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Review Article

Seed Technology: Advancing Agricultural Productivity and Sustainability

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ABSTRACT

Seed technology encompasses the scientific principles and practices involved in the production, processing, certification, treatment, storage, and distribution of high-quality seeds for sustainable agriculture. Quality seeds serve as the foundational input for crop production, directly influencing germination, plant vigour, yield potential, and overall agricultural productivity. This review examines the key domains of modern seed technology, including seed production systems and multiplication classes, seed processing and quality assessment, certification standards enforced by agencies such as the Association of Official Seed Certifying Agencies (AOSCA), and advanced seed treatment and priming techniques. The paper further explores emerging innovations such as CRISPR-based gene editing, nanotechnology-enabled seed coatings, blockchain-driven seed traceability, and artificial intelligence applications in seed quality analysis. By integrating these technological advances, seed technology continues to play a pivotal role in ensuring food security, enhancing crop resilience, and promoting environmentally sustainable agricultural practices worldwide.

Keywords: *Seed Technology; Seed Certification; Seed Priming; Crop Productivity; Sustainable Agriculture.*

INTRODUCTION

Seed is the most critical and fundamental input in agriculture, serving as the carrier of genetic potential that determines crop performance, yield, and quality. According to Copeland and McDonald (2001), quality seed alone can contribute to a 15–20% increase in crop productivity, making seed technology one of the most cost-effective interventions in modern farming systems. Seed technology, as a discipline, encompasses the scientific study and application of methods involved in the development, evaluation, production, processing, storage, certification, and distribution of seeds to ensure that farmers receive planting material of the highest genetic and physical quality.

The global seed market has experienced remarkable growth, valued at approximately USD 63 billion in 2023 and projected to reach USD 92 billion by 2030, reflecting the increasing demand for improved seed varieties driven by population growth, climate change, and the need for food security (FAO, 2023).

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The significance of seed technology extends beyond mere seed supply; it represents an integrated system that connects plant breeding innovations with farmer-level crop establishment. As Bewley et al. (2013) emphasised, the physiological quality of seeds—including vigour, viability, and dormancy regulation—fundamentally determines the success of crop establishment under diverse agro-climatic conditions.

Modern seed technology has evolved significantly from traditional seed-saving practices to a highly sophisticated, science-driven industry. Contemporary approaches integrate molecular biology, nanotechnology, precision agriculture, and digital technologies to enhance seed quality and traceability. Bradford (2018) noted that advances in seed enhancement technologies, including priming, coating, and pelleting, have substantially improved germination uniformity and seedling establishment, particularly under adverse environmental conditions such as drought and salinity. Furthermore, the integration of CRISPR-Cas9 gene editing technology has revolutionised the development of climate-resilient crop varieties with enhanced nutritional profiles and disease resistance (Zhu et al., 2020).

This review provides a comprehensive examination of the major domains of seed technology, encompassing seed production and multiplication systems, seed processing and quality assessment, certification and regulatory frameworks, seed treatment and priming methodologies, seed storage and viability management, biotechnological innovations, and emerging digital technologies. The objective is to synthesise current knowledge and highlight the role of seed technology in advancing agricultural productivity and sustainability in the context of global food security challenges.

