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Digital transformation in the seed industry: A comprehensive review on ICT-based applications

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Abstract

The global seed industry, a cornerstone of agricultural productivity and food security is undergoing a profound transformation driven by Information and Communication Technologies (ICT). This review article synthesizes the current landscape of ICT applications across the seed value chain spanning research and development to production, processing, quality control and distribution. Emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), block chain, big data analytics and digital platforms are enhancing operational efficiency, accelerating plant breeding cycles, improving traceability and fostering innovation. The article also explores the challenges associated with digital adoption including infrastructure gaps, data governance, and capacity building. Finally, it offers future perspectives on the increasingly data-driven, connected and resilient future of the global seed sector.

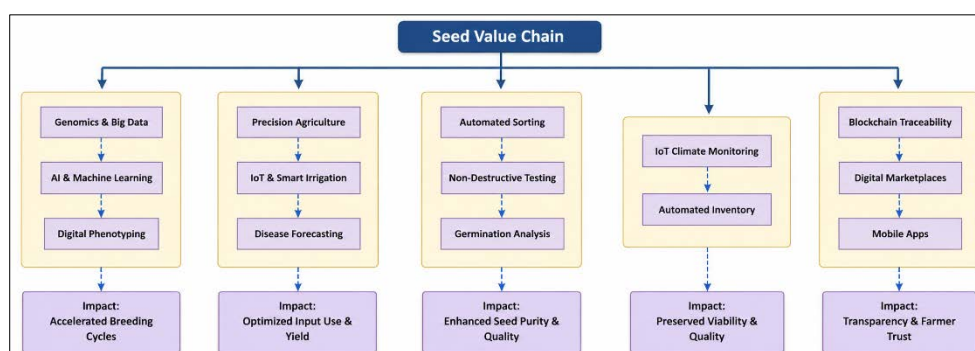
Keywords: Seed industry, ICT, Seed Value Chain, AI, block chain

Introduction

Seeds are the primary vehicle for delivering genetic advancements to farmers. The efficiency and innovation within the seed industry directly impact global agricultural output, sustainability and the ability to address challenges like climate change and population growth. Traditionally, the industry has been reliant on manual processes, extensive field trials and fragmented data management. As the demand for higher yields, climate-resilient crops and transparent supply chains intensifies the sector is increasingly turning to Information and Communication Technologies (ICT) for solutions. With advancements in ICT, the seed industry has witnessed significant transformations across various aspects of seed production, distribution, research and management. Innovations such as the Internet of Things (IoT), Artificial

Intelligence (AI), blockchain, big data analytics and digital platforms are revolutionizing the entire seed value chain from precision breeding and automated production to traceable distribution and enhanced quality assurance. This integration marks a strategic shift from traditional fragmented processes toward a "Data-centric Seed Industry" characterized by cyber-physical systems and connected intelligence. This review examines the precise role of ICT in advancing efficiency and innovation within the seed industry explores persistent challenges to adoption and envisions a future defined by predictive, sustainable and democratized seed systems.

ICT Applications across the Seed Value Chain



Research & Development (Breeding and Genetics)

This is where ICT is making some of the most revolutionary impacts, notably through the adoption of Predictive Analytics and AI-Driven Breeding.

Genomics and Big Data

Next-generation sequencing (NGS) generates terabytes of genetic data. NGS is a cornerstone technological advancement that has fundamentally reshaped the landscape of modern genomics. Its high-throughput parallel sequencing capability generates the foundational genomic data driving the digital and genetic transformation of agriculture (Goodwin *et al.*, 2016^[1]; Rhoads and Au, 2015^[2]). Within the seed value chain, NGS applications are most transformative in the research and breeding phases acting as the critical enabler for precision and acceleration. In essence, NGS is the foundational technology that generates the big data with technologies like AI and machine learning then analyze. ICT provides the computational power and cloud storage needed to manage and analyze this genomic big data. It provides the comprehensive genetic blueprint that makes data-driven breeding and digital agriculture possible.

