa and Bosemark, 1993). Based on genetics, male sterility can be classified into three groups: (1) genetic male sterility (GMS), (2) cytoplasmic male sterility (CMS), and (3) cytoplasmic genetic male sterility (CGMS).

Table 1: Genes responsible for male sterility in vegetables

Crops	Gene number/condition	Gene
Tomato	Single recessive gene	*ps*-2
Chilli	Single recessive gene	ms-12 & ms-3
Muskmelon	Single recessive gene	*ms-1, ms-2, ms-3, ms-4, ms-5*
Winter squash	Single recessive gene	*ms-1*
Summer squash	Single recessive gene	*ms-2*
Cucumber	Single recessive gene	*ms-2*

Source: Singh and Singh 2022

The male sterility system has a number of benefits. It lowers the cost of producing hybrid seeds. It expedites hybrid breeding programs, prevents hand pollination and emasculation enables large-scale production of hybrid seeds, and allows for the economic exploitation of hybrid vigour (Sharma et al., 2019). However, it also has several limitations, including the identification and transfer of male sterility in a suitable background, which is a time-consuming process. Adequate cross-pollination should occur between lines A and R to obtain a good seed set. Synchronization of flowering occurred between lines A and R. Fertility restoration should be complete; otherwise, the F_1 seed should be sterile. Cytoplasmic male sterility can be utilized in vegetables, where the economic aspect is the vegetative aspect. Male sterility is influenced by environmental factors that can lead to plant selfings. In the hybrid seed production field of the GMS system, 50% of male fertile segregants (*Ms/ms*) need to be identified and removed before they shed pollen. Isolation is required for the maintenance of parental lines and production of hybrid seeds, which are often difficult to find. The male sterility system has been commercially exploited, and several hybrids have been released by public sector organizations, as shown in Table (2).

Table 2: Hybrids released by the public sector using the male sterility system

Crop	Variety	Male sterility system	Institute
Chilli	CH-1, CH-3 & CH-27	GMS	PAU, Ludhiana
	Kashi Surkh, Kashi Tej	CGMS	ICAR-IIVR, Varanasi
	Arka Meghana (MSH-172), Arka Shwetha (MSH-149), MSH-96	CGMS	ICAR-IIHR, Bengaluru
Carrot	Pusa Nayanjyoti Pusa Vasudha	CGMS CMS	ICAR-IARI, New Delhi
Onion	Arka Kirtiman and Arka Lalima	CGMS	ICAR-IIHR, Bengaluru
Okra	Arka Nikita	GMS	ICAR-IIHR, Bengaluru
Cabbage	Pusa Hybrid-82(KTCBH-822)	CMS	ICAR-IARI, New Delhi
Cauliflower	Pusa Hybrid 301 (KTH-301)	CMS	ICAR-IARI, New Delhi
Tomato	Pusa Divya	CGMS	ICAR-IARI, New Delhi

Self-Incompatibility

Self-incompatibility is a common occurrence in vegetable crops that discourages inbreeding and promotes outcrossing. Numerous multiallelic loci control the genetic reaction to self-incompatibility, which is dependent on complex interactions between self-incompatible pollen and pistil combinations (Hiscock, 2002). It is a genetically controlled phenomenon that prevents self-pollination in cole crops and other vegetables such as tomatoes. The two types of self-incompatibility are gametophytic and sporophytic, while in the sporophytic technique, pollen phenotype (self-incompatibility response) is identified with the genotype on the female plant on which pollen is developed, and the self-incompatibility response of pollen and stigma is determined by the genotype of the female plant on which pollens are developed (e.g., tomato) in gametophytic techniques. (e.g. cole greens). Sporophytic self-incompatibility (SSI), has been used effectively for the development of commercial hybrids in Brassicaceae (Singh et al., 2020). Utilizing the self-incompatibility system ICAR-IARI, New Delhi has developed and released Pusa Cauliflower Hybrid 101 (DCH-1467) suitable for zone IV (Punjab, Uttar Pradesh, Bihar) with a higher yield potential. One of the major advantages of, self-incompatibility is that, during hybrid seed production with appropriate parent combinations, seeds can be harvested from both parents. Self-incompatibility system has some limitations: the purity of hybrid seeds is doubtful because of the presence of sib-seeds produced on the SI line during environmental aberrations, which makes it unsuitable.

Hybrid seed production using protected structures

The lack of sufficient isolation, insect vectors, diseases, and a virus-free environment in the production of disease-free, healthy, and genetically pure seeds for commercial cultivation are the major challenges to the quality of hybrid seed production of vegetables. Compared to open field conditions, protected cultivation can result in higher seed yields with better quality (Tomar and Jat, 2015). Insect vectors and viral diseases are the most devastating problems for quality seed production in most vegetable crops grown in open fields, and the use of pesticides will automatically reduce if insect vectors are checked by protected structures. Seed production in the summer season is affected by a sudden increase in temperature and severe infestation of mottle mosaic virus and other insect pests in the rainy season; however, there is still no effective and reliable management measure. The change in climatic conditions, such as unseasonal rains during April- June and increased temperature, drastically reduced the seed yield and quality even in the summer season crop. Raising seed crops in insect-proof net houses can overcome these problems by protecting crops from various insect vectors and unfavorable climatic conditions. It also provides an option for high-quality and off-season seed production. The insect-proof net house is the most suitable and low-cost protected structure for quality hybrid seed production of open-pollinated varieties in a large number of vegetables. The major interest is to grow virus-free seed crops and protect them against major insects/pests. Insect-proof net houses are more suitable for hybrid seed production of tomato, sweet pepper, chilli, okra, brinjal, and cucurbits than open field conditions (Jat et al., 2016). The semi-climate-controlled greenhouse is suitable for hybrid seed production of indeterminate-type varieties and hybrids of standard tomato, cherry tomato, sweet pepper, bitter gourd, and parthenocarpic cucumber varieties. The seed yield of such crops can be to 3-4 times more compared to that of open-field cultivation (Kaddi., 2014; Kalyanrao et al., 2012; Jat et al., 2017). Similarly, naturally ventilated greenhouses are also suitable for hybrid seed production, where the seed yield is usually 2-3 times more than that of an open field; however, the cost of seed production is only 1/3rd of that produced under semi-climate-controlled greenhouse conditions (Kalyanrao et al., 2014; Singh and Tomar, 2015). The major advantages of hybrid vegetable seed production under protected conditions are as follows:

- Higher seed yield (generally 2-4 times more) and seed quality as compared to open field
- Thus, the requirement for isolation distance in cross-pollinated vegetables can be minimized.
- Thus, the problem of flowering synchronization can be minimized.
- Maximum plant population can be maintained.
- Seed production under adverse climatic conditions is also possible.
- Training, pruning, and hand pollination practices are easily manageable under protected conditions compared with field seed crops.
- Emasculation of female parents is not required because there are no insect pollinators.
- Seed crops are not damaged by seasonal rain at the time of their maturity.
- Seed viability and vigor can be extended through better nutrient management in seed crops under protected conditions.

Conclusion

The vegetable seed industry offers immense potential for job creation and economic growth, particularly through the production of hybrid seeds. Hybrid seed production of tropical vegetables, such as solanaceous crops that need careful hand pollination, has already created 2.71 million man-days of work in rural areas, showing how it can support steady livelihoods and help farmers possibly double their incomes. With its diverse climates, soils, and a large pool of skilled workers, India is in a strong position to become a global leader in exporting high-quality vegetable seeds, promoting rural prosperity and sustainable farming. Moreover, advances in hybrid seed technology can boost yields, improve crop resilience, and strengthen nutritional security for consumers. As the demand for healthy and assorted vegetables continues to grow worldwide, investing in hybrid seed production not only brings economic rewards but also uplifts rural communities, empowering millions of farmers to aim for a brighter future. By including these approaches, India can lead vegetable seed exports, ensuring ongoing rural development and long-term success.

