SEED SCIENCE IN THE 21ST CENTURY: FROM GENOMES TO SMART SYSTEMS

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ABSTRACT

Seed science in the 21st century has evolved into a multidisciplinary frontier encompassing biotechnology, nanotechnology, AI, and omics-based approaches. Gene-editing tools like CRISPR, advanced priming methods, and hologenomics are redefining seed improvement strategies. Smart coatings, nanocarriers, and intelligent packaging enhance seed viability and delivery efficiency. AI-driven trait prediction and speed breeding are revolutionizing crop cycles and performance. Integration of cryopreservation and artificial seeds ensures long-term conservation and uniform propagation. These technologies collectively engineer seed systems that are resilient, productive, and responsive to environmental stimuli. This review outlines key innovations shaping seed science for climate-resilient and sustainable agriculture.

KEYWORDS: Artificial Seeds, CRISPR, Multi-Omics, Seed Enhancement Technologies, Seed Priming

INTRODUCTION

The 21st century has witnessed a paradigm shift in seed science, integrating genomics, digital technologies, and sustainable practices to reshape modern agriculture. Seeds, the starting point of the food chain, are being transformed into intelligent biological systems capable of enhanced performance, resilience, and predictability. Innovations such as precision gene editing, nanotechnology-enabled seed coatings, and artificial seeds have accelerated breeding cycles and increased stress tolerance. Meanwhile, the use of artificial intelligence, hologenomics, and multi-omics platforms enables more accurate trait prediction and better understanding of seed physiology. With global climate variability, rising food demands, and increasing pressure on land and water resources, seed science is becoming a cornerstone of sustainable agriculture and food security. This article explores how advances in seed priming, storage,

microbiome engineering, and digital systems are converging to develop next-generation seeds that are not only productive but also adaptive and ecologically harmonious, ensuring global agricultural resilience and long-term sustainability.

1. SEED HOLOGENOMICS: PLANT-MICROBE INTERACTIONS

Seed hologenomics views seeds as holobionts—an integrated unit of plant and microbial genomes. Microorganisms associated with seeds play vital roles in germination, nutrient acquisition, and stress adaptation. Advancements in metagenomics, such as 16S rRNA and ITS sequencing, enable the profiling of seed-associated microbiota. Recent research supports the use of microbial inoculants (e.g., *Trichoderma*, *Pseudomonas*) through bio-priming or coating to enhance seedling vigor and root colonization (Reed, 2008). These microbial consortia can induce systemic resistance and modulate hormonal signaling, supporting robust early growth. By engineering seed microbiomes, scientists aim to develop tailored microbial environments that improve plant resilience, even under abiotic stress conditions such as drought or salinity. This bio-symbiotic approach fosters sustainable agriculture by reducing the dependency on synthetic fertilizers and agrochemicals, positioning seed hologenomics as a vital pillar in seed enhancement. Furthermore, microbial-assisted seeds represent a next-generation strategy for achieving ecological intensification and soil health restoration in degraded agro-ecosystems.

2. SEED COATING AND PELLETING TECHNOLOGIES

Seed coating involves applying external materials onto the seed surface to improve physical handling, germination efficiency, and protection. Modern coatings employ biodegradable polymers, hydrogels, and smart polymers that release active compounds such as nutrients, growth stimulants, or pesticides in response to environmental cues. In pelleting, small or irregular seeds are reshaped with inert fillers and binding agents to standardize size and weight for mechanical sowing. Materials such as clay, bio-based adhesives, and polymer blends are used to facilitate uniform field distribution. Advanced coatings may integrate beneficial microbes, biostimulants, or micronutrients, enhancing early seedling development and disease resistance. Research has shown improved field emergence and crop establishment in coated seeds, especially under stress-prone conditions (Watson et al., 2018). These innovations reduce input costs and enhance seedling uniformity, critical for precision agriculture. As smart agriculture progresses, intelligent coatings that sense temperature or moisture levels will further automate and optimize seed-soil interactions in diverse agro-climatic conditions.

3. SEED PRIMING TECHNIQUES

Seed priming is a physiological pre-sowing treatment that initiates metabolic activity in seeds without actual germination. Techniques like hydro-priming (water soaking) and osmo-priming (PEG solutions) condition seeds for faster and uniform emergence. Hormonal priming uses gibberellic acid, brassinosteroids, or salicylic acid to modulate growth signaling pathways, while bio-priming introduces beneficial microbes for stress mitigation and plant defense activation. Emerging priming technologies include nano-priming (using ZnO, AgNPs), which enhances water uptake and germination, and electro-priming or magneto-priming, which use electric and magnetic fields to stimulate cellular activity. Chemo-priming and halo-priming apply salts or chemicals like nitrate and ascorbate to induce adaptive stress tolerance. These techniques increase germination speed, improve seedling vigor, and enhance stress resilience under drought, salinity, or low temperature. Multi-priming approaches combine physical, chemical, and biological methods to create synergistic effects on seed performance. Priming is now a vital component in seed technology, especially for climate-resilient and organic farming systems.