AI and Machine Learning (ML)

Machine learning (ML) and artificial intelligence (AI) algorithms are powerful tools for deciphering the complex non-linear relationships between genotype and phenotype. By analyzing high-dimensional genomic and phenomic datasets these computational methods can identify predictive patterns and associations that are often imperceptible to traditional statistical approaches. This capability is fundamental to accelerating the discovery of genetic markers linked to agronomically important traits enabling more efficient and targeted crop breeding programs.

Machine vision technology has become a critical tool in modern agriculture enabling high-throughput, non-destructive and objective data acquisition. Its applications span numerous domains including automated phenotyping for trait selection, yield prediction, assessment of plant physiological responses to biotic and abiotic stresses and the enhancement of precision farming practices through targeted interventions (Diaz-Garcia *et al.*, 2016)^[3]. ML approaches are increasingly critical for advancing plant biology research particularly in the domain of high-throughput plant trait discovery. By leveraging complex, multi-dimensional datasets, ML models facilitate the prediction of phenotypic traits from environmental variables and the analysis of large-scale image-based and genomic data. This capability allows for the identification of complex non-linear interactions between genetic and environmental factors that influence plant growth, development and ultimate yield, thereby accelerating the breeding cycle and enhancing the precision of crop improvement programs (Mansoor *et al.*, 2025)^[4]. ML algorithms analyze vast datasets encompassing genomic, phenotypic (from digital phenotyping) and environmental data. This allows breeders to predict hybrid performance and accelerate Genomic Selection.

Digital Phenotyping

Drones and ground-based robots equipped with multispectral, hyperspectral and LiDAR sensors autonomously scan trial fields. They collect high-resolution

data on plant height, biomass, chlorophyll content and water stress phenotypes that were once measured manually. This enables high-throughput, non-destructive and highly precise trait measurement. The integration of agronomy, plant ecology and genetics through advanced plant phenotyping has emerged as a powerful framework for agricultural research. However, traditional field-based phenotypic evaluation remains a critical bottleneck, often characterized by labor-intensive processes, subjective scoring and limited throughput, which constrains scalability and data-driven discovery (Li *et al.*, 2021)^[5]. To overcome these limitations, High-Throughput Phenotyping (HTP) platforms have been developed. These systems integrate advanced sensing technologies, such as hyperspectral imaging, LiDAR and UAV-based remote sensing with sophisticated data processing techniques to automate the capture and analysis of phenotypic traits. This approach significantly enhances the efficiency, scale and objectivity of data collection while providing the distinct advantages of being non-destructive and highly reproducible (Neumann *et al.*, 2015)^[6]. The integration of advanced phenotyping technology encompassing sophisticated sensors and autonomous robotics holds immense promise for unlocking the genetic potential of plant systems (Arakeri *et al.*, 2017; Eraslan *et al.*, 2019)^[7;8]. This technological synergy effectively bridges the genotype-to-phenotype gap, providing unprecedented, high-resolution insights into plant behavior and its dynamic interactions with the environment.

Seed Production (Cultivation)

ICT enables a shift from blanket management to precision agriculture in seed production fields that will enhance seed yield and quality.

Precision Agriculture

GPS-guided tractors ensure optimal planting patterns and minimize overlaps saving inputs (Grisso *et al.*, 2009)^[9]. Variable Rate Technology (VRT) allows for the precise application of water, fertilizers and pesticides based on spatial variability within the field as mapped by drones or satellites (Zhang *et al.*, 2002)^[10]. Remote sensing technology and machine learning (ML) can revolutionize seed production by enhancing precision, efficiency and decision-making across the entire pipeline field monitoring to quality control and yield prediction (Yang *et al.*, 2017)^[11]. These tools bridge critical gaps between genetic potential and phenotypic expression enabling data-driven management at unprecedented scales. Remote sensing detects variability in water and nutrient status (Liakos, 2018)^[12].

IoT and Smart Irrigation

The integration of *in-situ* soil moisture sensors on-field weather stations and connected irrigation systems forms a closed-loop cyber-physical system that is fundamental to precision water management. This Internet of Things (IoT) framework creates a real-time feedback loop where continuous sensor data drives automated decisions or informs farm managers via digital dashboards and mobile applications (Ayaz *et al.*, 2019; Vellidis *et al.*, 2016)^[13;14]. This system enables precise irrigation applying water only when and where it is needed. This optimization is a critical factor for achieving high germination rates and vigorous seed

development while simultaneously conserving water an especially vital consideration for ensuring the sustainability and resilience of seed production in water-scarce regions (Yadav *et al.*, 2018)^[15].