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Non-Invasive Seed Priming Strategies for Vegetable Seeds

P. SIVAMMA[1*], KALYANI KUMARI[2], UDAYA BHASKAR K[3], ANJITHA GEORGE[4], NAVEEN KUMAR MAHANTI[5], P.V.K. JAGANNADHA RAO[6]

[1]Scientist, Agricultural Structure & Process Engineering;

[2]Senior Scientist, Seed Science and Technology, ICAR-National Institute of Seed Science & Technology, kushmaur, Mau, Uttar Pradesh – 275 103

[3]Senior Scientist, Seed Science and Technology;

[4]Senior Scientist, Entomology, ICAR-National Institute of Seed Science & Technology, Regional Station, Bangalore, Karnataka – 560 065

[5]Scientist, Agricultural Engineering, Post Harvest Technology Research Station, Dr Y.S.R Horticultural University, Venkataramannagudem, West Godavari, Andhra Pradesh, 534 101

[6]Principal Scientist & Head, Processing and Food Engineering, AICRP on PHET Centre, RARS, ANGRAU, Anakapalle – 531 001

Email: sivamma.p@icar.gov.in; psm9604@gmail.com

Lead Author

P. SIVAMMA

Scientist, Department of Agricultural Structure & Process Engineering, ICAR-Indian Institute of Seed Science, Kushmaur, Mau, UP, India

P. Sivamma is a Scientist in the Department of Agricultural Structure & Process Engineering at ICAR-Indian Institute of Seed Science, Kushmaur, Mau. Her research area of interest is on novel seed priming strategies for cucurbits as well as seed processing for crops produced at ICAR-NISST, Mau. Currently, she is acting as Co-Principal Investigator for Seed Processing component under AICRP on Seed (Crops).

She has developed continuous rice starch based edible film making machine for paper sweet and process technology for fortification of rice starch based edible films with carrot and beetroot juices. Sivamma has received Best Innovative Ideation award from Eruvaaka Foundation (2023), Andhra Pradesh and 3 Gold Medals for her Master of Technology (2020). Sivamma secured AIR-3 in ICAR-SRF, 2019 and AIR-47 in ICAR-JRF, 2017 examinations.

Abstract

To maximize market returns, it is common strategy to sow vegetable seeds sunder suboptimal conditions. However, this often necessitates the use of higher seed rates to compensate for poor seedling emergence. To address this issue, farmers and seed producers globally employ various seed priming techniques—such as on-farm priming and wet/dry priming—that improve seed performance by synchronizing flowering and fruiting, thereby enhancing overall yield. Seed priming approaches are generally classified into invasive and non-invasive methods. Invasive techniques include hydropriming, osmopriming, hormonal priming, halopriming, solid matrix priming, nutrient priming, biopriming, and nanopriming. Conversely, non-invasive techniques involve physical treatments such as exposure to magnetic fields, ultraviolet (UV) radiation, gamma (γ) rays, cold atmospheric plasma, low-energy electron beams, and laser irradiation. These non-invasive methods offer notable advantages over chemical-based priming, particularly in terms of environmental safety and their capacity to enhance plant productivity. Magneto-priming, which utilizes magnetic fields, is an eco-friendly, cost-effective, and non-destructive approach that has shown promising results in improving seed germination, vigor, and crop yield. UV radiation, especially UV-A and UV-C, has demonstrated positive effects on seed health, germination rate, and seedling vigor. Similarly, low-dose gamma radiation can effectively enhance germination and seedling establishment. Cold plasma treatment modifies the seed coat by generating reactive oxygen and nitrogen species that induce microcracks, thereby facilitating water uptake and improving germination. Low-energy electron beam exposure has also been

reported to benefit seed germination. In addition, laser beam priming has been shown to accelerate germination, promote plant growth, and ultimately increase crop yield.

Key words: *Germination, non-invasive, seed priming, vegetable crops, vigor*

Introduction

Vegetables are essential for meeting the nutritional needs of the human diet. However, several factors hinder their optimal productivity, including the prevalence of abiotic and biotic stresses, limited access to high-quality seeds, and the high cost of premium seed varieties. Efforts to achieve sustainable vegetable production through the extensive use of chemical inputs have led to significant negative impacts on both environmental health and human well-being. Seed priming is an effective approach to enhance the planting value of vegetable crops. This pre-sowing treatment involves controlled hydration of seeds, allowing them to initiate the early physiological processes of germination without radical emergence. By advancing metabolic activities prior to sowing, priming helps mitigate the effects of abiotic stress during germination, thereby facilitating successful seedling establishment (Ashraf and Foolad, 2005). Primed seeds exhibit improved germination rates, more uniform and earlier emergence, enhanced growth parameters, and stronger crop establishment (Farooq et al., 2006).

Priming techniques

Seed priming techniques are broadly classified into invasive and non-invasive categories, based on their ability to induce changes in the seed coat and internal structures such as the endosperm or cotyledons. Invasive methods involve wet treatments and include hydropriming, osmopriming, hormonal priming, halopriming, solid matrix priming, nutrient priming, biopriming, and nanopriming. While these techniques are generally cost-effective (Thakur et al., 2022), they are less environmentally sustainable due to the generation of chemical waste and are unsuitable for large-scale seed treatment. Additionally, invasive priming typically involves hydrating seeds, which enhances germination performance but compromises seed storability. Consequently, primed seeds must be sown shortly after treatment to retain their viability and effectiveness. Non-invasive seed priming methods employ a range of physical technologies, including exposure to magnetic fields, ultraviolet (UV) radiation, gamma (γ) rays, cold atmospheric plasma, low-energy electron beams, and laser beams. These approaches are environmentally friendly, as they do not generate chemical waste during treatment, making them suitable for integration into organic farming practices. However, a notable limitation of non-invasive methods is their reliance on cost-intensive equipment and the need for trained personnel to operate these advanced systems.

Non-invasive seed priming methods

1. Magnetopriming

Magnetopriming is a dry seed treatment that has been extensively employed to improve seedling vigor and promote plant growth under diverse environmental conditions. According to Ahmad et al. (2007), plant perception and signaling of magnetic fields (MF) are likely mediated through blue light photoreceptors known as cryptochromes. A noteworthy aspect of magnetic field treatments is their potential to enhance plant tolerance to both biotic and abiotic stresses. This improved stress resilience is attributed to the activation of the plant's antioxidant defense system (Javed et al., 2011; Anand et al., 2012; Thomas et al., 2013; Sarraf et al., 2020).

Magnetopriming has been shown to enhance the activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione reductase (GR) in cucumber (Cucumis sativus L.) seeds (Bhardwaj et al., 2012). As a result, magnetic field (MF) treatments hold promise for mitigating the adverse effects of drought and disease on crop productivity. While environmental factors like light, temperature, and humidity are known to influence seed performance, the interactive effects of these factors when combined with MF treatments are not yet fully understood. Poinapen et al. (2013) investigated the combined influence of MFs and environmental parameters on seed viability and performance in tomato (Solanum lycopersicum L. var. MST/32) under controlled laboratory conditions. Their findings identified relative humidity as a critical factor influencing the performance of magneto-primed seeds, particularly during the initial phases of germination and imbibition. A summary of magnetopriming responses across various vegetable crops is presented in Table 1.

Table 1. Effect of magneto priming on various vegetable seedlings (Thakur et al., 2022)

Vegetable seed	Effects	Reference
Radish	Enhanced seedling growth, plant height, root length, root mass, root girth, yield, activation of antioxidant enzymes, increased production of polar lipids, glycol lipids and phospholipids, stimulation of lipid biosynthesis in chloroplast, mitochondria and cell membranes	Zia et al., 2012 Novitskii et al., 2014
Capsicum	Enhanced germination, seedling growth, yield and fruit quality	Ahmed et al., 2017
Parsley	enhanced activity of CAT, increased contents of AsA, MDA, iron and ferritin, reduced APX activity	Rajabbeigi et al., 2013
Tomato	Enhanced rate of germination, seedling growth, shoot-root length, emergence index, percent emergence, mitotic activity in meristematic plant cells, reduced electrolyte leakage, increased plant height, shoot diameter, number of leaves per plant, fresh and dry weight, number of flowers, yield, enzymatic activities (CAT, APX, GPOX) activity, phosphorus content, upregulation of ABA 8' - hydroxylase and GA3 oxidase1 genes	Poinapen et al., 2013 Efthimiadou et al., 2014 Gupta et al., 2015 Mroczek-Zdyrska et al., 2016
Okra	Increased germination percentage, number of flowers per plant, leaf area, plant height at maturity, number of fruits, pod mass and number of seeds per plant	Naz et al., 2012
Potato	Increased length and number of stems, weight of leaves and stems, and germination index	Marks and Szecowka, 2010

2. UV irradiation priming

Ultraviolet (UV) radiation is categorized into three types based on wavelength: UV-A (320–400 nm), UV-B (280–320 nm), and UV-C (200–280 nm). UV-C radiation is non-ionizing and penetrates only the outer layers of plant tissue, making it effective as a germicidal agent. Low-dose UV-C treatments (e.g., 3.6 kJ m^{-2}) have been successfully applied to induce host resistance against black rot in cabbage (Brassica oleracea L.) and to enhance plant quality and growth under greenhouse conditions (Brown et al., 2001). Similarly, Ouhibi et al. (2014) reported that lettuce seeds treated with UV-C doses of 0.82 and 3.42 kJ m^{-2} exhibited improved tolerance to high salinity, potentially due to increased free radical scavenging activity in leaf tissues. In contrast, UV-B exposure has been associated with DNA damage, protein degradation, and membrane disruption, ultimately impairing photosynthesis and plant growth (Hideg et al., 2013; Choudhary and Agrawal, 2014). UV-B treatment also resulted in reduced root and shoot development. On the other hand, UV-A irradiation has been shown to enhance germination rates and seedling vigor, as reflected in improved specific leaf area, root and shoot length, and dry biomass (Hamid and Jawaid, 2011). Overall, both UV-A and UV-C have demonstrated beneficial effects on seed germination, seedling performance, and seed health. The effects of UV radiation priming on various vegetable seedling traits are summarized in Table 2.

