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The Convergence of Seed Systems and Digital Technologies : Implications for Quality Food Production in South Asia

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ABSTRACT

This in-depth review takes a closer look at the blending of seed systems and digital technologies, with a specific focus on South Asia and India. With the ever-growing global population, increasing food demand, and environmental concerns, the integration of digital technologies like Information Technology (IT), Artificial Intelligence (AI), and block chain into seed systems offers a unique opportunity for sustainable agricultural intensification. In this review, we carefully examine existing research, regional case studies, and technological developments to develop a wide-ranging framework for understanding the impact of this convergence on agricultural productivity, food quality, and overall sector resilience. Furthermore, we shed light on the challenges that come with adopting these technologies and propose potential solutions, stressing the importance of inclusive approaches and digital literacy among small-scale farmers. Our aim with this review is to ignite educated dialogue, influence research and policy, and position the convergence of digital technologies as a vital catalyst for transforming agriculture in South Asia and enhancing food security.

Keywords : Seed systems; Digital technologies; Sustainable agriculture; Food security; South Asia; Agricultural productivity

Introduction :

The global population is rapidly growing, and as result, there is an increasing demand for food. By 2050, it is projected that the world's population will exceed 9 billion, which means there needs to be a 60-70% increase in food production (UN DESA, 2019). This is a pressing issue, particularly in South Asia and India, where agriculture contributes to 18% of GDP, yet hunger, malnutrition, and environmental degradation persist (FAO, 2019). It is crucial to find innovative approaches that can enhance agricultural productivity while maintaining sustainability and nutrition.

Seeds play a critical role in agriculture as they determine the species cultivated, their productivity, and the quality of the food produced (Scoones & Thompson, 1994; Sumberg& Thompson, 2012). While traditional seed systems have supported

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diverse crops adapted to local environments and improved community food security (Jarvis *et al.,* 2011), modern formal seed systems have resulted in genetic uniformity, leading to concerns about genetic erosion (Maxted*et al.,* 1997). This highlights the need for an integrated seed system that combines traditional and formal approaches (Louwaars & de Boef, 2012; Sthapit *et al.,* 2016).

Digital technologies such as IT, AI, and blockchain are emerging as transformative forces in addressing agricultural challenges (Johnson & Zhang, 2019; Li *et al.,* 2023). These technologies, including sensors, predictive analytics, and automation, are revolutionizing agriculture (Dhanaraju*et al.,* 2022; Semaniuk& Melnyk, 2022). However, challenges such as infrastructure limitations and investment gaps, particularly in South Asia, hinder their widespread adoption (Lal, 2015; Dziatkovskii, 2022).

The integration of seed systems with digital agriculture is a relatively unexplored area in scholarly literature. This integration presents an opportunity to enhance productivity, sustainability, and food quality in South Asia. This review aims to systematically analyze literature on seed systems, digital agriculture, and regional case studies to develop an integrated framework. It seeks to address the limitations in existing literature and define future research agendas. This analysis is timely as it aligns indigenous seed expertise with data-driven solutions to tackle the challenges posed by climate change and resource scarcity. The goal is to promote essential scholarship and dialogue that contribute to agricultural development and food security in South Asia and globally.

Digital technologies in Indian agriculture : Progress and barriers

Digital technologies, including precision farming, data analytics, and blockchain, are transforming agriculture globally (Fernandez *et al.,* 2021). India, being a pioneer in IT adoption for agriculture, has made significant advancements. From AGMARKNET and IKSL to smart apps used by a third of its farmers, India has embraced technology (Singh & Surendra, 2022; Tiwari *et al.,* 2022). Remote sensing and AI are now utilized for pest management on over 50 million hectares, and platforms like e-NAM have integrated over 1000 markets (Krishnan *et al.,* 2021). However, challenges such as awareness, infrastructure, and digital literacy gaps hinder technology adoption, especially among marginalized groups such as smallholder and women farmers (Lal, 2015; GoI, 2021; Sonkar & Murthy, 2022).