Crop Monitoring and Disease Forecasting

Satellite imagery e.g., from Sentinel-2 (Segarra *et al.*, 2020)^[16] and drone data are processed using AI to monitor crop health detect pest and disease outbreaks early and even forecast their spread. This allows for targeted interventions protecting the genetic purity and yield of the seed crop.

ICT driven decision support systems enable variable-rate application of inputs maximizing resource use efficiency and seed quality. Combining time-series remote sensing data with historical climate and soil information ML models (e.g., recurrent neural networks, support vector machines) forecast seed yields with high accuracy (Van *et al.*, 2020)^[17]. This allows producers to optimize harvest scheduling, resource allocation and logistics.

Seed Processing, Quality Control, and Storage

In post-harvest management ICT ensures seed integrity, viability and traceability.

Automated Sortation and Processing

The application of computer vision and robotics in seed processing plants represents a significant advancement in post-harvest quality assurance (Armstrong and McNeill, 2019)^[18]. Automated systems utilize high-resolution cameras and sensors to capture detailed morphological and optical characteristics including size, shape, color and spectral signatures of individual seeds (Dennis and Özkaya, 2016)^[19]. AI particularly deep learning algorithms like convolutional neural networks(CNNs) is then deployed to analyze this data in real-time (Baranwal *et al.*, 2022)^[20]. These AI models are trained to recognize and classify seeds with a high degree of precision enabling robotic ejectors or air jets to automatically identify and remove damaged, diseased or genetically off-type seeds from the production lot. This automated, non-destructive method achieves a level of accuracy, consistency and speed unattainable through manual sorting dramatically enhancing the overall purity, quality and value of the final seed product.

Enhanced Quality Testing

The evaluation of seed viability and health has been transformed by non-destructive automated technologies that provide rapid, objective and highly detailed analyses. These systems move beyond traditional manual methods offering deeper insights into seed composition and physiological potential.

Automated Germination Analysis with Image Analysis

These systems utilize controlled environments equipped with cameras that capture images of seeds at regular intervals as they develop. Sophisticated image analysis algorithms often based on machine learning then process these images to track and quantify seedling growth in real-time. They automatically classify seeds as germinated or non-germinated based on radicle emergence and can even measure morphological parameters like coleoptile length. This provides a faster more consistent and less labor-intensive

alternative to manual counts eliminating human subjectivity (Hoffmaster *et al.*, 2002; Bai *et al.*, 2016)^[21;22].

Non-Destructive Seed Health and Composition Analysis

X-ray Imaging: This technology reveals the internal physical structure of a seed without damaging it. It can detect hidden defects such as insect damage, hollow seeds, physical cracks and poor embryo development, which are not visible externally (Gomes and Cicero, 2012)^[23]. This allows for the precise rejection of low-quality seeds.

Near-Infrared (NIR) Spectroscopy: NIR spectroscopy measures the absorption of light by organic compounds in the seed. By analyzing the resulting spectral signature, it can accurately predict internal chemical composition, including moisture content, oil, protein and carbohydrate levels (Ambrose *et al.*, 2016)^[24]. Furthermore, it can discriminate between viable and non-viable seeds based on their biochemical profiles.

Smart Warehousing

The preservation of seed viability and genetic integrity during storage is critically dependent on maintaining optimal environmental conditions. The IoT has revolutionized this aspect of the seed supply chain by enabling continuous real-time monitoring and automated control (Farooq *et al.*, 2019)^[25]. Networks of wireless sensors are deployed throughout storage facilities to collect data on key parameters such as temperature, humidity and carbon dioxide (CO₂) levels. This data is transmitted to a central platform where it is analyzed against pre-set thresholds. If conditions deviate from the optimal range for a specific seed lot, the system can automatically trigger climate control systems (e.g., heaters, dehumidifiers, aerators) and send immediate alerts to managers via SMS or mobile applications. This proactive approach prevents spoilage due to mold, pests or loss of viability, thereby safeguarding valuable genetic resources. Concurrently, automated inventory management systems, often integrated with these IoT platforms utilize barcode or RFID technology to track seed packets, bags or containers. This provides real-time visibility into stock levels, location within a warehouse, and movement history streamlining logistics preventing stock outs and ensuring efficient stock rotation based on viability testing dates.