Table 2. Effect of UV radiation priming on various vegetable seedlings (Thakur et al., 2022)

Vegetable seed	Effects	Reference
Lettuce	higher tolerance against salinity stress in lettuce	Ouhibi et al., 2014
Beans	Improved germination rate, specific leaf area, root and shoot length and dry weight, two-fold higher flavonoid content, increased soya saponin Af, Ba, and αg	Hamid and Jawaid, 2011

3. γ-radiation priming

Gamma (γ) radiation priming involves exposing seeds to low doses of high-energy ionizing radiation. Due to their strong penetration capability, gamma rays can interact directly with various cellular components, including nucleic acids, membranes, and proteins (Majeed et al., 2018). When applied at low doses, gamma rays function as effective priming agents, enhancing seed germination and seedling establishment under both optimal and stress-prone conditions (Farooq et al., 2019).

At the cellular level, low-dose gamma irradiation promotes cell proliferation and growth, while also improving stress tolerance, ultimately contributing to increased crop productivity (Beyaz et al., 2016). In chickpea, for instance, low gamma radiation doses significantly enhanced root system development. One proposed mechanism behind this response is the radiation-induced production of reactive oxygen species (ROS), which serve as signaling molecules to activate antioxidant defense systems. This antioxidant response helps mitigate various abiotic stress factors, such as temperature fluctuations, light stress, and water loss during plant development (Qi et al., 2015). A summary of the effects of γ-radiation priming on the performance of different vegetable seedlings is provided in Table 3.

Table 3. Effect of γ-radiation priming on various vegetable seedlings (Thakur et al., 2022)

Vegetable seed	Effects	Reference
Potato	20 Gy dose stimulated germination	Salomon et al., 2017
Okra	Low dose (400 Gy) significantly improved shoot height, number of branches and leaves per plant	Hegazi and Hamideldin, 2010

4. Cold atmospheric plasma priming

Cold atmospheric plasma consists of a mixture of ionized gases, including electrons, positively charged ions, and neutral gas molecules. It is generated when gas molecules absorb external energy sufficient to overcome their electrostatic potential, leading to ionization. Cold plasma is widely utilized in biological applications due to its production of highly reactive species at relatively low temperatures, especially in comparison to the temperature of free electrons. In seed treatment, cold plasma generates various reactive oxygen and nitrogen species (ROS and RNS), which interact with the seed coat and induce microcracks on the seed surface. These structural changes enhance water uptake, facilitating dormancy breaking and accelerating the germination process (Zhou et al., 2011). The effects of cold atmospheric plasma priming on the performance of various vegetable seedlings are summarized in Table 4.

Table 4. Effect of cold atmospheric plasma priming on various vegetable seedlings (Thakur *et al.*, 2022)

Vegetable seed	Effects	Reference
spinach	Increased content of total phenols	Ji et al., 2016
Capsicum	Increased seed germination, seedling vigour, chlorophyll a, carotenoid, soluble phenols content, increased activities of POX and phenylalanine ammonia lyase	Adhikari et al., 2020
Tomato	Increased germination, vigor, stem length, yield, POX activity, phytohormones, defense gene expression, and drought stress tolerance	Zhou et al., 2011 Jiang et al., 2014 Sivachandiran and Khacef, 2017

5. Low energy electron beam priming

Low-energy electron beam (LEEB) treatment is a form of ionizing radiation applied at doses ranging from a few kilograys (kGy) up to approximately 300 kGy. LEEB generates ions through the action of accelerated electrons, which remove electrons from atoms or molecules. This process requires a cathode within a vacuum environment to produce and accelerate electrons to near-light speeds during irradiation. Hertwig et al. (2018) demonstrated the application of LEEB for wheat disinfection in organic farming systems. Sitton et al. (1995) reported improved germination capacity in wheat grains treated with LEEB. However, in a separate study, low-dose LEEB exposure (up to 12 kGy) had no significant impact on the germination capacity of clover, mung bean, and fenugreek seeds (Fan et al., 2017). The effects of low-energy electron beam priming on the performance of various vegetable seedlings are summarized in Table 5.

Table 5. Effect of low energy electron beam priming on various vegetable seedlings (Thakur et al., 2022)

Vegetable seed	Effects	Reference
Lentil	Accelerated lentil seed germination at 3 days (8-60 kGy). However, even the lowest dose of electron beam treatment at 8 kGy caused root abnormalities in seedlings.	Waskow et al., 2021

6. Laser priming

Seed priming with low intensity of laser light exerts a photobiomodulation effect which is based on the synergism between the photoreceptors and the polarized monochromatic laser beams. Seeds when irradiated with low-intensity laser light, result in their biostimulation that enhance seed germination, vegetative mass, photosynthesis and crop yield (Swathy *et al*., 2021). Laser priming involves capture of light energy by seeds which is further transformed into chemical energy that is utilized for growth as well as development. Laser priming of seeds results in stimulation of plant growth, reduction in germination time which ultimately leads to enhanced yield. The laser irradiation may also interact with the gene associated with chlorophyll biosynthesis, mainly involved in the synthesis of protochlorophyllide. The repairing role of red laser has also been reported that enhances the physiological characters in the plants exposed to various abiotic stress conditions such as salinity, drought and UV-B induced stress. Responses of laser priming on various vegetable seedlings performance are presented in Table 6.

Table 6. Effect of laser priming on various vegetable seedlings (Thakur et al., 2022)

Vegetable seed	Effects	Reference
Brinjal	enhanced germination index, germination time, seed vigor index, photosynthetic rate, stomatal conductance, and transpiration rate	Swathy et al., 2021
Radish	Presowing seed treatment with low-intensity red spectrum laser irradiation positively affected the growth and development	Sevostyanova et al., 2020

Conclusion

In commercial vegetable farming, transplants are often used for crop cultivation, although some crops are directly seeded. The traditional practice of growing seedlings in nurseries for later transplantation into fields or controlled environments, such as polyhouses, is common. However, one major limitation of this method is the inconsistency in seedling quality, as some may be unsuitable for transplanting due to uneven emergence or delayed growth. Non-invasive seed priming techniques present a potential solution by enhancing seed traits at multiple levels, such as structural development, gene activity, and the accumulation of proteins or metabolites, providing advantages over conventional methods. Nevertheless, further research is essential to identify the optimal parameters—such as dose, exposure duration, and genotype- and environment-specific conditions—for effective non-invasive priming treatments.

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Seeds to Supremacy: India's Rise to Vegetable Production Dominance

PARDEEP SINGH[1] AND SANJEEV KUMAR[2]

[1]Research Associate, ICAR-NIAP, Pusa, New Delhi

[2]Agricultural Economist, Punjab Agricultural University, Ludhiana, Punjab

Email: pardeepmahal1994@gmail.com

Lead Author

DR. PARDEEP SINGH

Research Associate,
ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi

Dr. Pardeep Singh is Research Associate, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi

He holds a Ph.D. in agricultural economics and has expertise in agricultural sustainability, environmental conservation, and evidence-based policy research. His academic and professional work broadly addresses the challenges posed by climate change to Indian agriculture, with a particular focus on vegetable production systems. His research explores the intersection of climatic vulnerabilities, adaptive strategies, and farm-level decision-making to enhance agricultural resilience and profitability. He has contributed significantly to understanding how environmental and socioeconomic factors influence crop returns and farm sustainability, especially in the context of hill and mountain agriculture. Through his scientific publications and policy-oriented studies, he advocates for diversified and climate-resilient farming systems, promoting integrated nutrient management and agroecological transitions to support India's long-term food and environmental security.