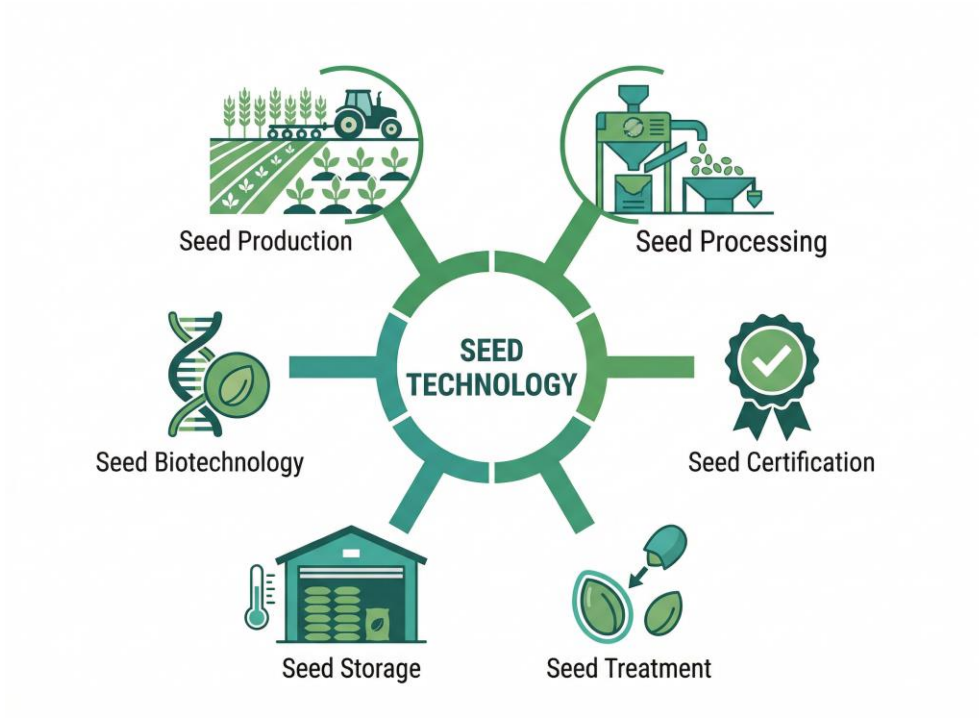

Figure 1: Key Components of Seed Technology in Modern Agriculture

2. Seed Production and Multiplication

Seed production is a systematic process designed to maintain the genetic purity and physical quality of seed from breeder level through to the commercial farmer. The seed multiplication chain follows a well-defined generational system to ensure that varietal identity is preserved at each stage of production (Agrawal, 1995). The four universally recognised classes of seeds, as defined by the Association of Official Seed Certifying Agencies (AOSCA), include Breeder seed, Foundation seed, Registered seed, and Certified seed (AOSCA, 2020).

2.1 Classes of Seed

Breeder seed is the initial seed stock produced by the originating plant breeder or sponsoring institution, maintaining the highest level of genetic purity (100%). It serves as the source for all subsequent seed multiplication. Foundation seed, the progeny of breeder seed, is produced under careful supervision to maintain specific genetic identity and purity, typically requiring field inspections and laboratory testing. Registered seed is produced from foundation seed under the oversight of certification agencies, while Certified seed—the class most widely distributed to farmers—must maintain a minimum genetic purity of 99% (Singhal, 2003). In India, the National Seeds Corporation (NSC) and state seed certification agencies oversee the production and certification process following a three-to-five generation model depending on the crop species (Trivedi & Gunasekaran, 2013).

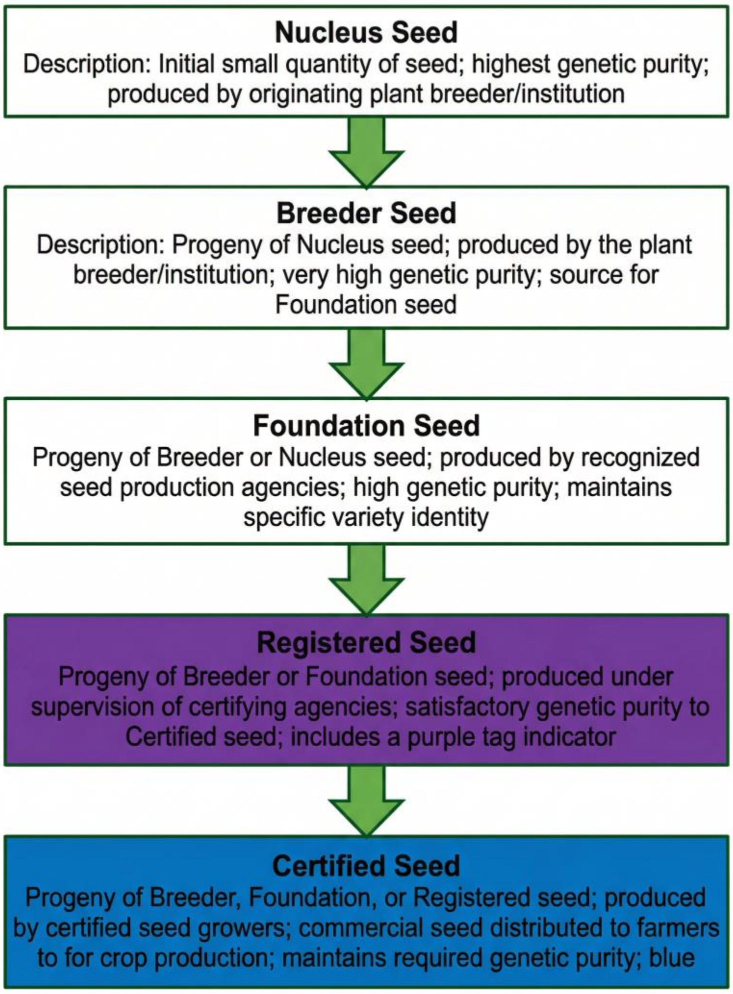

Figure 2: Classes of Seed in the Certification System

2.2 Hybrid Seed Production

Hybrid seed production is a specialised domain that exploits heterosis, or hybrid vigour, to produce superior F1 progeny with enhanced yield, uniformity, and stress tolerance. The success of hybrid seed production depends critically on preventing self-pollination in the female parent and ensuring adequate cross-pollination from the male parent (Virmani, 1994). Key mechanisms employed in commercial hybrid seed production include hand emasculation and pollination, cytoplasmic male sterility (CMS), genetic male sterility (GMS), and selfincompatibility systems. In crops such as rice, supplementary pollination through rope pulling techniques enhances outcrossing rates in CMS-based hybrid production systems (Yuan, 2004). The adoption of hybrid varieties has contributed significantly to yield improvements globally; for example, hybrid rice varieties have achieved yield advantages of 15–25% over conventional inbred varieties in Asia (Spielman et al., 2013).