4. CRISPR AND PRECISION GENE EDITING

CRISPR-Cas9 and its derivatives such as base and prime editing are revolutionizing seed genetics by enabling precise, heritable modifications without introducing foreign DNA. Applications include gene knockout for trait elimination, and gene insertion or substitution for desired trait enhancement. Multiplex editing allows simultaneous editing of multiple genes, accelerating the breeding of complex traits. In wheat and rice, CRISPR has enabled resistance to diseases and improved yield traits (Zhang et al., 2016). Unlike traditional breeding, CRISPR is faster, cost-effective, and transgene-free, making it publicly acceptable and regulatory-friendly. The technology's integration with speed breeding and genomic selection further reduces breeding cycles. Novel delivery methods like nanocarriers and ribonucleoprotein complexes are improving gene-editing efficiency in recalcitrant species. CRISPR's scalability is driving its adoption in seed companies and public breeding programs for crops such as maize, sorghum, and millet, marking a transformative shift in seed biotechnology toward customized and adaptive seed solutions.

5. PANGENOMICS AND SUPER-PANGENOMES

Conventional reference genomes represent a limited view of a species' genetic diversity. Pangenomics overcomes this by compiling core and accessory genes across multiple genotypes, revealing a broader spectrum of alleles associated with stress tolerance, productivity, and adaptation. Super-pangenomes

further include genes from wild relatives, enhancing gene discovery across interrelated species. For example, the African rice pangenome revealed unique alleles for heat and drought tolerance not present in conventional cultivars. These resources facilitate genomic-assisted breeding by identifying novel trait-linked markers. Computational platforms such as PanTools and VG-Flow enable the analysis of pangenomic data. Pangenomics also supports seed system development by identifying genotypes suitable for specific ecologies or marginal environments. This approach allows breeders to mine natural variation efficiently, accelerating the deployment of climate-smart cultivars. As climate variability escalates, pangenomics and super-pangenomes will play a critical role in safeguarding agricultural biodiversity and delivering high-performing seeds across diverse agro-ecological regions.

6. MULTI-OMICS INTEGRATION IN SEED BIOLOGY

Modern seed science embraces a systems biology approach through integration of genomics, transcriptomics, proteomics, metabolomics, and epigenomics. Each omics layer provides unique insights—genomics reveals gene structure, transcriptomics identifies gene expression profiles, while metabolomics and proteomics offer downstream phenotypic data. Tools like OmicsBox and Galaxy facilitate the simultaneous analysis of these datasets, leading to predictive models for traits like dormancy, vigor, and desiccation tolerance. Epigenomic data inform how DNA methylation and histone modifications regulate seed responses to environmental stress. This integrative approach enables identification of key regulatory networks and molecular markers for use in marker-assisted or genomic selection. In crops like soybean and chickpea, omics-driven discoveries have led to improved seed longevity and germination under stress. Multi-omics is also central to understanding seed microbiome interactions. As data acquisition and computational capacities improve, multi-omics will be indispensable in designing smart seeds tailored for both high performance and resilience across environments.

7. AI AND MACHINE LEARNING IN SEED TRAIT PREDICTION

Artificial intelligence (AI) and machine learning (ML) are revolutionizing trait prediction and seed selection by processing complex datasets from genomics, weather, and field phenotyping. Supervised learning models like support vector machines (SVMs), random forests, and neural networks are trained to predict traits such as germination rate, stress resistance, and yield. Deep learning techniques, including convolutional neural networks (CNNs), are used for image-based seed phenotyping. AI tools such as DeepVariant assist in variant calling for genome editing, while Breeding Insight helps breeders prioritize lines based on predictive modeling. Integration with IoT sensors and satellite data enhances real-time decision-making. AI is especially useful in screening thousands of genotypes, accelerating varietal

selection in breeding programs. This predictive capacity reduces trial-and-error and enhances precision in seed technology. With increasing data availability and algorithm sophistication, AI will be instrumental in designing custom-tailored seeds for specific climates, geographies, and market needs.