To fully leverage digital agriculture, it is essential to adopt a comprehensive approach that involves community participation, infrastructure enhancement, and digital skills development for smallholders (Dhanaraju *et al.,* 2022; Tiwari *et al.,* 2022). While the policy focus on digital agriculture is evident with initiatives like the “Digitizing the Agriculture Sector” mission, more multidisciplinary research is needed to effectively integrate digital technologies in this field.

The integration of IT and AI into seed systems holds significant potential for improving agricultural efficiency,

productivity, and sustainability. However, there is a noticeable lack of comprehensive literature on this convergence, particularly in South Asia and India. This paper seeks to fill this gap by focusing on the current state of seed systems in South Asia, the integration of digital technologies, their impact on agricultural productivity and food quality, and providing insights and policy recommendations.

Scope

The proposed review primarily focuses on South Asia, with a special emphasis on India. South Asia, known for its diverse agro-ecological zones and a wide range of cropping systems, provides a unique perspective for studying agricultural practices and innovations. Within this context, India offers an extensive canvas for analysis due to its significant agricultural sector, which plays a vital role in the nation's economy and the livelihoods of a large proportion of its population. India's diverse climatic zones and varied agricultural practices, ranging from traditional subsistence farming to technology-driven agriculture, make it an ideal case study. This geographical focus allows for a nuanced understanding of the challenges and opportunities specific to the region, providing insights that are locally grounded and broadly applicable to similar contexts in South Asia.

Rationale

The need for sustainable and high-quality food production is more urgent than ever in the face of escalating global challenges. South Asia, particularly India, is at a critical juncture where the increasing demands of a growing population clash with the constraints posed by climate change and depleting natural resources. The agricultural sector in this region is particularly susceptible to the impacts of climate variability, exacerbating existing challenges related to water scarcity, soil health, and crop productivity. These challenges are further compounded by socio-economic factors such as small landholdings, limited access to quality seeds, and inadequate technological resources. Therefore, exploring the integration of seed systems and digital technologies has the potential to revolutionize agricultural practices, leading to more sustainable and efficient methods of food production that can contribute significantly to food security and agricultural resilience in the face of these challenges.

Seed systems in South Asia : An overview

Seed systems in South Asia exhibit a fascinating combination of traditional and formal approaches, each with its unique characteristics and challenges.

Traditional seed systems

Central to South Asia's agricultural heritage, traditional seed systems rely on farmer-saved seeds and local varieties. These systems play a crucial role in preserving agricultural biodiversity and traditional agricultural knowledge (Vernooy *et al.,* 2019). While they support genetic diversity and adaptability, traditional seed systems face challenges such as lower yields, vulnerability to pests and diseases, and genetic erosion as farmers shift to commercial options (Jarvis *et al.,* 2011; Spielman *et al.,* 2017; FAO, 2019).The reliance on traditional seed systems in South Asia has historically provided resilience and nutritional

security. However, it has been disrupted by the push towards commercial hybrids during the Green Revolution, leading to significant genetic erosion.

Formal seed systems

In contrast, the formal seed system in South Asia involves the commercial seed sector, research institutions, and government agencies. Its primary focus is on improved seed varieties, including hybrids and genetically modified organisms (GMOs). This system has had a profound impact on South Asian agriculture, particularly with the introduction of high-yielding varieties during the Green Revolution (Spielman *et al.,* 2017). However, concerns regarding the high cost of seeds, input needs, and issues related to seed quality and accessibility persist, especially for smallholder farmers (Tripp, 2001).

Both traditional and formal seed systems face challenges that need attention. Genetic erosion, particularly in the context of climate change, poses a significant threat (Fowler & Hodgkin, 2004). In traditional systems, issues like low germination rates and disease susceptibility due to a lack of quality control are prevalent. Access to quality seeds remains a barrier, with improved and adaptable seeds often being unaffordable for smallholder and marginal farmers (Tripp, 2001). Socio-economic factors, including land tenure, market access, and education levels, further influence the adoption of new varieties, often putting smallholder farmers at a disadvantage (Morris *et al.,* 1998).