3. Seed Processing and Quality Assessment

Seed processing encompasses a series of mechanical and physical operations designed to improve the quality of harvested seed lots by removing impurities, damaged seeds, weed seeds, and other crop seeds. The primary objective is to upgrade seed lots to meet established certification standards for physical purity, germination percentage, and moisture content (Vaughan et al., 2009).

3.1 Processing Operations

The standard seed processing sequence involves pre-cleaning, primary cleaning using air-screen cleaners, grading by size and density using gravity separators, and specialised separation using indent cylinders, spiral separators, or colour sorters. Modern seed processing facilities increasingly employ optical sorting technology and near-infrared (NIR) spectroscopy for rapid, non-destructive assessment of seed quality parameters including moisture content, protein composition, and viability (Dell'Aquila, 2009). According to Gregg and Billups (2010), proper seed conditioning can improve seed lot purity from 85% to over 99%, significantly enhancing the value and performance of the seed.

3.2 Seed Quality Testing

Seed quality assessment follows standardised protocols established by the International Seed Testing Association (ISTA). Key parameters evaluated include germination percentage, determined through standard germination tests under controlled conditions; seed vigour, assessed through accelerated aging tests, electrical conductivity measurements, and seedling growth rate evaluations; and physical purity, determined by separating seed lots into pure seed, other crop seed, weed seed, and inert matter fractions (ISTA, 2022). The tetrazolium test provides a rapid assessment of seed viability by staining metabolically active tissues, while molecular techniques such as DNA fingerprinting and isozyme analysis are increasingly employed for variety identification and genetic purity verification (Marcos-Filho, 2015).

4. Seed Certification and Regulatory Frameworks

Seed certification is a formal, legally mandated process that verifies the genetic identity, genetic purity, physical purity, and germination capacity of seed lots before they are distributed to farmers. Certification agencies conduct field inspections during the growing season and laboratory analyses of harvested seed to ensure compliance with crop-specific standards (Trivedi & Gunasekaran, 2013).

Internationally, the Organisation for Economic Co-operation and Development (OECD) Seed Schemes provide a framework for varietal certification that facilitates international seed trade among member countries. The OECD guidelines stipulate requirements for control plot testing, field inspection, and post-harvest evaluation to maintain seed quality standards (OECD, 2023). In India, the Seeds Act of 1966 and the subsequent Seeds (Amendment) Act provide the legislative framework for seed quality regulation, with the Central Seed Certification Board coordinating certification activities across state agencies (Pal et al., 2019).

Field certification standards typically specify minimum isolation distances to prevent genetic contamination through cross-pollination, maximum permissible levels of off-type plants, and requirements for roguing to remove variant plants. For instance, foundation seed production of cross-pollinated crops such as maize requires isolation distances of 200–400 metres depending on the seed class, while self-pollinated crops like wheat and rice require substantially smaller isolation distances of 3–10 metres (Singhal, 2003). Laboratory certification involves testing seed lots for germination percentage, physical purity, moisture content, and the presence of seed-borne pathogens, with each parameter required to meet minimum thresholds before certification tags are issued.

Table 1: Minimum Seed Certification Standards for Major Crops

Crop	Pure Seed (%)	Germination (%)	Moisture (%)	Genetic Purity (%)
Rice	98.0	80	13.0	99.0
Wheat	98.0	85	12.0	99.0
Maize	98.0	90	12.0	99.0
Soybean	98.0	70	10.0	98.0
Cotton	98.0	65	10.0	99.0
Sorghum	98.0	75	12.0	99.0

Source: Adapted from Indian Minimum Seed Certification Standards (Trivedi and Gunasekaran, 2013)

5. Seed Treatment and Priming Techniques

Seed treatment refers to the application of chemical, biological, or physical agents to seeds before sowing to protect against seed-borne and soil-borne pathogens, insects, and environmental stresses. Seed priming, a complementary technique, involves controlled hydration of seeds to initiate pre-germinative metabolic processes without allowing radicle emergence, resulting in faster and more uniform germination upon sowing (Paparella et al., 2015).

5.1 Chemical and Biological Seed Treatments

Chemical seed treatments commonly employ fungicides such as thiram, captan, and carboxin for protection against damping-off pathogens including Pythium, Rhizoctonia, and Fusarium species. Insecticidal seed treatments using neonicotinoids (e.g., imidacloprid, thiamethoxam) provide systemic protection against early-season insect pests, though environmental concerns regarding pollinator health have prompted the development of alternative approaches (Taylor et al., 2020). Biological seed treatments utilising Trichoderma spp., Pseudomonas fluorescens, and Bacillus subtilis have gained increasing adoption as sustainable alternatives, offering both plant protection and growth promotion through mechanisms including induced systemic resistance, antibiosis, and nutrient solubilisation (Harman, 2006).