Introduction

India is the second-largest vegetable producer in the world, following China, with a contribution of 15%. It is the leading producer of ginger and okra, and ranks second in the production of crops such as potato, onion, cauliflower, brinjal, cabbage, and others (FAO, 2021). In the 2021-22 period, the total area devoted to vegetables in India was 113.74 lakh hectares, yielding a production of 2091.43 lakh tonnes (GOI, 2024). The share of vegetable area was 1.72% of the total cropped area. However, this contribution was 3.37% in 2000-01 and increased to 5.19% in 2021-22. From 1980-81 to 1999-00, the area under vegetable crops grew at an annual rate of 4.14%, while from 2000-01 to 2021-22, it increased by 3.51%. Production also saw growth, increasing by 2.79% from 1980-81 to 1999-00 and by 4.41% from 2000-01 to 2021-22.

Vegetable crops play a crucial role in meeting domestic nutritional needs and enhancing export performance. India's vegetable exports reached US$ 2.1 billion in 2023, marking a 20% increase compared to the previous year. The top 10 vegetables exported from India include onions, tomatoes, cabbage, potatoes, beans, garlic, spinach, cauliflower, okra, and cucumber. The quality of vegetables, including factors like size, color, and nutritional value, significantly impacts exports. Additionally, vegetable seeds are vital for boosting both domestic production and India's export capabilities.

Importance of Seed Quality in Sustainable Vegetable Production

Seed quality plays a pivotal role in achieving sustainability, enhancing production, and boosting exports in vegetable farming. Among all the intercultural operations in crop cultivation, seeds are the most crucial input. They form the foundation for high yields, quality crops, and overall farm productivity. The selection of seed variety, its genetic potential, and quality directly influence germination rates, plant health, disease resistance, and adaptability to various environmental conditions. High-quality seeds ensure robust crop establishment, leading to higher yields and better market value. Conversely, low-quality or untreated seeds can lead to poor germination, weak plants, and reduced productivity, making seed selection essential for sustainable vegetable farming. The impact of seed quality extends beyond just yield—it also affects economic and environmental factors. High-yielding, disease-resistant varieties can lower input costs for fertilizers and pesticides while promoting environmentally sustainable practices. Furthermore, high-quality seeds, such as hybrids and genetically enhanced varieties, offer improved pest resistance, better climate adaptability, and superior nutritional value. In the long term, investing in quality seeds not only supports food and nutritional security but also enhances farmer profitability and ensures more efficient use of land, making it a critical factor in the success and sustainability of vegetable production.

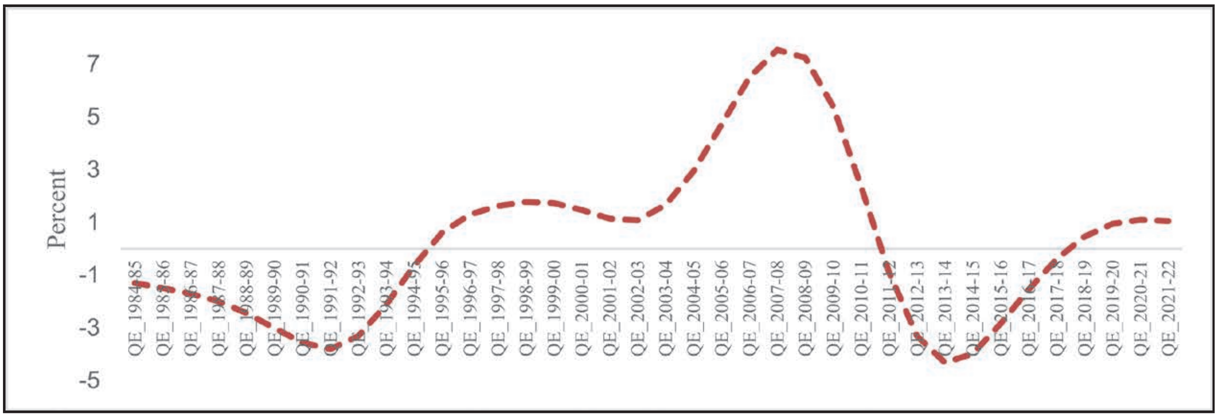
Evolution of India's Seed Industry

Over the past 50 years, the seed industry has evolved significantly, transitioning from simply producing and marketing publicly breed varieties to a comprehensive system that includes research, product development, production, sales, and marketing—all aligned with global standards. In the late 1960s and 1970s, private companies like Sutton Seeds India, Pahuja, and Mahyco controlled less than 5% of India's vegetable seed market. During this period, the public sector, led by the National Seed Corporation (NSC), was dominant. Farmers largely relied on saved seeds, leading to seed replacement rates as low as 25%, which resulted in suboptimal yields (Tikoo, 2023). The introduction of hybrid seeds marked a milestone in India's vegetable industry. As multinational corporations entered the market, early research focused on crops such as tomato, pepper, okra, tropical cauliflower, and eggplant. Over time, research expanded to include cucumber and bitter gourd. Indian firms like East-West Seeds and VNR initially concentrated on gourds and cucumber, before diversifying into other crops. About a decade ago, companies such as Rijk Zwaan, Enza Zaden, and Syngenta began focusing on high-value crops suited for protected cultivation, including tomato, sweet pepper, and cucumber.

Today, seed companies play a pivotal role in increasing vegetable crop yields by optimizing sowing times and crop durations. India has become a major hub for the production of indigenous hybrids and a global center for contract hybrid seed production across several crops. These production plots, often under protected cultivation, maintain high global purity standards and ensure seed quality free of seed-borne diseases. This seed production model relies on large-scale organizations and collaborations with seed-producing farmers. Once the seeds are produced, the sales and marketing departments ensure they reach the market effectively. The vegetable seed industry has significantly boosted employment, increased yields, and improved the income of farmers. Looking ahead, we can anticipate further innovations in the industry, with continued collaboration between the private and public sectors.

Trends in Vegetable Yield Growth in India

The growth rate trend of vegetable yield in India follows a cyclical pattern, with alternating periods of growth and decline over time (Fig. 1). From 1984-85 to the early 1990s, the yield growth rate was negative, reaching its lowest point around 1991-92 due to the low dissemination of technology and the poor quality of seeds. The seed replacement rate among farmers was also very low during this period. However, after 1994-95, a significant upward trend emerged, peaking around 2007-08. This period of growth can be attributed to improvements in agricultural practices, technological advancements, and possibly favorable policy changes. Despite this, the growth rate began to decline sharply after 2009-10, reaching another low point in 2012-13.



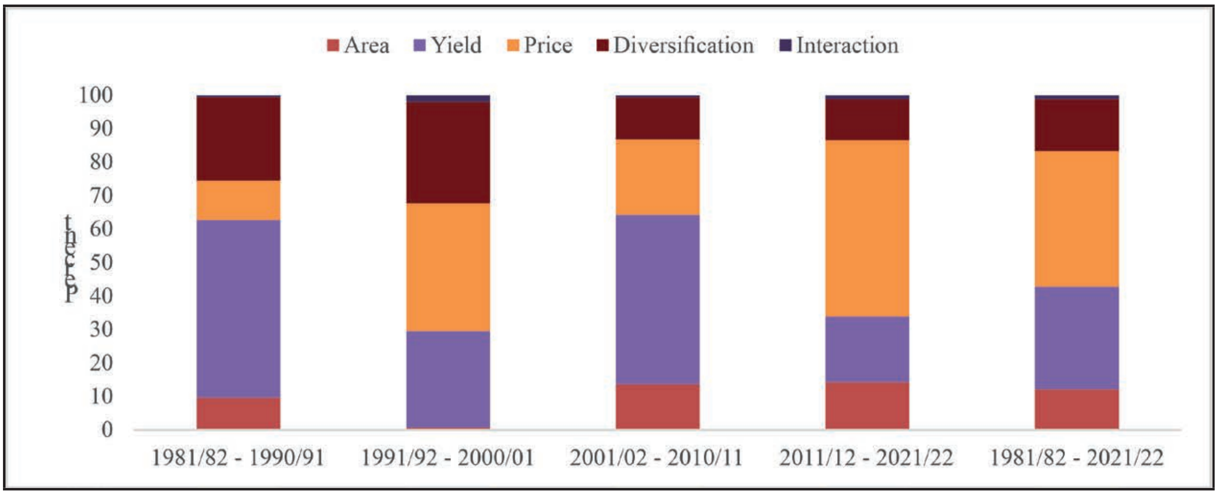
Data Source: GOI, 2024

Figure: 1 Five yearly trends in the growth rate of vegetable yield in India

Following this decline, a recovery phase began around 2016-17, with the yield growth rate turning positive once again. While the pace of recovery has been slower compared to previous periods of growth, recent trends suggest a more stable and moderate increase in vegetable yields. The cyclical nature of the yield growth rate indicates that external factors such as climate conditions, government interventions, and market fluctuations play a critical role in influencing productivity. To ensure long-term stability and continued positive growth in vegetable yield production, it is essential to make strategic investments in agricultural technology, resource management, and climate resilience.

