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Innovations in Agricultural Inputs and Services Markets in India: A Pathway to Sustainable Agricultural Growth*

Shalander Kumar[1]

ABSTRACT

The evolution and adoption of innovations in agricultural input and services markets (AI-SM) have been among the primary drivers of agricultural growth and development. Facing increasing challenges, including climate change, market volatility, global supply chain disruptions, and unsustainable farming practices alongside emerging opportunities from digital technology advances, innovation in AI-SM has become essential for achieving sustainable farming and food systems. This paper provides a comprehensive analysis of AI-SM and related innovations, emphasizing their critical role in promoting sustainable agriculture and food systems. It examines the mechanisms, institutions, and service provisions that can facilitate access to agri-input technologies, including advances in seeds, machinery, fertilizers, bio-inputs, livestock services, climate services, and data-driven digital tools and innovations, to enhance productivity, income, and environmental sustainability. The paper also analyses smallholder farmers' challenges in accessing AI-SM through current public and private delivery systems, identifying possible strategies for overcoming the barriers. It also explores policy pathways to leverage emerging digital technologies to improve farmers' access to high-quality agri-inputs and services, thereby supporting current and future farming systems focused on increasing farm incomes, resilience, and long-term sustainability. This paper seeks to promote inclusive and sustainable farming and food systems that can meet global food demands while conserving natural resources by offering practical insights for policymakers, investors, and agricultural practitioners.

Keywords: Agricultural input markets, agri-tech Start-ups, digital agriculture, sustainable farming systems, policy innovation

JEL codes: Q16, Q18, Q55, O13, O33

I

INTRODUCTION

The global population is projected to reach approximately nine billion by 2050, necessitating a 70 per cent increase in food production to meet demand (FAO, 2017). Concurrently, climate change is exerting additional stress on already-depleted natural resources, exacerbating the vulnerabilities inherent in resource-intensive agricultural sectors (IPCC, 2018). Sustaining food production worldwide will require innovations that enhance the agri-food system's climate resilience, sustainability, and associated livelihoods. A primary pathway for achieving this is expanding access to quality agricultural inputs and services supporting sustainable practices, such as resilient seeds, appropriately scaled mechanization, renewable energy sources, integrated nutrient management, biological inputs, and animal husbandry services. Additional technological advances, including decision support systems, can help optimize farming decisions across enterprise selection, input utilization, and market access. Supporting

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[1]Deputy Global Research Program Director: Enabling Systems Transformation & Cluster Leader: Markets, Institutions and Policies, International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, India.

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services—such as agricultural credit, insurance, market outlooks, context-specific climate information, and technology dissemination—play a pivotal role in facilitating the adoption of improved technologies and sustainable practices. However, adoption rates for quality inputs and innovative solutions remain far lower than necessary. Fertilizer and pesticide use is frequently unbalanced and unscientific, adversely impacting environmental health, soil quality, farmers' incomes, and export opportunities. In India, public and private extension systems focus primarily on a limited number of major agricultural commodities, neglecting diverse crops and diminishing the sector's overall performance. Furthermore, innovations in agricultural inputs and service markets must align with emerging agri-food system priorities, which emphasize climate-resilient and regenerative agriculture, carbon farming, circular economy principles, gender-sensitive and nutrition-focused food systems, urban farming, and farmer-led agribusiness initiatives through Farmer Producer Organizations (FPOs). Digital innovations, including artificial intelligence (AI), machine learning (ML), and drone technologies, offer unprecedented opportunities to revolutionize agri-input and service markets, enhancing productivity, reducing transaction costs, promoting sustainability, and increasing farmers' incomes. However, mainstreaming these advancements requires targeted policy and institutional support (OECD, 2018). Timely and affordable access to these innovations is crucial for fostering agricultural growth, meeting rising food demands, and improving farmers' livelihoods.

A significant proportion of the world's food production comes from smallholder farmers who frequently lack access to essential, affordable technologies, timely farm management information, risk-mitigating insurance, and financial resources to invest in their operations (World Bank Group, 2019). Inadequate agri-input and service markets limit farmers' access to necessary innovations. With the added challenges of climate change, resource degradation, youth alienation from agriculture, and supply chain disruptions, access to modern agri-inputs and services has become increasingly critical for fostering sustainable, technology-driven agricultural growth. Public extension systems prioritize food security and major commercial crops, while traditional private sector initiatives focus on high-potential regions and farming systems. Consequently, low-productivity and vulnerable regions face limited access to Agricultural Inputs and Services Markets (AI-SMs). In India, for example, tribal areas, neglected traditional food commodities, small ruminants, and drier agro-ecologies receive disproportionately lower access to AI-SMs. Such disparities are also seen globally; poorer access to agri-inputs and services in Sub-Saharan Africa than in Asia has led to slower agricultural production growth and farmers' incomes (Adesina *et al.*, 2014). Policies emphasizing food security around a limited range of crops, alongside the revenue-driven focus of private enterprises, have stifled the availability of diverse inputs needed for sustaining traditional local food systems, negatively impacting ecosystem services, resilience, and nutritional outcomes. Addressing these gaps presents opportunities to improve AI-SM access and drive inclusive, technology-led agricultural development. This need also creates a space for non-traditional players, such as agri-tech Start-ups, to offer innovative, context-specific solutions for varied agro-ecologies. In 2018, for instance, agri-food tech Start-ups globally attracted $16.9 billion in venture capital, marking a 43 per cent increase over the previous year (Defrance, 2019). Bridging these gaps is essential for enabling smallholder farmers to fully engage with and benefit from agricultural innovations, equipping them with the necessary inputs, tools, information, and financial backing to enhance productivity and sustainability. Such initiatives hold immense potential for advancing food security and economic stability in rural areas. Thus, directing the efforts of governments, innovators, investors, and the private sector toward addressing key agricultural challenges, fostering inclusive livelihoods across the agri-food value chain, and promoting sustainable practices represents a significant and timely opportunity (Goedde *et al.*, 2020).