5.2 Seed Priming Techniques

Modern seed priming encompasses several approaches, each tailored to specific crop requirements and environmental challenges. Hydropriming involves soaking seeds in water for a predetermined duration, activating pre-germinative enzymes and repair mechanisms. Osmopriming utilises polyethylene glycol (PEG) solutions to control water uptake rates, allowing metabolic activation while preventing radicle protrusion. Halopriming with salt solutions such as KNO_3 and NaCl has demonstrated significant improvements in germination performance; studies by Paparella et al. (2015) reported that KNO_3 priming at 6% concentration for 96 hours significantly enhanced germination rate, seedling vigour, biomass production, and protein content across multiple crop cultivars.

Biopriming combines seed hydration with inoculation of beneficial microorganisms, creating a synergistic effect that enhances both germination and plant defence mechanisms. Hormonal priming using gibberellic acid (GA_3), salicylic acid, or abscisic acid modulates seed dormancy and stress tolerance pathways. The emerging field of nanopriming represents a cutting-edge advancement, wherein seeds are treated with nanoparticle solutions containing materials such as silver (Ag), zinc oxide (ZnO), iron oxide (Fe_2O_3), or chitosan nanoparticles to enhance germination, stress tolerance, and nutrient uptake efficiency (Yan et al., 2022). Research has shown that AgNP-primed rice seeds exhibited enhanced resistance to cold, salt stress, and rice blast fungus through activation of MAPK signalling and plant hormone signal transduction pathways, effectively creating a molecular "stress memory" in seedlings (Yan et al., 2022).

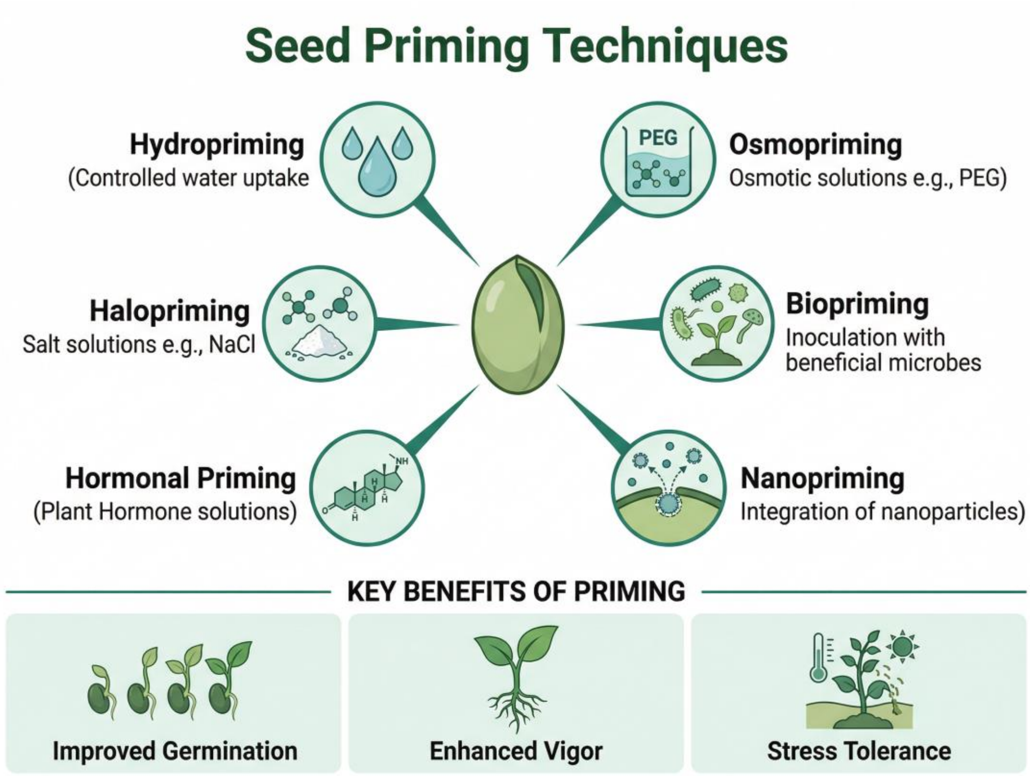

Figure 3: Overview of Seed Priming Techniques and Their Benefits

6. Seed Storage and Viability Management

Seed storage is a critical component of seed technology aimed at maintaining seed viability and vigour from harvest to sowing. The longevity of seeds during storage is influenced by several interacting factors, including seed moisture content, storage temperature, relative humidity, oxygen levels, and the initial physiological quality of the seed lot (Roberts, 1972).