In response to these challenges, experts advocate for a balanced approach that leverages both traditional and formal seed systems. This includes the establishment of community seed banks in India and contributions from both the private and public sectors. The aim is to address the needs of farmers who still rely on informal seed sources (Scoones & Thompson, 2011; Sthapit *et al.,* 2016; Chand, 2020).

Digital technologies in agriculture

Digital technologies are revolutionizing agriculture, significantly enhancing productivity, sustainability, and resource management. The integration of Information Technology (IT), Artificial Intelligence (AI), and the Internet of Things (IoT) is fundamentally altering agricultural practices.

i) Information Technology (IT) in agriculture

IT applications in agriculture encompass various tools and systems that offer efficient planning, monitoring, and management capabilities. Farm management software, such as Cropio and FarmLogs, assist farmers with real-time data on soil health, crop conditions, and market trends. Additionally, traceability systems that utilize blockchain technology ensure transparency and accountability from farm to table, contributing to food safety and quality (Bronson & Knezevic, 2016; Kamilaris *et al.,* 2019).

ii) Artificial Intelligence (AI) in agriculture

AI is playing a transformative role in agriculture through predictive analytics and machine learning algorithms. Predictive tools help forecast weather patterns, pest infestations, and diseases,

while machine learning optimizes crop selection and genetic breeding. Platforms like Plantix and Agrosmart utilize AI to determine the best crop choices based on environmental factors, enhancing yield predictions, and fostering the development of climate-resilient crops (Liakos *et al.,* 2018; Ghosh *et al.,* 2019). Recent examples of AI in agriculture include the work of Fraisse *et al.* (2022), AI Tool Advisor (2023), Gupta *et al.* (2022), and Intel (2021).

iii) Internet of Things (IoT) in agriculture

The integration of Internet of Things (IoT) and Artificial Intelligence (AI) in agriculture is transforming the sector in Asia. In India, IoT-based smart farming systems are increasingly adopted, using sensors for soil moisture and nutrients, coupled with AI for predictive analysis of crop needs (Vijaya *et al.*, 2022). AI-powered drones are used for crop monitoring and precision agriculture, significantly improving yield and resource efficiency (WEF, 2021).Integration with drones and satellite imagery further enhances crop health assessment and targeted interventions (Wolfert *et al.,* 2017).

Innovative applications of digital technologies

India : Microsoft's Project FarmBeats and IBM's Watson Decision Platform for Agriculture are transforming agriculture in India. By combining AI, IoT, and weather data, these technologies enhance crop yields, reduce costs, and enable comprehensive farm management. These innovative solutions are revolutionizing the way farmers operate (Gupta *et al.,* 2022).

Netherlands : Lely's Astronaut A5 is showcasing the potential of IoT in dairy farming optimization. With advanced data analytics and real-time monitoring, farmers can optimize their operations, improve efficiency, and ensure sustainable dairy production. The integration of digital technologies is reshaping the future of the dairy industry (Gupta *et al.,* 2022).

a) Digital Seed Tracking and Tracing System (STTS) in Uganda

Uganda has implemented a groundbreaking digital system called the Seed Tracking and Tracing System (STTS). This system comprises a centralized database, web platform, and mobile app, streamlining seed tracking and tracing processes. It has revolutionized the agricultural landscape by providing real-time seed availability information to farmers and simplifying online processes for seed growers, leading to expanded markets and reduced costs (ISSD Uganda, 2020).

b) Early Generation Seed (EGS) demand dorecasting dystem in Ayeyarwady Delta

In the Ayeyarwady Delta, an innovative Early Generation Seed (EGS) Demand Forecasting System has been implemented. This system, consisting of mobile apps and a web platform, has greatly improved the efficiency of seed ordering and EGS allocation. As a result, production volumes and overall operations have been enhanced, benefiting both farmers and seed suppliers (Gupta *et al.,* 2020).