Enhancing access to agricultural inputs and services through innovation is critical in promoting sustainable agriculture by increasing efficiency, productivity, farmers' incomes, and environmental stewardship (FAO, 2018; OECD & FAO, 2020). Access to reliable support services and quality inputs strengthens farming resilience while lowering transaction costs for farmers and other value chain participants (World Bank, 2019). Technological advancements, including high-quality inputs, sustainable farming practices, and access to finance and risk management tools, are pivotal for driving productivity, resilience, profitability, and sustainability within farming systems (IFPRI, 2019; OECD & FAO, 2020). However, widespread adoption of these innovations is contingent upon timely, affordable, and inclusive access to agri-inputs and services, underscoring the importance of effective policy and institutional support (World Bank, 2019; FAO, 2018).

Therefore, this paper contributes to the existing literature by presenting a comprehensive analysis of the evolution, recent advancements, and future trends in agri-input technologies and services within the context of transforming agri-food systems. It provides actionable insights for policymakers, researchers, investors, and agricultural practitioners. Following this introduction, the next section provides an overview of the dynamics of agri-input use and its possible association with agricultural productivity, followed by an exploration of the evolution of agri-inputs and service delivery mechanisms. The subsequent section discusses the relevance and challenges of conventional agri-inputs and services markets. The following section discusses trends in innovations in agri-input and services markets and delivery systems. Emerging priorities, policy recommendations, and conclusions are then presented, highlighting the need for continued innovation and strategic policy support to achieve sustainable agriculture.

II

DYNAMICS OF VARIED AGRI-INPUTS USE AND SERVICES AND AGRICULTURAL PRODUCTIVITY

Access to appropriate agricultural inputs and services is vital for adopting tailored technologies and innovations that boost productivity, resilience, and farm profitability. Effective policies and institutions foster science-driven innovations, raise farmers' awareness, and structure functional markets and public institutions are key to facilitating access to necessary agri-inputs and services. This access significantly influences technology adoption, productivity, and broader agricultural development outcomes (Aich *et al.*, 2022; Goyal & Nash, 2017; Hemming *et al.*, 2018; Pathak, 2019; Sheahan & Barrett, 2017). Limited access to these inputs and services often results in agricultural productivity that falls short of its potential, with especially severe consequences in regions like Sub-Saharan Africa, which missed much of the Green Revolution's benefits (Adesina *et al.*, 2014). Furthermore, many agricultural innovations achieve sustainable impacts when introduced as bundled solutions. For instance, implementing a new crop or cropping system or adopting conservation agriculture requires access to quality seeds of adapted varieties, appropriate machinery, credit facilities, markets for new commodities, and technical support during initial stages to ensure successful adoption. Without adequate access to these inputs and services as bundled solutions, even farmers who adopt recommended technologies may experience sub-optimal outcomes and significant yield gaps (Nayak *et al.*, 2022; Sendhil *et al.*, 2014; Snyder *et al.*, 2016). Also, an analysis of agricultural trends across Indian states and districts (Figure 1) reveals considerable regional variation in input use, including nitrogen, phosphorus, and potassium (NPK) application rates, pesticide use, the availability of farm machinery, and veterinary services. Productivity trends for major crops (Figure 2) similarly exhibit high variability, with noticeable yield gaps across districts in India. These data suggest crop yields strongly correlate with input use levels and access to agri-services. Multiple factors likely influence access to these resources, including the development of functional and inclusive markets. Consequently, examining the specific drivers of functional, inclusive markets for agricultural inputs and services can help shape strategies for scaling context-specific, improved agricultural technologies.

III

EVOLUTION OF AGRI-INPUTS AND SERVICE MARKET

The agricultural inputs and services market has evolved significantly, progressing from basic, traditional practices to a technologically advanced industry. Understanding this evolution is essential for contextualizing current innovations and assessing advancements in productivity and sustainability.

Historically, agriculture was largely subsistence-based, with farmers relying on simple tools and natural cycles (Lal *et al.*, 2007; Galloway *et al.*, 2013). Crop rotation and rudimentary irrigation techniques were among the few practices that improved productivity (Yoder, 1994; White, 1970). Inputs consisted primarily of seeds saved from previous harvests and organic fertilizers like manure (Harrington & Kozlowski, 1972; Parr & Hornick, 1992).

A major shift occurred during the 18th-century Agricultural Revolution (Van Bath, 1969) when innovations such as Jethro Tull's seed drill, advanced crop rotation methods, and selective animal breeding significantly increased productivity. This era emphasized scientific methods in farming, laying the foundation for modern agricultural practices.