The fundamental principle governing seed storage is that low temperature and low humidity slow metabolic activity, thereby extending seed life. Harrington (1972) established the widely cited rule of thumb that the sum of storage temperature (°F) and relative humidity (%) should not exceed 100 for safe storage. Furthermore, seed longevity is approximately halved for each 10°F increase in storage temperature or each 1% increase in seed moisture content. For most crop species, optimal long-term storage requires temperatures of 0–5°C with relative humidity below 40% and seed moisture content of 5–8% for orthodox seeds (Walters et al., 2005).

Storage systems range from traditional methods using hermetic containers, desiccants, and cooled warehouses to advanced facilities such as the Svalbard Global Seed Vault in Norway, which preserves over one million seed samples at −18°C as a global backup for crop genetic resources. The development of hermetic storage technologies, including the Purdue Improved Crop Storage (PICS) bags and metal silos, has significantly reduced post-harvest seed losses in developing countries by creating oxygen-depleted environments that suppress insect activity and fungal growth without chemical inputs (Murdock & Baoua, 2014). Ultra-dry storage techniques, in which seed moisture content is reduced to 3–5% using desiccants, have demonstrated the potential to maintain seed viability for decades, even at ambient temperatures, offering a low-cost alternative for gene banks in tropical regions (Zheng et al., 1998).

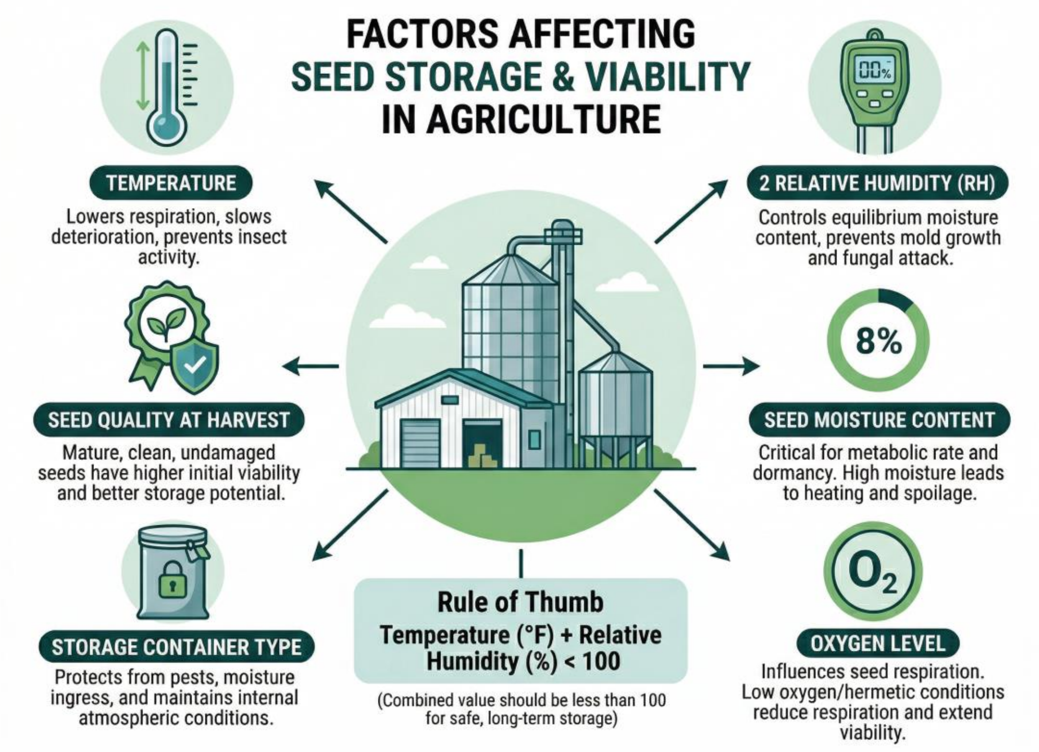

Figure 4: Factors Affecting Seed Storage and Viability

7. Biotechnological Innovations in Seed Technology

Biotechnology has profoundly transformed seed technology through the development of genetically improved crop varieties with enhanced yield potential, nutritional quality, and resistance to biotic and abiotic stresses. The integration of molecular biology tools into seed science has accelerated breeding cycles, improved selection accuracy, and enabled the creation of novel traits not achievable through conventional breeding alone (Moose & Mumm, 2008).

7.1 Genetically Modified (GM) Seeds

Genetically modified seeds, incorporating transgenes for insect resistance (Bt crops), herbicide tolerance, and nutritional enhancement, have been commercially cultivated since 1996. Bt cotton, expressing Cry proteins from Bacillus thuringiensis, has reduced pesticide use by approximately 50% in India while increasing yields by 30–40%, demonstrating the transformative impact of GM technology on smallholder farming systems (Qaim, 2009). Golden Rice, engineered to produce beta-carotene, represents a nutritional biofortification approach designed to address vitamin A deficiency in rice-dependent populations (Paine et al., 2005). However, the adoption of GM seeds remains subject to regulatory frameworks, biosafety assessments, and public acceptance considerations that vary significantly across countries.