Response to the COVID-19 pandemic

The COVID-19 pandemic has posed unprecedented challenges to the agricultural sector. However, it has also accelerated the adoption of digital

solutions. Efforts in Myanmar and Nigeria have exemplified this shift, with technologies like Seed Tracker™ and Seedcodex being employed to ensure efficient EGS utilization and subsidized EGS supplies. By leveraging digital tools, the agricultural industry has been able to adapt and overcome the challenges presented by the pandemic (Gupta *et al.,* 2022).

These diverse initiatives demonstrate the transformative impact of digital technologies in agriculture. From improving seed systems to enhancing supply chain efficiency, these innovations are shaping the future of farming.

The convergence: Seed systems and digital technologies

The integration of digital technologies into seed systems represents a significant milestone in the field of agriculture. This convergence has greatly enhanced the efficiency and productivity of the entire seed value chain, from variety development to certified seed utilization (Fig 1).

Variety development and variety uptake

Cutting-edge platforms, like Benson Hill's Crop OS, leverage the power of AI and machine learning to accelerate the development of resilient and high-yielding crop varieties. By analyzing genetic and environmental data, these platforms revolutionize the process of variety development, ultimately leading to improved agricultural productivity. Furthermore, digital methods such as crowdsourcing trials and remote sensing contribute to enhanced data quality and real-time monitoring of variety performance (van Etten *et al.,* 2017; Ray *et al.,* 2019).

Seed multiplication and production

In the territory of seed multiplication and production, IoT and AI play pivotal roles. These technologies monitor growing conditions, ensuring the production of superior quality seeds. By providing real-time data on soil and environmental conditions and predicting pest outbreaks, IoT and AI enable precision agriculture, revolutionizing seed production. Additionally, digital demand forecasting tools optimize seed production planning, further enhancing efficiency (Gupta *et al.,* 2020).

Distribution and usage

Digital platforms have transformed the way seeds are distributed and utilized. Farmers now have access to a wide range of diverse seed varieties and essential cultivation information. Automated and digitized inventory management systems, such as ABS (https://agrosolutions.nl/) , streamline the entire process from seed plant to end-user. These multi-modal tools offer quality assurance, package tracking, and inventory approval systems, eliminating errors and reducing paperwork. Digital advisory services and precision farming tools also optimize the use of certified seeds, ensuring effective sowing and cultivation practices (Cropin, n.d).

Challenges in the seed value chain

Despite the numerous benefits brought about by digital technologies, the seed value chain still faces challenges. Conventional cultivation practices and biotic and abiotic stresses can distort

demand and disrupt the efficiency of the system. The existence of an inefficient marketing system is evident in the significant price spread from farm gate to end-user, indicating the need for further improvements.

Strategic framework for digitalization

To address these challenges, a strategic framework for digital intervention in the seed value chain has been developed. This framework identifies key stages where digital technologies can be leveraged to enhance traceability, efficiency, and quality. From genetic resource management to marketing and distribution, digitalization promises to revolutionize every aspect of the seed value chain. Technologies like digital genebank databases, blockchain, IoT, and AI are driving this comprehensive digital transformation, improving data accessibility, breeding program efficiency, seed processing, and sales tracking (Gupta *et al.,* 2022).

The integration of digital technologies within seed systems is shaping the future of agriculture. With enhanced efficiency, traceability, and sustainability, the seed value chain is becoming more resilient and productive. The transformative impact of technology in agriculture is undeniable, paving the way for a more sustainable and food-secure future.

Exemplifying digital agriculture initiatives in India

India's Digital Agriculture (DA) initiatives from 2021 to 2025 are revolutionizing the agricultural landscape by integrating cutting-edge digital technologies. This transformative approach aims to enhance efficiency, productivity, and sustainability in the agricultural sector. Let's delve into the key elements of these initiatives and explore their implications for the seed sector and quality food production.