The Shift from Productivity to Profitability through Better Seeds

Multiple factors, including yield improvements, price effects, diversification, area expansion, and interaction effects, have driven the growth of vegetable production in India (Fig. 2). A significant shift in the factors driving growth is influenced by government policies and advancements in seed technologies. In the early years (1981/82 - 1990/91), yield played the most significant role, indicating that productivity improvements were the key growth driver. However, in the following decade (1991/92 - 2000/01), the contribution of price effects increased, suggesting that better market conditions encouraged farmers to expand vegetable cultivation. This shift highlights the growing importance of market-driven production rather than just technological advancements.



Data Source: GOI, 2024

Figure: 2 Driver of growth of vegetable and fruit production in India

In recent years (2011/12 - 2021/22), diversification has emerged as a major driver, surpassing yield in importance. Farmers increasingly adopt diverse cropping patterns to optimize returns and reduce price fluctuations and climate change risks. The role of area expansion has remained relatively small, indicating that most growth has come from intensification rather than increased cultivated land. Over the entire period (1981/82 - 2021/22), the combined effects of price, diversification, and yield improvements have shaped India's vegetable sector. This trend indicates a transition from a yield-driven approach to a more market-oriented and diversified agricultural system. Government policies such as the National Horticulture Mission (NHM), Rashtriya Krishi Vikas Yojana (RKVY), and Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) have supported infrastructure, irrigation, and market linkages, fostering diversification. The introduction of high-yielding and hybrid seed varieties, promoted by institutions like ICAR, NSC, and SAUs, has also boosted productivity. Policies like the Seed Act and National Seed Policy have improved seed availability, encouraging the adoption of improved varieties that enhance yield and resilience. This transformation underscores the importance of seed quality. High-quality seeds improve germination, disease resistance, and climate adaptability, leading to sustainable growth. Government initiatives promoting hybrid and genetically improved seeds have reduced reliance on low-yield varieties, increasing the role of yield and diversification in vegetable growth. Going forward, continued advances in seed technology and supportive policies will ensure long-term profitability, growth, and food security in India's vegetable sector.

Achieving Sustainable Development Goals Through Vegetable Production

The 2030 Agenda for Sustainable Development includes 17 Sustainable Development Goals (SDGs), and achieving these ambitious goals by 2030 presents significant challenges. The vegetables can play a crucial role in advancing these SDGs, both directly and indirectly. Vegetable production can contribute to achieving SDGs 1 and 2—No Poverty and Zero Hunger. It is a labour-intensive practice, primarily carried out by small and marginal farmers in India, who generate higher output from smaller land areas. This increased production from limited land helps address hunger in the country. SDG 3, Good Health and Well-being, is another key area where vegetables can play an essential role. Vegetables are vital components of a balanced diet, rich in vitamins, minerals, and phytochemicals necessary for good health. Consuming nutrient-rich vegetables helps prevent diseases linked to malnutrition. In India, 189.2 million people are malnourished, and 34.7% of children under five are stunted, meaning around 14% of the population is undernourished. Vegetable cultivation can also contribute to SDG 5—Gender Equality. About 86% of farmers in India are small and marginal, cultivating 47% of total cultivable land and producing more than half of the agricultural output. Vegetable farms are largely small-scale, with women playing a significant role in all stages of production, from seed sowing to harvesting and seed extraction. This involvement fosters self-reliance and boosts a sense of achievement and empowerment among women farmers. Technological advancements in vegetable production, protection, and preservation help to reduce labour intensity and improve working conditions, contributing to SDG 8—Decent Work and Economic Growth. These improvements also increase farmers' earnings, fostering economic growth. However, farmers face challenges due to climate change, which affects vegetable crops, aligning with SDG 13—Climate Action. To mitigate the effects of climate change, high-temperature resilient hybrid varieties have been developed for cultivation during hot summer months (>38°C day temperatures) in northern India. These varieties are adaptable to high-temperature regimes, and farmers can adjust sowing times to better cope with changing climate conditions. This resilience is essential for ensuring sustainable vegetable production amidst climate challenges.

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Seed Quality Enhancement in Vegetables

HITESH KUMAR YADAV[1*], S.C VIMAL[2], V.K CHOURASIYA[3], VIKRAM JEET SINGH[3] AND SHIVANI DUBEY[1]

[1]Research Scholar, [2]Professor, [3]Assistant Professor; Acharya Narendar Deva University of Agriculture & Technology Kumarganj, Ayodhya - 224 229 (U.P.), India
Email: hiteshagnd@gmail.com

Lead Author

MR. HITESH KUMAR YADAV

Research Scholar
ANDUA&T Kumarganj, Ayodhya, (UP)

Mr. Hitesh Kumar Yadav earned his undergraduate degree in Agriculture from CSJMU University, Kanpur, and pursued a Master's specialization in Seed Science and Technology from Acharya Narendra Deva University of Agriculture and Technology (ANDUA&T), Kumarganj, Ayodhya. He has published three research papers, three book chapters, and eight articles in reputed magazines and journals. Additionally, he has participated in more than 15 training programs, conferences, seminars, and workshops organized by various ICAR Institutes and Universities. Currently, he is a research scholar in the Department of Seed Science and Technology at ANDUA&T, Kumarganj, Ayodhya.

Abstract

Seed quality plays an important role in the success of crop production, since it influences the plant's genetic and physiological potential throughout its lifespan.

High-quality seeds, characterized by genetic and physical purity, promote uniform germination, robust growth, resistance to pests and diseases, and enhanced yields. Advanced seed enhancement techniques have reshaped agriculture by optimizing seed performance, handling, and resilience to environmental stress. Techniques such as seed priming, hardening, pelleting, fortification, magnetic treatment, and irradiation enhance seed vigour and viability, enabling crops to thrive even under suboptimal conditions. These advancements, coupled with genetic engineering, have significantly improved crop production efficiency. This article explores the key factors influencing seed quality and the methodologies for seed enhancement, highlighting their benefits in sustainable agricultural practices.

Introduction

Seed quality is a critical factor in determining the success of crop production. Good quality vegetable seed are the most important input in agriculture. Seed stores genetic information for the plant's subsequent lifespan (Wimalasekera, 2015). Seeds are crucial for food production and human nourishment due to their ability to propagate. Using high-quality seeds, regardless of crop species, region, or season, leads to higher yields (Bradford and Bewley, 2002). Nothing will work upon a poor-quality seed, no matter how lavishly other inputs are spent on crop to be established from this seed (Vanangamudi, 2010). High-quality seeds are genetically and physically pure that improve germination rates, homogeneous plant growth, and resistance to pests and diseases. This leads to higher yields, enhanced crop quality, and overall increased production. Quality seed provides a 15 to 20% boost in production. Seed treatment, in broad terms, is the application of biological, physical, and chemical agents and technique to the seed and plants and improve the establishments of healthy crops. Taylor et al. (1998) describes seed quality enhancement as "post-harvest treatments that improve germination or seedling growth". Seed quality enhancement means the application of physical, physiological, biological and chemical agents to the seed in order to enhance the physical, physiological, genetical, biochemical and health qualities of seed. Seed enhancement' technologies boost a genotype's planting value across many growth environments. Seed enhancements aim to optimize the physiological ability of seeds, which may not be present in normal sowing practices (Black and Peter 2006; Patel and Gupta 2012). They also improve seed handling and protection against biotic and abiotic stresses, particularly during the early vegetative growth stage. Seed corporations have used genetic features including insect and pest resistance, water efficiency, and higher yields to improve crop production through breeding and genetic engineering.

Factors Affecting Seed Quality

Good quality seed is the first step toward a good season. Farmers cannot control elements such as weather or prices, using excellent seed is a critical production aspect that they can control. There are various biotic and abiotic factors which affect the quality of seeds are:

- **Genetic Purity**

The genetic makeup of seeds determines their potential for uniformity, disease resistance, and yield. High genetic purity ensures that the seeds produce plants that exhibit the desired traits consistently.

- **Physical Purity**

This refers to the percentage of pure seeds in a lot, free from contaminants like other crop seeds, weed seeds, and inert material. Higher physical purity is crucial for ensuring that the seeds germinate uniformly and do not introduce unwanted species into the field.

- **Moisture Content**

The moisture level in seeds affects their storability and germination potential. Properly dried seeds (usually below 12% moisture content) are less likely to deteriorate and lose viability during storage. Moisture content in seeds should be below 8% for longer storage and quality.