7.2 CRISPR-Cas9 Gene Editing

The CRISPR-Cas9 gene editing system has emerged as the most versatile and precise tool for targeted genetic modification in crop improvement. Unlike traditional transgenesis, CRISPR enables precise editing of endogenous genes without introducing foreign DNA, potentially simplifying regulatory pathways in many jurisdictions (Zhu et al., 2020). Notable applications in seed technology include the development of CRISPR-edited cowpea varieties with improved plant architecture and synchronised flowering for mechanised harvest, deregulated by the USDA in 2023. CRISPR-edited rice varieties with enhanced photosynthetic efficiency through the C4 rice project have shown potential yield increases of up to 50% while reducing water and fertiliser requirements (Ermakova et al., 2021). Additionally, CRISPR technology has been applied to reduce seed shattering in pennycress by up to 90%, improving harvest efficiency for this emerging cover crop species.

7.3 Molecular Markers and Genomic Selection

Molecular marker technologies, including Simple Sequence Repeats (SSR), Single Nucleotide Polymorphisms (SNP), and Kompetitive Allele-Specific PCR (KASP) platforms, have become indispensable tools for variety identification, genetic purity testing, and marker-assisted selection (MAS) in seed production. Genome-wide association studies (GWAS) and genomic selection approaches enable the prediction of breeding values for complex traits such as drought tolerance and yield stability, significantly accelerating the development of improved seed varieties (Varshney et al., 2021). DNA fingerprinting databases are increasingly integrated with quality management systems for seed certification, providing molecular-level verification of varietal identity complementary to morphological DUS (Distinctness, Uniformity, and Stability) testing.

8. Emerging Technologies in Seed Science

8.1 Nanotechnology in Seed Enhancement

Nanotechnology applications in seed science represent a frontier of innovation with the potential to revolutionise seed treatment and crop establishment. Nano-encapsulation enables the controlled release of nutrients, growth regulators, and crop protection agents directly to the seed and developing seedling, improving delivery efficiency and reducing environmental contamination (Kumar et al., 2021). Research has demonstrated that chitosan nanoparticles enhance seed germination, seedling vigour, and enzymatic activity across multiple crop species, while zinc oxide and iron oxide nanoparticles improve micronutrient delivery and stress tolerance. Smart nano-seed coatings are being developed to release active ingredients in response to specific environmental triggers such as soil moisture, temperature, or pH changes, representing a paradigm shift toward precision seed enhancement (Fellet et al., 2021).

8.2 Blockchain-Based Seed Traceability

Blockchain technology offers a transformative solution for ensuring seed authenticity, quality verification, and supply chain transparency. By creating immutable, decentralised digital records of every transaction in the seed supply chain—from breeding and testing through certification and distribution—blockchain systems enable farmers to verify seed origin, genetic purity, and certification status by scanning QR codes on seed packets. In India, the Professor Jayashankar Telangana State Agricultural University (PJTSAU) partnered with TraceX Technologies to implement blockchain-based seed traceability, combating the widespread issue of spurious seeds entering the market (TraceX, 2023). Smart contracts embedded in blockchain platforms can automate compliance verification, ensuring that seeds meet certification criteria before progressing through the supply chain, thereby reducing fraud and building farmer trust.

8.3 Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) are increasingly integrated into seed technology for automated quality assessment, predictive analytics, and precision breeding. Computer vision systems employing deep learning algorithms can classify seed quality based on morphological parameters including size, shape, colour, and surface texture with accuracy exceeding 95%, replacing subjective visual inspection with objective, high-throughput analysis (Medeiros et al., 2020). AI-powered phenotyping platforms analyse drone and satellite imagery to evaluate field performance of seed varieties across diverse environments, accelerating variety selection and recommendation. Furthermore, machine learning models are being developed to predict seed vigour and storability based on spectral, thermal, and biochemical data, enabling proactive quality management throughout the seed supply chain.