The mid-20th and early 21st centuries marked another critical phase in agricultural history, often called the Green Revolution (Evenson & Gollin, 2003; Pingali, 2012). This period introduced diverse, sophisticated agricultural inputs designed to enhance farming efficiency and sustainability. Today's agricultural inputs include improved seeds, scale-appropriate machinery, chemical and biological products, digital innovations, veterinary services, and guidance on soil health, livestock management, and post-harvest practices. These advances have enabled farmers to tackle low yields, biotic and abiotic stresses, climate change impacts, soil degradation, and nutritional insecurity while enhancing livelihoods and income. Further, agricultural inputs and service delivery have also transformed over time, with extension systems playing a central role. Extension programs—encompassing public, private, and informal initiatives—have supported farmers through knowledge dissemination, training, and technical assistance. Public extension programs, traditionally the cornerstone of agricultural support, have focused on disseminating agricultural technologies and promoting best practices through initiatives traditionally government-funded that have contributed to improved food security and rural development. Additionally, during India's Green Revolution, public extension initiatives such as Krishi Vigyan Kendra (KVKs)- the farm science centres and agricultural cooperatives enabled farmers to access improved seeds, fertilizers, pesticides, farm machinery, and knowledge on best agronomic practices and soil and water conservation. In livestock farming, public services promoted artificial insemination and health care for cattle. The poultry sector saw significant contributions from the private sector, which adopted contract farming models to support farmers and increase productivity.

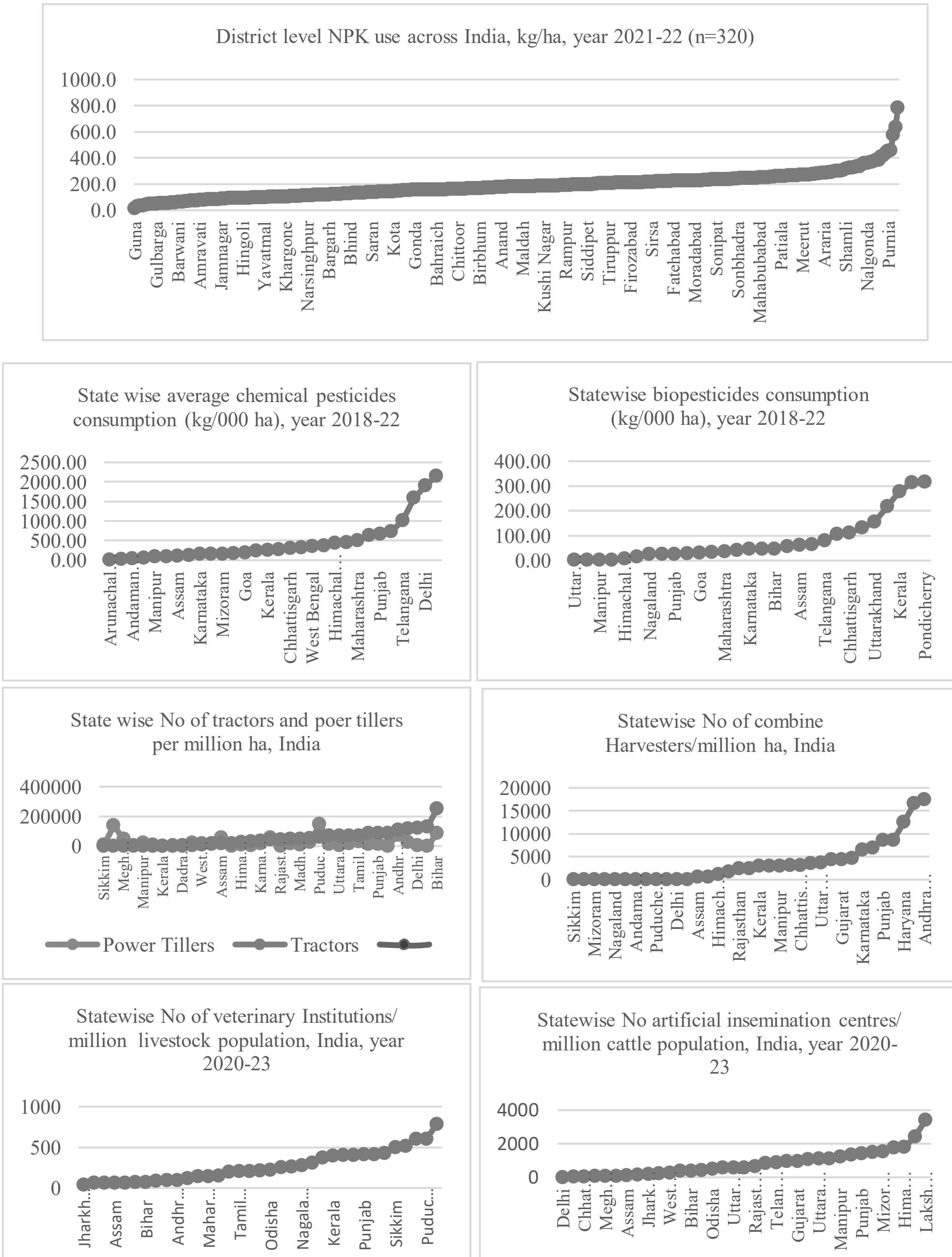

Figure 1: Trends in key agricultural inputs use and availability of infrastructure/services across districts and states, India

Source: Author's calculations based on several published secondary data

The increasing penetration of smartphones in the villages in recent years has improved farmers' access to information, especially climate forecasts and, in some cases, market information. Several KVKs and other institutions have started providing climate information and advisories through SMS and WhatsApp. However, systematic efforts are needed to harness the power of smartphones to promote data-driven decision-making in agriculture.