Supply Chain, Distribution and Sales

This area benefits immensely from ICT through enhanced traceability, market intelligence and farmer engagement.

Blockchain for Traceability

Blockchain technology offers a transformative solution for enhancing transparency and security in the seed industry. It functions as a decentralized immutable digital ledger that records every transaction and movement of a seed bag in a tamper-proof manner. Each step in the journey from the breeder's initial variety development through production fields, processing facilities, distributors and finally to the farmer is cryptographically recorded as a unique time-stamped block. This creates a complete and verifiable chain of custody. By providing an unforgeable record of a seed's origin and path, blockchain technology ensures product authenticity effectively combats the proliferation of counterfeit seeds and builds crucial trust among all

stakeholders. Furthermore, in the event of a quality issue or disease outbreak, the technology enables precise, rapid and targeted recalls minimizing financial loss and protecting agricultural productivity.

Digital Marketplaces and E-commerce

B2B and B2C platforms connect seed companies directly with distributors and farmers. These platforms provide detailed product information, reviews and digital payment options expanding market reach and simplifying the purchasing process.

Customer Relationship Management (CRM) and Analytics

Advanced CRM systems help companies understand farmer needs, track sales trends and tailor their marketing strategies. Data analytics on sales patterns can inform production planning and inventory management reducing waste and ensuring product availability.

Mobile Applications for Extension

Seed companies develop mobile apps that provide farmers with agronomic advice, pest management tips and product information specific to the seeds they purchased. This adds value, builds brand loyalty and ensures farmers achieve the best possible yield which is the ultimate validation of seed quality.

Challenges and Barriers to Adoption

Despite the clear benefits widespread adoption faces several hurdles:

High Initial Investment: The cost of sensors, drones, AI software and IT infrastructure can be prohibitive especially for small and medium-sized enterprises (SMEs).

Data Interoperability and Standards: Data is often generated in siloed systems using different formats. A lack of universal standards hinders the seamless integration and analysis of data across platforms.

Digital Literacy and Skills Gap: The industry requires a new workforce skilled in data science, bioinformatics and remote sensing alongside traditional agronomy and breeding knowledge. Up skilling the current workforce is a significant challenge.

Data Privacy and Security: Concerns about who owns the data (from genomic sequences to farmer field data) and how it is used and protected are paramount. Robust cyber security measures are essential.

Connectivity Issues: Effective use of IoT and cloud platforms relies on stable high-speed internet connectivity which is still lacking in many rural areas where seed production occurs.

Future Perspectives

The convergence of ICT with biology will continue to deepen. Future trends include:

The Rise of Digital Twins: Creating virtual replicas of

breeding programs, production fields or entire supply chains to simulate scenarios optimize processes and predict outcomes without real-world risks.

AI-as-a-Service (AIaaS): More accessible cloud-based AI platforms will lower the barrier to entry for smaller companies to leverage predictive analytics.

Advanced Gene Editing guided by AI: AI will not only predict traits but also help design optimal gene editing strategies for *CRISPR* and other technologies.

Hyper-Personalized Seeds: Using data on a specific farm's soil, micro-climate and management practices companies could recommend or even develop bespoke seed varieties tailored for maximum performance on that individual farm.

Conclusion

ICT is no longer ancillary to the seed industry; it is becoming its central nervous system. By weaving digital technologies into every link of the value chain the industry is achieving unprecedented gains in efficiency, speed and precision. From AI-accelerated breeding that delivers climate-resilient varieties faster to blockchain-secured supply chains that guarantee authenticity. ICT is empowering the seed sector to meet the daunting challenges of 21st century agriculture. While challenges related to cost, skills and data governance remain the trajectory is clear: the future of seeds is digital, data-driven and deeply connected. Embracing this digital transformation is imperative for any seed company aiming to remain competitive and fulfil its mission of nourishing a growing world.

Declaration of AI use

The authors used ICT tools to improve the language, grammar, readability and overall presentation of the manuscript.

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