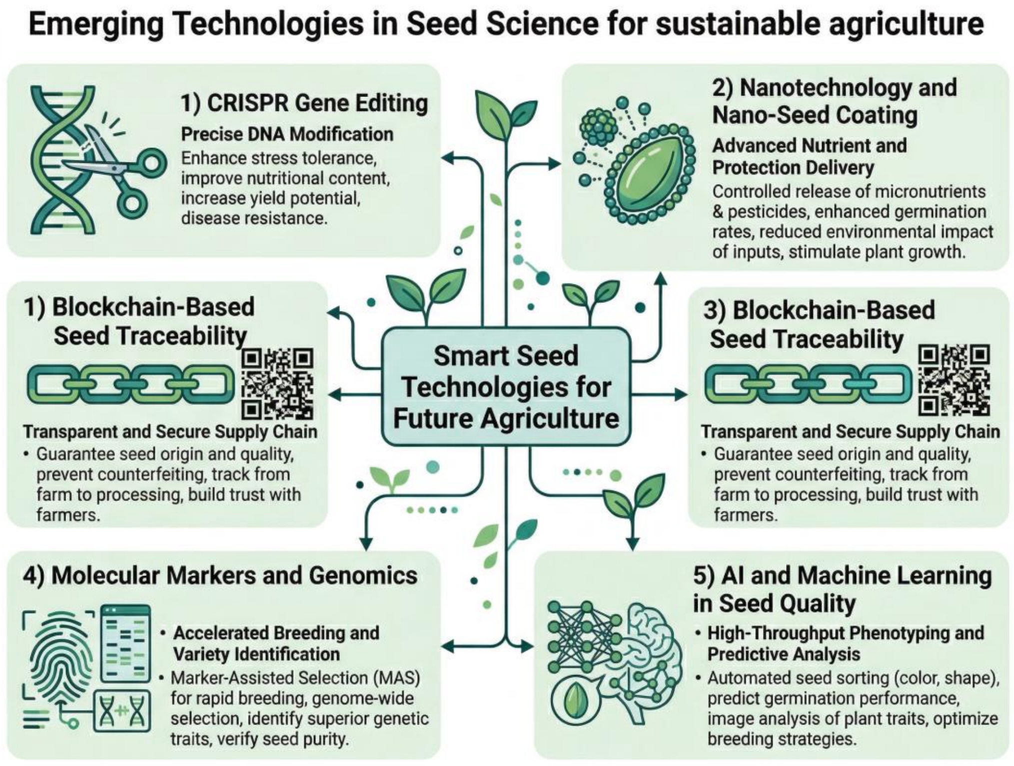

Figure 5: Emerging Technologies in Seed Science for Sustainable Agriculture

CONCLUSION

Seed technology stands as a cornerstone of modern agricultural systems, bridging the gap between genetic innovation and farmer-level crop productivity. This review has examined the multifaceted dimensions of seed technology, from the foundational processes of seed production, processing, and certification to the advanced frontiers of biotechnology, nanotechnology, and digital innovation. The evidence demonstrates that quality seed, supported by robust certification systems, advanced treatment techniques, and proper storage management, remains the most effective and accessible intervention for improving crop yields and ensuring food security.

The integration of CRISPR-Cas9 gene editing, molecular marker platforms, and genomic selection has fundamentally accelerated the pace of variety development, enabling the creation of climate-resilient, nutritionally enhanced crop varieties tailored to specific agro-ecological conditions. Simultaneously, nanotechnology-based seed enhancements offer unprecedented precision in delivering nutrients, growth regulators, and protective agents at the seed level, reducing chemical inputs and environmental impacts. The adoption of blockchain technology and AI-driven quality assessment systems promises to transform seed supply chain management by enhancing transparency, combating counterfeit seeds, and enabling data-driven decision-making across all stakeholders.

However, significant challenges remain, including the need for harmonised international regulatory frameworks for gene-edited crops, equitable access to advanced seed technologies for smallholder farmers in developing countries, the integration of digital infrastructure in rural agricultural communities, and the long-term environmental assessment of nanotechnology applications in agriculture. Future research should prioritise the development of cost-effective, scalable seed enhancement technologies, the establishment of open-access genomic databases for crop improvement, and the creation of inclusive seed systems that connect formal and informal seed sectors to ensure that the benefits of seed technology reach all farmers globally. By addressing these challenges through collaborative research, supportive policies, and technology transfer, seed technology will continue to serve as a driving force for sustainable agricultural development in the face of growing global food demand and climate uncertainty.

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REFERENCES

Agrawal, R. L. (1995). Seed technology (2nd ed.). *Oxford and IBH Publishing*.

AOSCA. (2020). Operational procedures, crop standards, and service programs publication. *Association of Official Seed Certifying Agencies*.

Bewley, J. D., Bradford, K. J., Hilhorst, H. W. M., & Nonogaki, H. (2013). Seeds: *Physiology of development, germination and dormancy* (3rd ed.). Springer.

Bradford, K. J. (2018). Seed production and quality. In M. B. Murray (Ed.), Seeds: Biology, *technology and role in agriculture* (pp. 95–132). CABI Publishing.

Copeland, L. O., & McDonald, M. B. (2001). *Principles of seed science and technology* (4th ed.). Springer.

Dell'Aquila, A. (2009). Digital imaging information technology applied to seed germination testing: A review. *Agronomy for Sustainable Development, 29*(1), 213–221.

Ermakova, M., Danila, F. R., Furbank, R. T., & von Caemmerer, S. (2021). On the road to C4 rice: Advances and perspectives. *The Plant Journal, 101*(4), 940–950.

FAO. (2023). The state of food and agriculture 2023: Revealing the true cost of food. *Food and Agriculture Organization of the United Nations*.

Fellet, G., Pilotto, L., Marchiol, L., & Braidot, E. (2021). Tools for nano-enabled agriculture: Fertilizers based on calcium phosphate, silicon, and chitosan nanoparticles. *Agronomy, 11*(6), 1239.