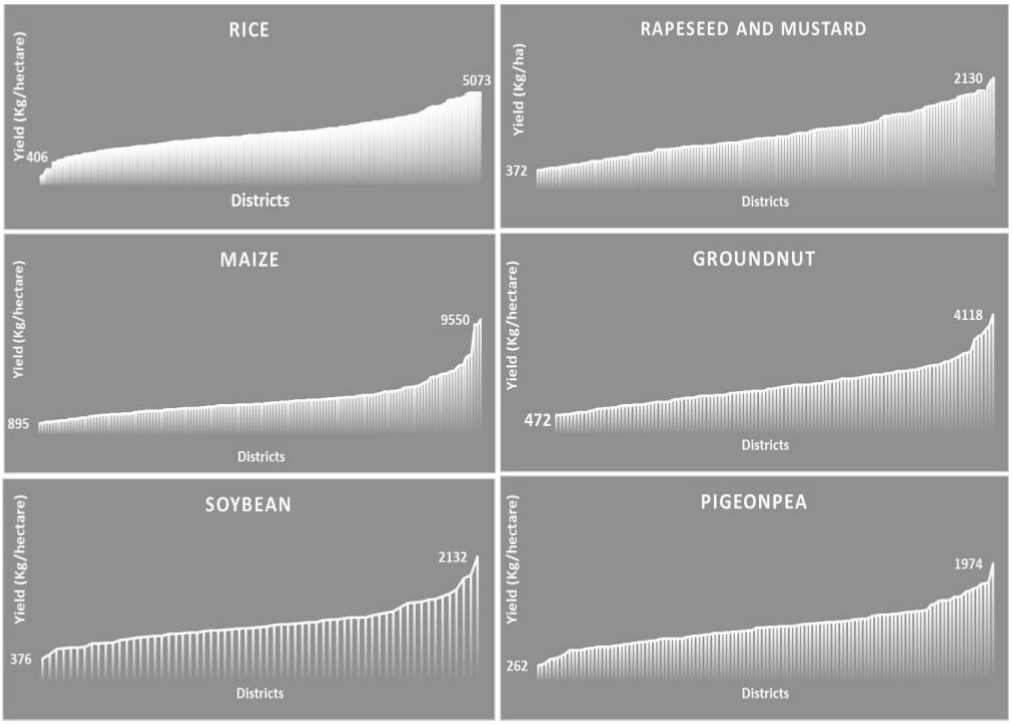

Figure 2: High heterogeneity in district-level crop yields (kg/ha) of various crops in India (year 2015-17)

Source: Author’s calculations based on several published secondary data

Evolution of Private Extension Systems

Over time, the role of public agencies in delivering agri-inputs and services has diminished, with private sector companies and their dealers emerging as major players, particularly in providing hybrid seeds, fertilizers, pesticides, biofertilizers, and plant growth promoters. Agri-input dealers have become the most accessible sources of information on agri-inputs and related agronomic practices. Input dealers serve as significant sources of technological information for farmers (Dar *et al.*, 2024). These dealers supply agri-inputs and often advise and recommend product use and best practices. However, this sales-driven model can sometimes result in biased advice and negative externalities, such as the overuse of chemical inputs and associated environmental impacts.

In response to the limitations of public programs, private extension systems have gained prominence. These systems include private agribusiness companies, consultants, agri-tech Start-ups, and farmer-led organizations, each offering specialized services tailored to the needs of individual farmers. Private services often deliver more personalized and responsive support than public programs (Steinke *et al.*, 2021). Notably, agri-tech Start-ups are at the forefront of this transformation, developing innovative solutions that leverage artificial intelligence (AI), remote sensing, and big data analytics. These Start-ups provide real-time data and actionable insights through mobile apps, online platforms, and IoT devices, enabling farmers to optimize their operations (Srishailam *et al.*, 2022). However, their reach at present is limited to a small proportion of commercial high-value agriculture farms.

Farmers' associations and cooperatives also play a critical role in the private extension landscape (Bizikova *et al.*, 2020; Candemir *et al.*, 2021). Often formed and led by farmers, these organizations facilitate knowledge sharing, collective problem-solving, and resource pooling. They offer training programs, workshops, and field demonstrations, fostering a community-based approach to agricultural extension. Farmer Producer Organizations (FPOs) exemplify this model, where farmers collectively manage their production, marketing, and resource management activities. However, the success of cooperatives and FPOs is limited to certain regions and commodities, such as milk cooperatives in Gujarat.

IV

RELEVANCE AND CHALLENGES OF CONVENTIONAL AGRI-INPUTS AND SERVICES MARKETS

The conventional sources of agri-inputs and services—both public extension systems and private agro-dealers—have played a critical role in advancing the growth and development of Indian agriculture. However, they have not sufficiently met the diverse and complex requirements of farming systems across different agroclimatic zones, falling short of harnessing the full potential of sustainable farming and food systems. This has led to imbalanced agricultural growth, benefiting only a few crops and better endowed regions; for instance, rain-fed farming systems have significantly less access to modern agri-inputs and services. Small ruminant and low-yielding cattle systems have also received inadequate public and private support in delivering modern inputs and services.

India's agricultural inputs and service markets face substantial challenges in addressing the multifaceted demands of sustainable and resilient food systems. Current markets and institutional arrangements for agri-inputs and services have predominantly focused on a limited number of commodities. One such example, Khejri (*Prosopis cineraria*), crucial for the socio-economic and ecological sustainability of arid systems in Western Rajasthan, lacks sufficient support. High labour costs due to a lack of appropriate machinery for harvesting its pods and leaves, besides other factors like tractorization, contribute to its diminished appeal. Similarly, several nutrition-dense commodities once integral to local food systems in various agro-ecoregions have been neglected, negatively affecting long-term sustainability and human and ecosystem health outcomes.