- **Seed Vigour**

Seed vigour is the overall health and robustness of seeds, influencing their germination rate and seedling growth. Vigorous seeds establish more quickly and uniformly, leading to better crop stands.

- **Seed Germination Rate**

The percentage of seeds that successfully sprout under ideal conditions. Higher germination rates indicate better seed quality. Industry standards generally support that a germination percentage of 80 per cent at seeding is considered acceptable.

- **Disease and Insects**

The presence of pathogens or insects on or within seeds can significantly impact seed quality. Seeds infected with fungi, bacteria, or viruses can lead to poor germination and the spread of diseases.

- **Seed Size and Weight**

Seed Size and Weight are also one of the important factors that determine the quality of seed. Generally, larger and heavier seeds have better nutrient reserves, leading to stronger seedlings and better initial growth.

- **Seed Age**

The age of seeds affects their viability. Older seeds tend to have lower germination rates and reduced Vigour compared to fresh seeds.

- **Handling and Storage Conditions**

The way seeds are handled and stored can impact their quality. Proper storage conditions, including temperature and humidity control, are essential for maintaining seed viability over time.

- **Environmental Factors during Seed Development**

The conditions under which the seeds are grown, including soil fertility, water availability, and climate, can affect seed development and quality.

Seed enhancements

Seed enhancements are the post-harvest treatments to the seed to enhance the physical, physiological, genetical, biochemical and health qualities of the seed. Many shotgun methods are being used since ages to enhance seed quality which includes seed priming, seed hardening, pelleting, seed coating, magnetic stimulation etc.

Advantages of seed enhancement

Seed enhancement treatments, whether applied separately or in combination, are predicted to have the following advantages:

- Facilitates precise planting and handling.

- Improved germination and rapid seedling growth lead to uniform and early emergence.
- Reduced the seed rate.
- Improved nursery management.
- Provide supplemental nutrients and growth stimulants for improved performance after seeding.
- Pest protection (including weed control), resulting in greater stand establishment.
- Use non-traditional upgrading procedures to remove weak or underperforming seeds.
- Seeds are tagged with visible pigments or other markers to ensure traceability and identity.

Methods of Seed Enhancement Techniques

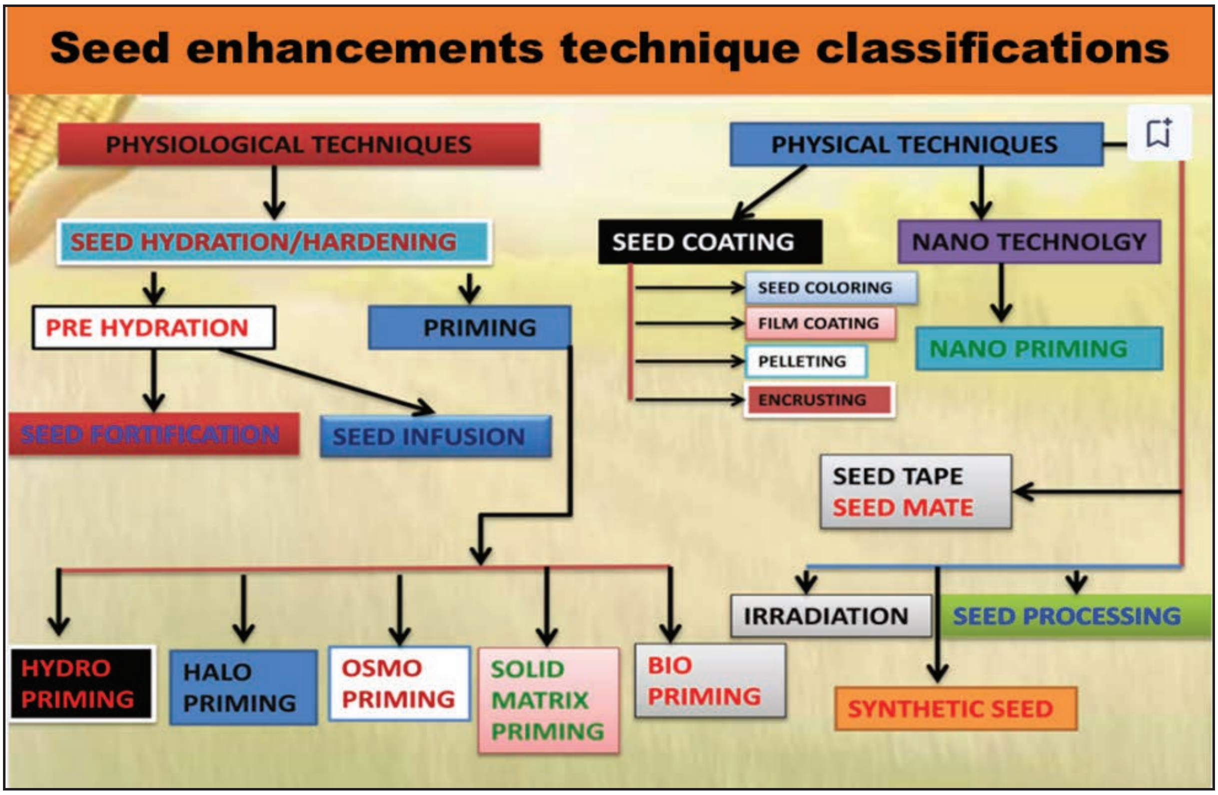

Fig. 1: Seed Enhancement Techniques

1. Seed fortification

Theophrastus (372-287) wrote one of the first studies on the uses of seed fortification, recommending that cucumber seeds be soaked in milk or water to accelerate their germination. Amlog and Naundorf sought to fortify radish seeds as early as 1937. In the early years, seed fortification was eagerly attempted with growth regulators. Landaw *et al*. (1940) described the stimulative effects of seed fortification with growth regulators in tomato.

Seed fortification is a pre-sowing seed enhancement technique that involves soaking seeds in solutions containing essential nutrients and bioactive chemicals. It is the impregnation of the needy substances into the seeds. This process enhances seed quality, improves germination rates, and boosts seedling vigour. Sometimes, it is also used as protective treatment. Here, seeds are soaked in nutrient solution of equal volume for a duration of 3-24 hours depending upon the crops to raise the moisture content of the seed to 20-25% just for impregnation of chemical into the seeds. The imbibed seeds are sown after dried under shade for easy handling. Seed fortification increased the field emergence by promoting the growth of the embryo.

Table 1: Seed fortification treatments in various crops

Crop	Nutrient	Concentration	Duration
Cowpea	$ZnSO_4$ + $MnSO_4$ + Na_2SO_4	100 mg/kg	3 hours
Clusterbean	$FeSO_4$	1%	3hours
Blackgram	$ZnSO_4$	100 ppm	3 hours
Vicia faba	Ammonium Molybdate KCl	500 ppm, 2 %	12 hours
Groundnut	$CaCl_2$	1%	6 hours
Sunflower	KNO_3 or $FeSO_4$ or $ZnSO_4$	0.1%	12 hours

2. Seed Hardening

The process of hydrating the seed to initiate the pre-germinative metabolism followed by dehydration which fixes the bio chemical events is called as seed hardening. It is done in order to impart resistance against stress condition (drought and cold) to the emerging seedlings. Seeds are allowed to take up to certain amount of water, and then they are kept moist at 10-25°C for several hours before drying in a steam of air. The best result can gain in two to three cycles of wetting and drying, although for some, one cycle is sufficient.

The timing of the initial imbibition period is critical, because as germination and growth proceeds the resistance to drying of the embryo decreases. The temperature of the soaking and the drying cycle and the rate of drying are very important. During hardening process, a number of physiochemical changes occur inside the seed.

Advantages of seed Hardening

- Treated plants are generally better in growth and yield
- Flowering is enhanced in treated plants.
- Plant from the treated seed recover quickly from wilting with compared to plant from untreated seed
- Seed hardening induces resistance to various abiotic stress such as drought and salinity.
- Treated seed can withstand higher temperature for long period of time without loss of viability.