Key elements of India's digital agriculture initiatives

Digital Agriculture Mission 2021-2025: Spearheading innovation, the Digital Agriculture Mission collaborates with industry leaders, including Cisco, Ninjacart, and Jio Platforms Limited. By integrating advanced technologies, such as AI, blockchain, remote sensing, and drones, into agricultural practices, this mission paves the way for a technologically empowered farming community (Press Information Bureau, Government of India, 2021).

Agri-tech Startups : Over 1,000 startups, backed by venture capital, are making significant strides in reshaping agricultural practices. These startups introduce innovations like mobile apps and e-commerce services, bridging the gap between technology and farming (NASSCOM, 2019).

NITI Aayog and IBM Collaboration: Joining forces, NITI Aayog and IBM focus on leveraging AI to enhance crop yields and soil quality through real-time data and valuable insights (NITI Aayog, 2023).

Cisco's Agricultural Digital Infrastructure (ADI): Cisco's ADI plays a vital role in knowledge exchange and farming efficiency as part of the National Agri Stack. By providing a robust digital infrastructure, it facilitates seamless

integration of technology into agricultural practices (Krishak Jagat, 2020).

Jio Agri Platform : Reliance Jio's Agri Platform, launched in 2020, is a game-changer for farmers. Leveraging data and AI algorithms, it offers tailored advice to optimize farming practices for higher productivity and profitability (Reliance Jio, 2020).

Microsoft's Unified Farmer Services Interface: Microsoft's innovative program employs AI and sensors to empower farmers with improved price management and enhanced yield. By harnessing the power of technology, it streamlines agricultural operations (Microsoft India, 2019).

Sensor-based Smart Agriculture (SENSAGRI): The government's SENSAGRI program utilizes drones for efficient land scouting and provides real-time data. This technological marvel enhances agricultural decision-making and optimizes resource allocation (Ministry of Agriculture & Farmers Welfare, 2020).

DeHaat: As an exemplary agri-tech startup, DeHaat demonstrates the transformative potential of digital tools in agriculture. It enables the transition from manual to AI-enabled technologies, empowering farmers to achieve unprecedented growth and efficiency (DeHaat, 2021).

Challenges, solutions, and implications

Challenges

Implementing Digital Agriculture in India poses several challenges that need to be addressed for widespread adoption and success. These challenges include :

- **Limited digital infrastructure**
- **Low digital literacy among farmers**
- **Data management issues**

Solutions

To overcome these challenges, the Indian government has implemented policies that support infrastructure development and capacity building. Platforms like AgriStack (deHaat) play a key role in providing comprehensive solutions, including soil health assessments, crop advisories, and market intelligence. These initiatives aim to bridge the digital divide and ensure that all farmers can benefit from digital agriculture advancements.

Implications for the seed sector

While the seed sector's specific tools are not explicitly identified in these initiatives, the broader Digital Agriculture initiatives have a significant impact. Collaborations between startups, technology platforms, and research organizations are crucial in driving innovation and transformation in the seed sector. These alliances pave the way for advanced research, development of improved seed varieties, and sustainable seed production practices.

Transforming quality food production

The integration of digital technologies in seed systems revolutionizes agriculture, transforming productivity, sustainability, and quality assurance in food production.

Enhanced productivity

Digital tools in seed systems facilitate precise plant breeding and seed selection. AI-driven predictive analytics identify promising plant varieties and analyze their

responses to environmental conditions. Digital phenotyping tools accurately measure plant characteristics, expediting the selection of high-yield traits. Furthermore, IoT devices used in precision agriculture optimize crop productivity by adjusting field conditions (Hickey *et al.,* 2019; Cobb *et al.,* 2019; Wolfert *et al.,* 2017).