The adverse consequences of chemical-led agriculture on soil and human health have been well recognized and have huge economic and sustainability implications. Integrated nutrient management (INM) and integrated pest management (IPM) are recommended and promoted as part of the package of sustainable practices. However, the current agri-inputs and services markets and institutions are constrained in promoting INM, IPM and other regenerative solutions on a large scale.

A lack of focus on holistic approaches and farmers' priorities has hindered the effectiveness of efforts to deliver specific agri-inputs and services. Despite extensive initiatives, such as the Soil Health Card (SHC) scheme and previous efforts to promote soil test-based fertilizers and nutrient application, the desired outcomes have not been achieved. The quality of soil testing, which farmers are acutely aware of, and ineffective communication between technology providers and the agricultural community remain significant challenges. Even when tests are conducted accurately, translating results into actionable recommendations often fails to reflect farmers' priorities. For example, since 2011, phosphate and potash prices have more than doubled, while urea prices have remained constant. Nonetheless, SHC guidelines aim to optimize crop yields while farmers prioritize profitability. Furthermore, the presentation of test results and recommendations on the SHC often uses scientific language that may be difficult for farmers to comprehend. Although programs like the SHC seek to address these issues, low farmer awareness, logistical challenges, policy incoherence, and inadequate resources restrict effective soil nutrient management (Ohlan *et al.,* 2025).

Applying compost from animal dung and other farm waste is a simple yet essential practice for improving the farming system's sustainability and profitability, and it has been recommended and promoted for several decades. Research-based fertilizer recommendations indicate that, in most cases, 50 per cent of nitrogen should come from compost or organic sources. However, only a small proportion of farmers scientifically prepare and use compost according to these recommendations. Factors contributing to low adoption include an inadequate focus of extension services, policy bias towards chemical fertilizers, a lack of appropriate machinery to reduce drudgery and high labour costs, and supply shortages without innovative business models. Although such practices are now being promoted as part of natural farming and paramparagat Krishi vikas yojana (traditional farming development scheme), these practices should be integral to integrated soil nutrient management. Innovations in agri-inputs and services markets can address these constraints. Currently, agri-input markets are fragmented, primarily focusing on individual inputs such as seeds, fertilizers, and pesticides rather than integrated solutions. This fragmentation hinders comprehensive farming approaches supporting environmental sustainability and economic resilience (Balkrishna *et al.*, 2021; Padmaja *et al.*, 2020). Further, creating level playing fields in terms of support for residue incorporation and organic sources of manure and nutrients similar to the subsidy provided on chemical fertilizers would lead to better soil health outcomes.

All stakeholders recognize water conservation and sustainable use as a key driver of growth and sustainability in Indian agriculture. Despite initiatives to promote water-efficient technologies, its inefficient use through flood irrigation methods and excessive reliance on groundwater for irrigation persists. Challenges include a lack of technical skills and extension support on soil and water conservation from farm to landscape scale, high upfront costs for technologies like micro-irrigation, and a lack of financing options for small and marginal farmers (Shah *et al.*, 2019). Additionally, institutional focus and policy support for water-intensive crops and free electricity exacerbate the strain on water resources.

Promoting farming systems that enhance agro-ecosystem services (ESSs) and biodiversity is critical for current and future food security and achieving sustainable farming and food systems. There is a need for agri-inputs and services markets that incentivize farmers and producers to adopt sustainable practices and diverse farming systems.

Scale-appropriate mechanization is a major driver for improving operational efficiency in agricultural activities, reducing drudgery for men and women, mitigating climate change impacts, lowering production costs, and enhancing the overall performance of farming systems. However, policies, institutions, and markets have predominantly promoted large farm machinery. There is significant potential to encourage scale-appropriate, innovative, low-cost machinery for smallholder farming systems to improve resilience, profitability, and gender empowerment.

Food waste in Indian agriculture poses a significant challenge, affecting food security, economic stability, and environmental sustainability. It is estimated that 16 per cent of all produce is lost between harvest and consumption (Artiuch, & Kornstein, 2012; Sinha & Tripathi, 2021). Although there is increasing emphasis on post-harvest infrastructure, significant food waste continues due to a lack of appropriate harvest and post-harvest management, fragmented supply chains, inadequate cold storage, and poor transportation facilities (Gulati *et al.*, 2024). Market inefficiencies and limited investment in rural logistics infrastructure remain major obstacles to minimizing food losses.

Adopting circular economy principles in food production and consumption promises to reduce environmental footprints and contribute to one-health goals. However, implementing a circular economy in agriculture faces technical and financial barriers, particularly for small-scale producers. Limited knowledge about the benefits of recycling agricultural waste into bio-fertilizers and bioenergy, along with a lack of support services and insufficient government backing for sustainable recycling practices, constrains the adoption of circular solutions (Govindasamy & Kumar, 2018; Nikolaou, Jones, & Stefanakis, 2021). Local food systems are recognized for their potential to support economic and environmental sustainability; however, market institutions largely favour large-scale supply chains over local networks. This centralization limits local food accessibility and discourages direct producer-consumer linkages in rural areas (Rucabado & Cuéllar, 2020). Furthermore, without supply and value chains, several nutrition-dense foods traditionally produced by farmers or gathered from common lands have fallen out of production and consumption. Certain tribal-dominated regions, once hubs for such foods, can still play a vital role in enhancing national food security in many regions. Innovative models are needed to ensure the supply of necessary inputs and services and connect small surplus produce with markets.

One of the most significant challenges—and opportunities—that can transform Indian agriculture towards resilience and higher incomes is providing cost-effective delivery of farmer-level customized agro-advisory services and climate and market information. While successful small pilots have utilized digital technologies in this direction, much work remains.