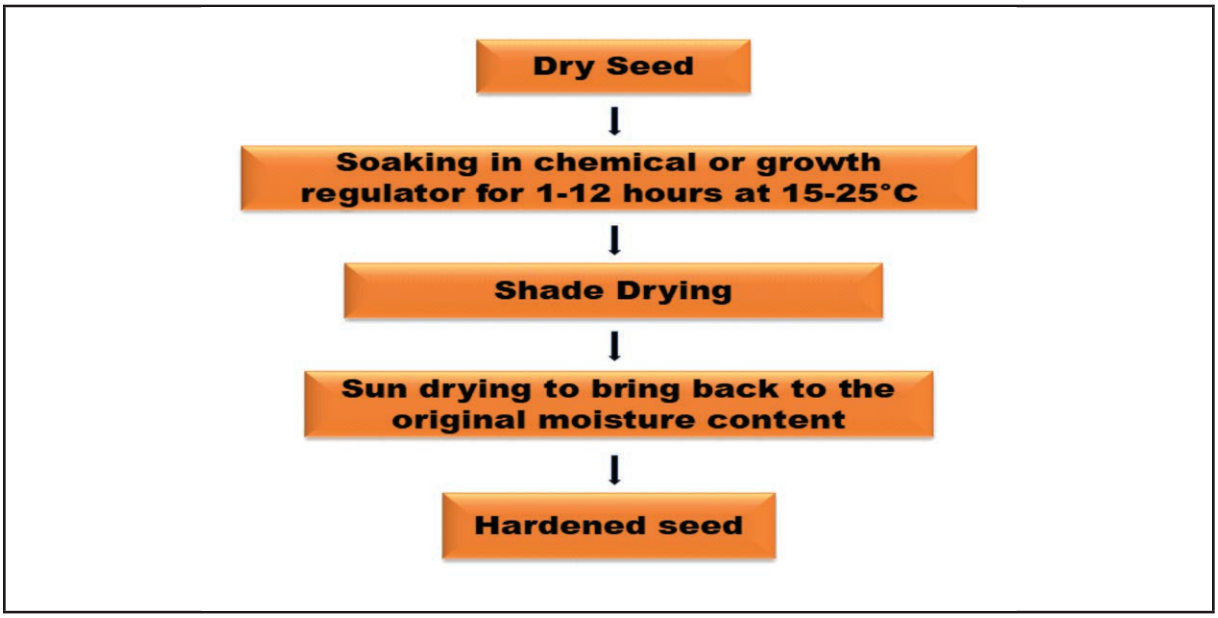

Fig. 2: Seed Hardening Process

3. Seed Priming

Seed priming is an economical, effective hydration technique that promotes seed germination. During priming, seeds undergo a physiological process that includes controlled hydration and drying, resulting in an accelerated and improved pre-germinative metabolic process for quick germination (Dawood, 2018). Seed priming can synchronize seed germination and boost emergence (Ghassemi *et al*, 2012; Dalil, 2014). Seed priming techniques have numerous advantages, including reducing the use of fertilizers, increasing agricultural output through synchronized seed germination, and inducing systemic resistance in plants, which is both cost-effective and environmentally benign.

Table 2: Seed priming treatments

Crop	Priming method	Duration
Carrot	Hydropriming	36 hours
Chilli	Sand matricpriming 80%	3 days
Onion	Sand matricpriming 80%	24 hours
Tomato	Hydropriming	48 hours
Okra	Sand matricpriming 80%	3 hours
Brinjal	Sand matricpriming 80%	3 days
Beet root	Hydropriming	36 hours
Radish	Hydropriming	12 hours

Advantages of seed priming

- Priming helps in faster emergence of the seedlings
- It enables seed to germinate and emerge even under adverse agro-climatic conditions
- Priming increases the uniformity of the crops.
- Increases vigour for fast and strong plant development
- Increases yield potential in many crops.

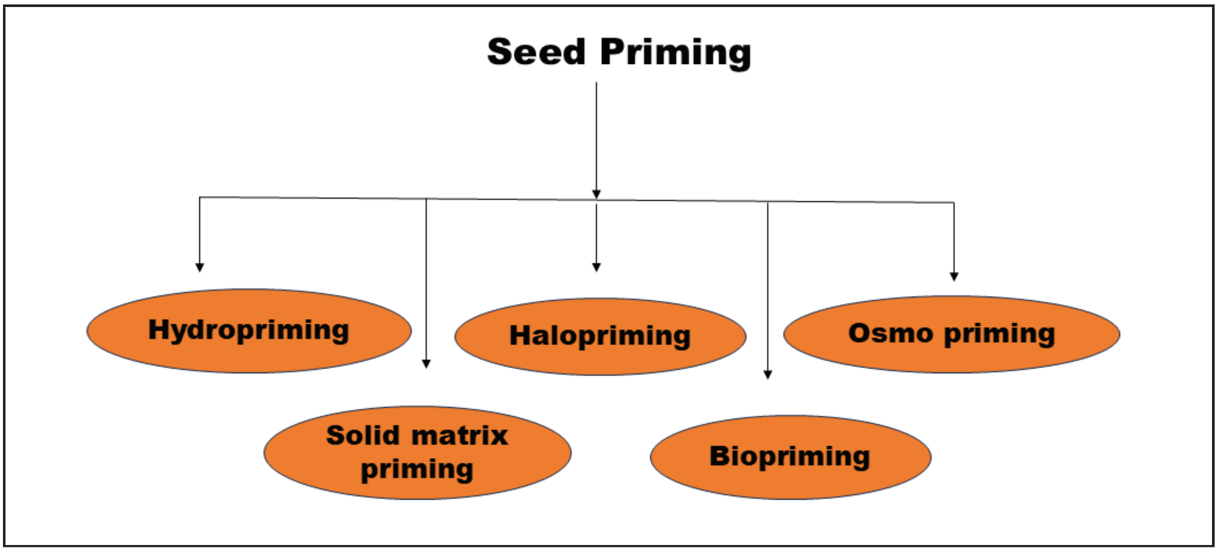

Fig. 3: Seed priming methods

I. Hydropriming

Hydro-priming is a traditional and cost-effective method for priming seeds before sowing. It involves treating seeds with water. This procedure involves soaking seeds in water and then re-drying to their original moisture content. This method promotes germination by allowing seeds to absorb water and initiate pre-germination metabolic activities, but blocking the subsequent two phases. In areas with unfavourable climatic conditions, such as high temperatures and water stress, hydro priming is particularly beneficial, as it enhances the efficiency of water absorption and seed hydration (McDonald, 2000).

Hydro-priming has advantageous effects on crop production. Specifically, the submersion of paddy seeds in water for a duration of 24 hrs resulted in a complete germination rate of 100%, accompanied by the maximization of shoot fresh weight, root length, α-amylase activity, and total and reducing sugar content. These results are indicative of increased physiological potential, manifested as improved germination and vigour.

II. Halo priming

Halo priming is the process of treating seed with inorganic salts such as sodium chloride (NaCl), potassium nitrate (KNO_3), calcium chloride ($CaCl_2$), and calcium sulphate ($CaSO_4$) to improve germination. It is well-known that halo-priming plays an important role in germination, seedling emergence, and plant growth at all developmental stages of the plants.

III. Osmo priming

Osmo priming is the soaking of seed in an osmotic solution such as sugar, polyethylene glycol (PEG), glycerol, sorbitol, and mannitol, then air dried to overcome germination and other metabolic activities under diverse agro-ecologies. Osmosis regulates water in the seed during imbibition, reducing ROS levels and protecting cells from oxidative damage. Osmo-priming improves crop performance in both salty and non-salty environments.

IV. Biopriming

Coating of seed with biological agents like *Pseudomonas fluorescence* and *Trichoderma viride* and liquid biofertilizer like *Azospirillum* and *phosphobacteria* and redrying to the original moisture content is called biopriming. Bio priming helps in promoting plant growth and development by regulating many biochemical and physiological processes, as well as stress tolerance and resistance mechanisms.

V. Solid Matric Priming

Mixing seed with an organic and inorganic carrier and water for a period of time is known as solid matric priming. The moisture content of the matric is brought to a level just below what is required for radicle protrusion. Seed water potential is regulated by the matric potential of seed and during priming the water is largely held by the carrier. Seed can imbibe water until the equilibrium is reached.

4. Magnetic Seed treatment

Magnetic treatment also called as "magnetopriming" is one of the non-destructive pre-sowing dry seed priming treatments which involves the exposure of seed to a magnetic field for a specific period of time to improve germination and vigour. Plant science has made amazing progress in the last ten years about the impacts of the MF in seeds and plants. There is currently solid evidence that magnetic pre-germination treatment of seeds prior to sowing reduces planting expenses by significantly increasing germination rates and promoting plant growth (Mahajan and Pandey, 2014; Efthimiadou *et al*., 2014). Scientists discovered that the MF improves seed germination by altering biochemical processes and boosting the activation of proteins and enzymes (Maffei, 2014). MFs have been described as eco-friendly, cheap, and non-invasive technique (Bilalis *et al*., 2012).