Sustainability

Digital tools like GIS and remote sensing technologies play a crucial role in better land use planning, ensuring ecological balance and sustainable resource utilization. They provide accurate data on soil health, enabling precise application of fertilizers and pesticides, thus minimizing environmental impact. Moreover, these technologies foster climate-smart agricultural practices, such as solar-powered irrigation, effectively reducing farming operations' carbon footprint (Ray *et al.,* 2019; Savary*et al.,* 2020). Crop variety deployment using crowdsourcing tools and digital post processing helps select the crop varieties best adapted to a certain agroclimatic, soil and other parameters, this feed in to the sustainability component (van Etten *et, al.*, 2019; de Sousa*et al.,* 2021).

Quality assurance

Blockchain technology plays a pivotal role in ensuring traceability in the food supply chain, enhancing transparency and quality control from seed production to consumption. Machine learning algorithms predict quality issues, enabling proactive quality management in food production (Kamilaris *et al.,* 2019; Liakos *et al.,* 2018).

India's Digital Agriculture initiatives are driving a revolution in the agricultural sector by harnessing the power of digital technologies. By addressing challenges, fostering collaborations, and embracing innovation, these initiatives hold the potential to shape a sustainable and technology-driven future for Indian agriculture.

Policy recommendations and future directions

Creating an environment that fosters digital agriculture (DA) requires the implementation of comprehensive regulatory frameworks that strike a balance between promoting innovation, protecting data privacy, and ensuring fair competition. To achieve this, governments should take on the roles of regulation and facilitation, while also providing incentives for the adoption of DA technology. On the other hand, the private sector should be responsible for driving innovation and disseminating technology. Moreover, involving farmers in the co-creation of digital solutions is crucial to ensure their relevance and effectiveness (Carolan, 2016; Bronson &Knezevic, 2016; European Commission, 2020; Jain *et al.,* 2020; Rose *et al.,* 2018).

Future research and directions

Moving forward, it is important to direct research efforts towards developing affordable and accessible digital tools specifically tailored for smallholder farmers. Additionally, assessing the socio-economic impacts of DA and studying the sustainable scaling of these technologies should be prioritized. It is crucial to invest in research and development to explore the

life-cycle impacts of these technologies on the environment, as this will essential for the responsible growth of both digital agriculture and seed systems (Fielke *et al.*,2020; Lowder*et al.,* 2017; Robertson *et al.,* 2017).

By collectively working towards launching robust regulatory frameworks, fostering inclusive stakeholder engagement, and conducting targeted research, we can ensure that advancements in digital agriculture align with global food security goals and environmental conservation.

Conclusions

This comprehensive review takes a plunge into the integration of digital technologies into seed systems within South Asian agriculture, with a particular focus on South Asia / India. The review uncovers both the immense potential and significant challenges associated with this technological revolution.

Digital tools such as Information Technology, Artificial Intelligence, and blockchain hold the promise of revolutionizing agricultural productivity, improving food quality, and enhancing the resilience of the sector. This, in turn, contributes to sustainable agricultural intensification in a region that plays a critical role in global food security.

However, the path towards digitalization in South Asian agriculture is not without its challenges. Limited digital literacy among farmers, infrastructural inadequacies, and socio-economic disparities are all significant barriers to technology adoption. Of particular concern is the disparity in digital resource access and the absence of tailored solutions for smallholder farmers.

To ensure successful integration of digital technologies into South Asian seed systems, a collaborative and inclusive approach is necessary. Policymakers play a crucial role in creating an enabling environment through appropriate policies and investments in digital infrastructure. Education systems and NGOs are key players in improving digital literacy and ensuring the inclusion of smallholder farmers in this digital revolution. The private sector must focus on developing context-specific, user-friendly, and affordable digital solutions, while research institutions should prioritize collaborative initiatives that align technological advancements with practical agricultural needs.

To evaluate the impact of digital interventions and refine successful models, robust monitoring and evaluation frameworks are essential. The digital transformation of South Asian seed systems requires the combined efforts of all stakeholders. By addressing the existing challenges and leveraging regional strengths, there is a significant opportunity to catalyze transformative impacts on food security, sustainable agricultural practices, and economic development in South Asia.

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Figure 1 : Strategic framework for embedding digital technologies within the seed value chain, mapping out key stages for potential digital interventions