While India's agricultural markets and institutions recognize the importance of sustainable practices, addressing these challenges requires systemic policy interventions, greater market efficiency, and more comprehensive institutional support.

V

INNOVATIONS IN AGRI-INPUT AND SERVICES MARKETS AND DELIVERY SYSTEMS

India's agricultural inputs and services markets are experiencing transformative innovations to foster sustainable growth in the sector. These innovations span domains like digital technology, precision farming, eco-friendly inputs, and institutional innovations, demonstrating significant potential to enhance productivity, resource use efficiency, profitability, and environmental stewardship.

5.1 Agri-tech Initiatives and Start-ups

A surge in Agri-tech initiatives drives a significant transformation in India's agricultural sector. This growth stems from two key factors: technological advancements offering solutions across the farming value chain and agriculture's immense potential for innovation. Agri-tech applies data-driven technologies and solutions to agriculture, promoting efficient resource management and demand-driven production to increase farmers' productivity and profitability. This phenomenal growth in Agri-tech has been fueled by expanding digital access across India, growing venture capital interest, and supportive government policies.

The Government of India and several state governments have prioritized the Agri-tech sector, encouraging digitalization to enhance yield and efficiency while mitigating risks from climate and socio-economic uncertainties. Agricultural budget allocation of the government of India has increased by 300 per cent in the last ten years, rising from 30,000 crore to 1.3 lakh crore (Source PTI). The Digital Agriculture Mission (DAM) of the government of India supports agri-tech Start-ups by leveraging cloud computing, earth observation, remote sensing, data analytics, and AI/ML models. Agri-tech solutions target key segments like Farming as a Service, big data analytics, market linkage models, and the Internet of Things (IoT).

Key Innovation Areas targeted by Indian Agri-Tech Start-ups:

i. Input Market Linkages & farming as a service (FaaS)
    a. Connect farmers to market information, products, and services like seeds, fertilizer, and other goods
    b. FaaS provides services to farmers, such as ordering inputs and equipment, with cash-on-delivery, eliminating intermediaries

ii. Weather-informed agro-advisories: Providing real-time weather data and insights helps farmers optimize strategies, anticipate challenges, plan better, and improve crop yields. For India, where unpredictable weather conditions often threaten agriculture, such predictive capabilities can be game-changing.

iii. Climate information combined with AI and ML for pest and disease forewarning

iv. Precision Farming & Analytics
    a. The Internet of Things (IoT) transforms farm management through real-time monitoring and automation (Awan *et al.*, 2021; Friha *et al.*, 2021; Fan *et al.*, 2021). IoT devices like soil moisture sensors, weather stations, and automated irrigation systems enable precise agricultural input control, improving operational efficiency while minimizing environmental impact through optimal resource use. Continued IoT technology development and adoption can drive significant precision agriculture advancements.
    b. Using drones to monitor crop health, apply pesticides, and map large areas is gaining acceptance. The drone didi (sister) scheme, where rural women are trained as drone pilot entrepreneurs, is a commendable government initiative to improve farmers' access to such services. However, research-backed development of protocols for different crops and regions will be necessary to achieve the desired outcomes.

v. Agri Fintech: Expanding access to financial products and services designed specifically for the agricultural sector. A few ag fintech Start-ups (e.g. Jai Kisan) have achieved good success in this challenging area of work and providing credit to farmers.

vi. Supply Chain & Output Market Linkage: Start-ups make farm inputs and equipment more affordable through online marketplaces and mobile applications while analyzing crop-related problems and offering specific solutions.

vii. Precision Livestock and Dairy tech Start-ups

viii. Blockchain Technology: Blockchain enhances transparency and traceability in the agri-food supply chain (Awan *et al.*, 2021; Dey and Shekhawat, 2021; Mirabelli and Solina, 2020). Providing secure, immutable transaction records can ensure the authenticity of organic and sustainable produce, build consumer trust, and create new market opportunities for farmers adopting sustainable practices. Blockchain's growing prevalence will promote ethical and sustainable food production.

Agricultural and allied sector Start-ups have grown to over 7,000 in nine years, driven by a conducive business environment and government support (Press Trust of India, 2024). By December 31st, 2023, nearly 2,800 Agri-tech Start-ups registered with Startup India, demonstrating rapid sector development (Kadyan *et al.*, 2024). The industry's potential is vast; Ernst & Young projects an achievable market size of $24 billion, with current penetration at only 1.5 per cent (Invest India, 2023). Sankhe *et al.* (2020) estimated that agri-tech Start-ups could add US$ 95 billion to India's economy by 2030 (figure 3).

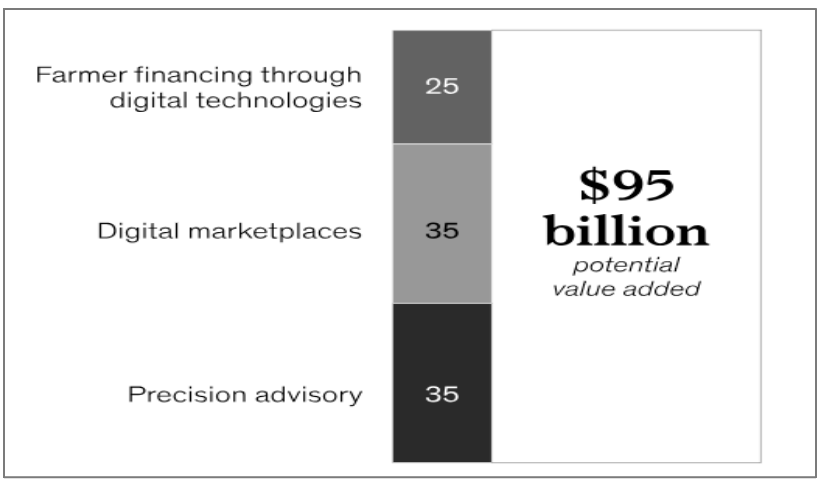

Figure 3: Agri-tech (Start-ups) potential to add to Indian economy by 2030
Source: Sankhe *et al.*, McKinsey *Global Institute, 26 August 2020*