Table 3: Magnetic Field treatments in various crops

Plant species	Plant organ	MF Intensity	Effects	References
Cucumis sativus L.	Seeds	200 mT SMF	Superiority germinative and increased activities of hydrolytic enzymes, reactive oxygen species, and antioxidant enzyme system during germinating seeds	Bhardwaj *et al.*, 2012
Solanum lycoperiscum Mill	Seed	50-332 mT SMF	Increase in germination rate, promoted biochemical and molecular changes involved in homeostasis of hydrogen peroxide (H_2O_2) promoting the seed Vigor	Anand *et al.*, 2019
Raphanus sativus L.	Seed	8-20 mT SMF	Increased the rate and vigour index of the germination	Konefał-Janocha *et al.*, 2019
Capsicum annum L.	Seeds, Seedlings	57-60 mT SMF	Enhancement of seed germination, seedling growth, and yield and fruit quality.	Ahamed *et al.*, 2013

5. Seed pelleting

Seed pelleting is the process of dressing the seed with suitable inert material, fungicides, insecticides, pesticides, plant growth regulator, fertilizer etc. to form a shell around the seed which facilitate easy sowing of the seed. After pelleting the seed is no longer visible and completely protected from fungus, insect, birds and animals, and its form is not distinguishable. The quality of the pellet depends on the pan's rolling motion as well as the precise timing and quantity of the pelleting ingredients. In addition to helping germination and supporting plant protection, pelleting seeds gives the farmer a way to speed up and improve the efficiency of the sowing process. The characteristics of the pelletized seed are significantly superior to those of conventionally available seed (Karivaradaraaju *et al*., 1999). Pelleting also helps the seed from desiccation, hot and dry wind, sunlight and soil pH. Species which do not germinate in open may be pelletized and used for aerial seeding.

Seed pelleting in onion increased the yield by stimulating the plant growth process (Gaizhutes, 1967). Olsen and Elkins (1977) stated that lime pelleting of the seed can overcome the soil acidity. Seed pelleting can increase the self-life of carrot and onion seed up to 3 years (Eric and Roos, 1979).

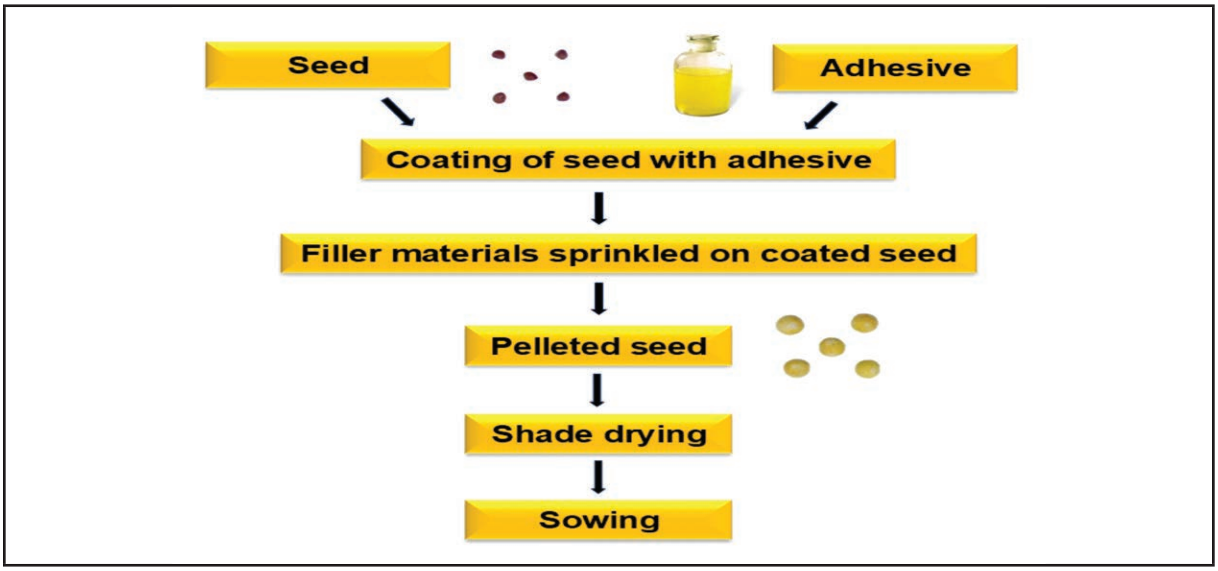

Fig. 4: Seed pelleting process

6. Polykote film Coating

Polykote film coating refers to a process where a thin layer of polymer-based material is applied to seeds. This coating can carry active ingredients like fungicides, pesticides, nutrients, or colorants, which help improve seed performance, protect against pests, and enhance germination rates. The film coating is designed to improve seed handling, planting efficiency, and overall crop establishment without altering the seed's shape. The plasticizer polymer forms a flexible film that adheres and protects the fungicides, preventing dusting off and loss of fungicides during handling. The film is water soluble, so it does not hamper germination.

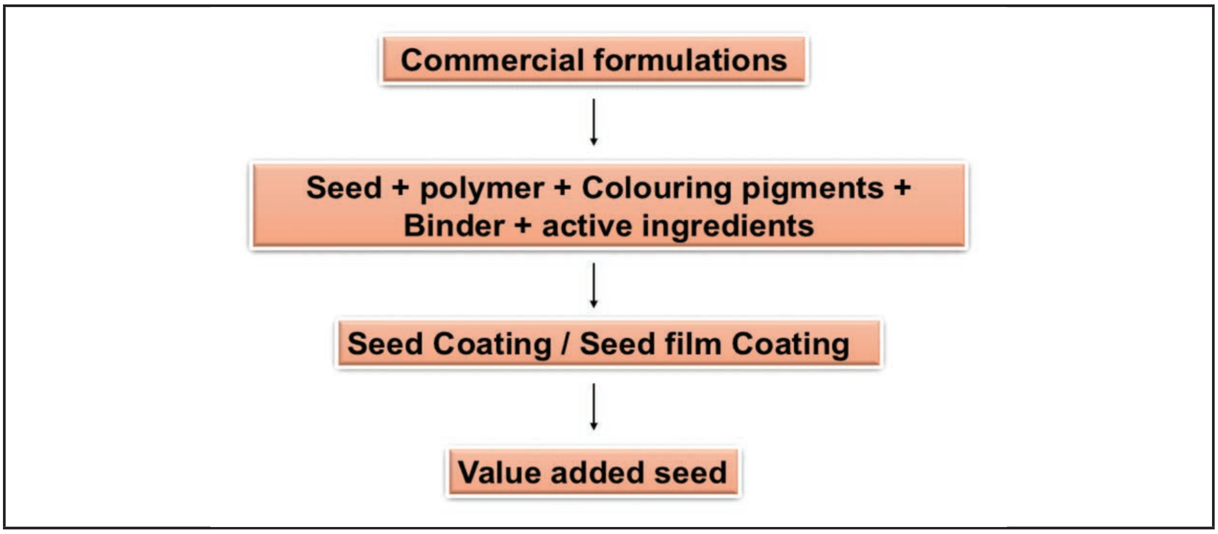

Fig. 5: Steps involved in Polykote film coating

7. Irradiation Treatment

Presowing irradiation of the seed is a novel measure which enables to harness atomic energy in the form of ionizing radiation to increase the yield potential. Thus, irradiation is a treatment that uses different types radiation to effect seed, seedling or other materials. The stimulatory effects of radiations especially with the ionizing radiation, ultraviolet radiation, ultrasonic vibrations and other sources of energy have been reported in seeds on germination, vigour and productivity of the plant. In the process of growth and development of the plant raised from irradiated seed, beginning from seedling emergence and ending with the ripening, there appears a new, quiet diverse changes manifested in the acceleration of the cell division rate, enhancement of growth and development, change of organogenesis, yield increases and its quality change. Doses of irradiation play a very important role during the treatment. Several investigators found that radiation induced stimulation of plant growth. In tomato, Nargis (1995) reported that germination percentage decreases with increases in dose.

Conclusion

Significant enhancements in seed performance can be attained through the application of enhancement technologies, whether individually or in conjunction, utilizing physical, chemical, or physiological means. However, a technology can only achieve success if it is economically viable. These advancements support farmers in achieving higher yields, reducing input costs, and mitigating the challenges posed by changing climate conditions.

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nsa National Seed Association of India

The National Seed Association of India

909, Surya Kiran Building,
19 Kasturba Gandhi Marg, New Delhi - 110001 (INDIA)

Ph.: 011-43553241-43, Fax.: 011-43533248
Email: info@nsai.co.in | Web: www.nsai.co.in