8. SPEED BREEDING IN CONTROLLED ENVIRONMENTS

Speed breeding leverages extended photoperiods, temperature control, and LED lighting in growth chambers to accelerate plant life cycles. Crops such as wheat, barley, and chickpea can achieve up to six generations per year under optimized conditions (Watson et al., 2018). This rapid generation turnover is particularly valuable when combined with genomic selection and CRISPR editing to compress breeding timelines from decades to a few years. Speed breeding also facilitates quicker trait fixation and early-stage testing under controlled stress simulations. Facilities now use fully automated phenotyping systems, light recipes tailored to crop type, and precision irrigation to optimize growth. The technique's success depends on integrating phenological modeling and predictive analytics to synchronize flowering and seed set. Its role in seed technology is indispensable for fast-tracking high-performing cultivars, especially in addressing climate-induced threats to crop productivity. Speed breeding is expected to be a mainstay in global crop improvement pipelines.

9. NANOTECHNOLOGY-ENHANCED SEED DELIVERY SYSTEMS

Nanotechnology introduces precision and efficiency in seed delivery through nano-encapsulation and nano-carriers. These systems provide controlled release of nutrients, growth regulators, and biocontrol agents, ensuring their targeted availability at critical growth stages. Nanoparticles like nano-silver and nano-clay are used in coatings to provide antimicrobial action and improve water retention around the seed. Nanogels and nano-emulsions are moisture-sensitive and enable smart, slow-release mechanisms that enhance germination and early seedling vigor. Additionally, nanoencapsulation allows thermal or pH-sensitive release of bioactives, protecting them from degradation. Such delivery systems enhance resource-use efficiency, reduce environmental contamination, and are particularly useful in resource-poor or marginal areas. Research indicates significant improvement in germination uniformity and seedling robustness when nanocarriers are employed. Moreover, nanotechnology facilitates the integration of sensors into seeds for real-time physiological monitoring, opening new frontiers for digital agriculture. These smart delivery systems are redefining seed enhancement, with a focus on precision, sustainability, and scalability.

10. ARTIFICIAL SEEDS AND SOMATIC EMBRYOGENESIS

Artificial seeds, generated through somatic embryogenesis, simulate the structural and physiological properties of natural seeds, enabling their use in propagation, storage, and planting. These synthetic units are produced from totipotent somatic cells and encapsulated in a gel matrix, often supplemented with nutrients or growth hormones. Artificial seeds are invaluable for the mass production of elite genotypes, particularly in horticultural and forestry crops where conventional propagation is slow or inefficient. This technique also supports biodiversity conservation by enabling ex situ preservation of rare or endangered species. The technology allows uniform planting material, facilitating mechanized sowing and reducing genetic variability in field performance. Research has shown that encapsulation-dehydration methods preserve somatic embryos with high post-thaw viability. Artificial seed systems can be enhanced with microbial inoculants or nanocarriers, combining tissue culture and seed enhancement technologies. Their potential in seedling uniformity, genetic conservation, and resource efficiency makes them a promising component of next-generation seed systems.

11. ADVANCED SEED STORAGE AND LONGEVITY TECHNOLOGIES

Seed storage is fundamental to genetic conservation, breeding, and seed system reliability. Traditional storage focuses on moisture control and temperature regulation to prevent deterioration. However, recent advancements offer more precise and longer-term solutions. Cryopreservation at -196°C using liquid nitrogen halts all cellular processes, enabling the indefinite storage of orthodox and recalcitrant seeds. Techniques like vitrification and encapsulation-dehydration improve survival rates post-thaw (Reed, 2008). Smart packaging materials embedded with sensors allow real-time monitoring of humidity, gas exchange, and temperature within seed containers. These sensors alert users to adverse conditions, enabling timely interventions to maintain seed quality. Moreover, active packaging with antimicrobial agents prevents fungal growth and insect damage. Such innovations ensure seed viability, vigor, and genetic stability across long storage durations, which is essential for national gene banks and seed banks. These technologies contribute significantly to global efforts toward food and genetic security in the face of climate uncertainty.

CONCLUSION

Seed science in the 21st century is at the intersection of biological innovation, data science, and engineering. Technologies like CRISPR, AI-based trait prediction, and multi-omics integration allow the precise design of seeds with enhanced traits. Nanotechnology, bio-priming, speed breeding, and smart

packaging further contribute to improving seed performance and longevity. These innovations enable the development of resilient, adaptive, and sustainable seed systems tailored for diverse agro-ecological zones. The incorporation of microbial symbiosis and artificial seed technology also supports conservation and uniform crop establishment. Collectively, these advances are positioning seed science as a cornerstone of climate-resilient agriculture and food security.

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