Yet most agri-tech Start-ups struggle to capture business potential and effectively meet stakeholder and farmer needs. Despite rapid sector growth and some successes, many Start-ups fail to sustain operations and struggle with market penetration. Challenges include inadequate funding due to extended break-even periods, limited access to public institutional data, insufficient subject matter expertise, and loss of core objective focus.

Digital transformation presents challenges for small farmers, who often cannot harness benefits due to their exclusion from design and governance processes, and the challenge for agri-tech Start-ups is the high transaction costs of serving scattered family farms. Smallholders face affordability and digital literacy barriers, limiting platform adoption and creating value chain gaps. Financial viability poses a significant challenge for agri-tech Start-ups, especially initially. Generating consistent demand for paid services from smallholder farmers remains difficult, necessitating innovative business models that monetize farmer data while providing free advisory services. Addressing these challenges is crucial for maximizing digital agriculture's potential across stakeholders.

Additionally, Start-ups require continuous data inputs, yet collecting data from smallholder farmers remains disorganized and difficult to scale. Platforms struggle to deliver optimal results without accurate, real-time data, limiting their impact and growth potential while complicating sustainable revenue model development. The inability to identify critical value chain gaps and capitalize on emerging opportunities further constrain growth. Without robust data-driven approaches incorporating real-time field feedback, Start-ups struggle to provide lasting value, hampering scalability. Overcoming these challenges requires a stronger alignment between research-driven science and technology solutions and farmers' practical needs to create a sustainable impact.

Unlocking digital agriculture's full potential in India requires fostering collaboration among National Agricultural Research Systems (NARS), Agri-tech Start-ups, and Farmer Producer Organizations (FPOs). While each entity serves crucial agricultural sector needs, their collective impact multiplies through unified platform cooperation. A National Digital Agriculture Data Policy should establish a shared, decentralized data ecosystem where farmers, agribusinesses, Start-ups, and NARS bodies collectively contribute to and access agricultural data. The system should incentivize farmer participation through benefits from data contributions, including tailored advisory services, market insights, and financial support. For example, Start-ups could monetize farmers' data while providing advisory services in return.

The policy must protect data ownership and privacy rights, ensuring farmers and FPOs maintain data control while enabling aggregated, anonymized datasets for research, market planning, and innovation. The government should facilitate partnerships between agri-tech companies and research institutions to leverage collective data for public and private sector development. Additionally, policy should prioritize digital infrastructure investment and public-private collaborations to scale agri-tech innovations. Capacity-building programs focusing on digital literacy and effective Agri-tech tool use are crucial for farmers and FPOs. NARS and extension services-led tailored training can empower smallholders to utilize digital platforms better, enhance productivity, and ensure the sustainability of innovation.

5.2 Vertical Farming and Controlled Environment Agriculture (CEA)

Vertical farming and CEA enable year-round production in controlled settings (Van *et al.*, 2021; Walters *et al.*, 2020; Butturini and Marcelis, 2020). These techniques significantly reduce water and land use compared to traditional farming, achieving greater efficiency through LED lighting, hydroponics, and aeroponics advances. Vertical farming promotes local food production, reduces transportation-related carbon footprints, and advances urban agriculture's sustainability goals. Such a production system can be promoted for selected high-value agricultural commodities.

5.3 Farmers Producers' Organizations (FPOs)/ Farmers Producers' Companies (FPCs)/ Self-help Groups (SHGs)

FPOs can be crucial vehicles for agricultural transformation, which the governments also prioritize. Registered FPOs in India increased eight-fold to 8,875 between 2017 and June 2024. FPOs empower smallholder farmers through collective bargaining, enhanced market access, and technology adoption, promoting improved livelihoods and sector sustainability. They enhance economies of scale, market access, financial inclusion, sustainable practices, and capacity building. However, the majority of the FPOs and FPCs show limited performance. Similarly, India's 9 million SHGs, comprising nearly 100 million women members, represent a powerful potential tool for agricultural and rural economy transformation and women's empowerment. Yet most women SHGs focus primarily on personal thrift savings, with few achieving economic entity success. Advancing these groups requires holistic, flexible approaches, innovative contextualized business models, and sustained support.

5.4 Regenerative Agriculture

Various initiatives promote regenerative agriculture, a land management philosophy emphasizing nature-harmonious growth rooted in Indigenous wisdom. Practices vary across regions and farming systems, focusing on soil health restoration, biodiversity enhancement, and water cycle improvement. Innovations include cover cropping, no-till farming, and agroforestry, supporting carbon sequestration and soil fertility. Advanced tools and technologies make regenerative agriculture increasingly accessible and effective for farmers. Increased adoption of these techniques can contribute to the sustainability and resilience of the farming ecosystem (Gordon *et al.*, 2022; McLennon *et al.*, 2021). This will need more scientific evidence on regenerative practices as bundled solutions and their increased integration into agricultural extension programs.