Gregg, B. R., & Billups, G. L. (2010). Seed conditioning: Technology—Part A. *Science Publishers*.

Harman, G. E. (2006). Overview of mechanisms and uses of Trichoderma spp. *Phytopathology, 96*(2), 190–194.

Harrington, J. F. (1972). Seed storage and longevity. In T. T. Kozlowski (Ed.), Seed biology (Vol. 3, pp. 145–245). *Academic Press*.

ISTA. (2022). International rules for seed testing 2022. *International Seed Testing Association*.

Kumar, S., Nehra, M., Dilbaghi, N., Marrazza, G., Tuteja, S. K., & Kim, K. H. (2021). Nano-based smart pesticide formulations: Emerging opportunities for agriculture. *Journal of Controlled Release, 294*, 131–153.

Marcos-Filho, J. (2015). Seed vigor testing: An overview of the past, present and future perspective. *Scientia Agricola, 72*(4), 363–374.

Medeiros, A. D., da Silva, L. J., Ribeiro, J. P. O., Ferreira, K. C., Rosas, J. T. F., Santos, A. A., & da Silva, C. B. (2020). Machine learning for seed quality classification: An advanced approach using merger data from FT-NIR spectroscopy and X-ray imaging. *Sensors, 20*(15), 4319.

Moose, S. P., & Mumm, R. H. (2008). Molecular plant breeding as the foundation for 21st century crop improvement. *Plant Physiology, 147*(3), 969–977.

Murdock, L. L., & Baoua, I. B. (2014). On Purdue Improved Cowpea Storage (PICS) technology: Background, mode of action, future prospects. *Journal of Stored Products Research, 58*, 3–11.

OECD. (2023). OECD seed schemes 2023: Rules and directions. *Organisation for Economic Co-operation and Development*.

Paine, J. A., Shipton, C. A., Chaggar, S., Howells, R. M., Kennedy, M. J., Vernon, G., & Drake, R. (2005). Improving the nutritional value of Golden Rice through increased pro-vitamin A content. *Nature Biotechnology, 23*(4), 482–487.

Pal, G., Ramasubramanian, T., & Udaya Sekhar, N. (2019). Indian seed sector: Current status and future perspective. *Indian Journal of Agricultural Sciences, 89*(8), 1227–1234.

Paparella, S., Araújo, S. S., Rossi, G., Wijayasinghe, M., Carbonera, D., & Balestrazzi, A. (2015). Seed priming: State of the art and new perspectives. *Plant Cell Reports, 34*(8), 1281–1293.

Qaim, M. (2009). The economics of genetically modified crops. *Annual Review of Resource Economics, 1*(1), 665–694.

Roberts, E. H. (1972). Viability of seeds. *Chapman and Hall*.

Singhal, N. C. (2003). Hybrid seed production in field crops: Principles and practices. *Kalyani Publishers*.

Spielman, D. J., Kolady, D. E., & Ward, P. S. (2013). The prospects for hybrid rice in India. *Food Security, 5*(5), 651–665.

Taylor, A. G., Harman, G. E., & Nielsen, P. A. (2020). Biological seed treatments: Factors involved in efficacy. *HortScience, 55*(6), 774–778.

TraceX. (2023). Seed traceability: Blockchain for authenticity and compliance. *TraceX Technologies*.

Trivedi, R. K., & Gunasekaran, M. (2013). Indian minimum seed certification standards. The Central Seed Certification Board, *Ministry of Agriculture,* Government of India.

Varshney, R. K., Roorkiwal, M., Sun, S., Bajaj, P., Chitikineni, A., Thudi, M., & Upadhyaya, H. D. (2021). A chickpea genetic variation map based on the sequencing of 3,366 genomes. *Nature, 599*(7886), 622–627.

Vaughan, C. E., Gregg, B. R., & Delouche, J. C. (2009). Seed processing and handling (3rd ed.). *Seed Technology Laboratory*, Mississippi State University.

Virmani, S. S. (1994). Heterosis and hybrid rice breeding. *Springer*.

Walters, C., Wheeler, L. M., & Grotenhuis, J. M. (2005). Coming of age for seed science: Linking science to management. *New Phytologist, 166*(3), 655–658.

Yan, A., & Chen, Z. (2022). Impacts of silver nanoparticles on plants: A focus on the phytotoxicity and underlying mechanism. *International Journal of Molecular Sciences*, *23*(8), 4386.

Yuan, L. P. (2004). Hybrid rice technology for food security in the world. *Crop Research, 28*(1), 1–9.

Zheng, G. H., Jing, X. M., & Tao, K. L. (1998). Ultradry seed storage cuts costs of genebank storage. *Seed Science and Technology, 26*(2), 461–468.

Zhu, H., Li, C., & Gao, C. (2020). Applications of CRISPR–Cas in agriculture and plant biotechnology. *Nature Reviews Molecular Cell Biology, 21*(11), 661–677.