5.5 Green Credit Program (GCP) and the Ecomark Scheme

This government of India initiative promotes environmental friendly practices rooted in tradition and conservation, which is initially focussed on water conservation and afforestation. Once operational, it will establish a national green credits market, potentially transforming the adoption of sustainable agriculture practices. Several private entities/companies and public institutions are standardizing protocols for measuring carbon sequestration and GHG emission reduction due to sustainable practices to potentially connect Indian farmers with global and national voluntary carbon markets. While farmers' participation in global voluntary carbon markets shows theoretical promise, further research must validate potential farmer benefits through concrete evidence.

VI

WAY FORWARD AND CONCLUSIONS

Innovations in agri-input and service markets must align with current priorities such as climate resilience, regenerative agriculture, and gender- and nutrition-sensitive food systems. Addressing these priorities requires strengthening the capacities of extension agents and value chain stakeholders, who are important sources of information for farmers. Fostering start-ups and Farmer Producer Organizations (FPOs), including women's Self-Help Groups (SHGs), is crucial for creating farmer-centric models. These institutional innovations need support to develop viable business models that promote sustainability and inclusivity in agriculture. Enabling policies and institutional arrangements that support these goals are essential.

6.1 Leveraging Digital Innovations

Digital technologies like artificial intelligence (AI), machine learning (ML), and drones can revolutionize agriculture by enabling precise assessments and data-driven decision-making. AI and ML can significantly enhance service delivery systems, while drones offer rapid and accurate assessments of pesticide residues, benefiting consumers, farmers, and exporters. Moreover, fintech solutions provide financial services to farmers and other agri-value chain stakeholders, fostering efficiency and financial inclusion. There is a need to develop sustainable business models to harness the power of digital innovations.

Enabling policies should also prioritize data-sharing frameworks, ensuring farmers retain ownership of their data while enabling real-time insights to drive innovation. Policies should also support investment in digital infrastructure and programs that improve digital literacy, helping farmers leverage agri-tech solutions effectively.

6.2 Convergence of NARES, Ag-tech Start-ups, Industry, FPOs, and Agro-Dealers

To leverage the potential of India's agri-tech sector, enabling policies are needed to foster collaboration among the National Agricultural Research and Extension System (NARES), agri-tech start-ups, FPOs, and agro-dealers. Each stakeholder has unique strengths essential for agricultural transformation. NARES provides domain-specific technologies, but start-ups often face challenges accessing this knowledge, especially given the sector's complexity and the heterogeneity in smallholder farming systems. Ag-tech start-ups delivering innovative solutions to farmers contribute directly to NARES' mandate, making it essential to incentivize knowledge sharing and collaboration. FPOs, with their capacity to provide scale, can help start-ups reach more farmers, lowering transaction costs and creating markets for their services. It may be possible to link at least one agri-tech start-up based on their competency with a certain number of FPOs/WSHGs (say, 100 to 500 FPOs). Similarly, agro-dealers, which are the main source of information for farmers, need to be leveraged by the NARES to disseminate and promote technologies and sustainable practices. Moreover, policies must encourage agriculture-related industries to work closely with NARES and FPOs to promote sustainable farming systems. Corporate social responsibility (CSR) funds could also support the development of these convergence models.

6.3 Crowd-Sourced Agro-Advisory Models

Diverse smallholder farming systems require contextualized solutions. Ag-tech start-ups can play a significant role in providing these tailored advisories. However, farmers' willingness to pay for advisory services is generally low, necessitating innovative business models that crowdsource contextual farming data. This data can inform the designing of contextual advisory services and agri-input companies. Data provided to input companies and governments can be the source of revenue for the agri-tech start-ups. Supportive policies are needed to facilitate these models while addressing potential implications. In return, farmers get free agro-advisory services.

6.4 Farmer Innovators and Practitioner Networks

Farmers across different agro-ecological zones continue to develop sustainable practices that improve resilience and income. Establishing networks of these innovators and incentivizing them to share knowledge can support other farmers. Extension agencies and Krishi Vigyan Kendras (KVKs) could utilize digital platforms like YouTube and others to share these success stories. This approach would be valuable for a broader agricultural digital public infrastructure.

6.5 Market-Led Extension and Service Delivery

Market-led extension services help align agricultural inputs and services with market demands. Ag-tech start-ups are central to this approach, providing solutions that enhance productivity and sustainability. By collecting data on farming systems, these start-ups can inform policymakers and businesses, facilitating better decision-making. Market integration is essential, as lacking market access can discourage farmers from adopting new technologies.

6.6 Integrated and Customized Approaches

An integrated approach to agri-input and services, combining market information, technology inputs, market linkage, and capacity development is needed to create a comprehensive support system for farmers. Decision-support tools powered by data analytics can offer customized solutions, improving farmers' practices and outcomes. This convergence of information can facilitate effective knowledge exchange among stakeholders, including farmers' representatives. For example, the agricultural extension system must adopt an integrative approach to promote regenerative agriculture. It will also require various departments such as agriculture, animal husbandry, irrigation, watershed, horticulture, rural development, and financial institutions in a convergence mode to promote regenerative solutions.

6.7 Empowering Rural Youth and Job Creation

Rural youth have significant potential to provide agricultural services on a fee basis, driving innovation and sustainability. Several such initiatives launched in the past, like agri-clinics, were not so successful and need to be revisited to facilitate such models grounded on sustainable economic viability. Supported by schemes similar to the Production-Linked Incentive (PLI) and impact funds, they can create jobs and strengthen rural economies. Financial mechanisms that empower youth and early-stage start-ups can significantly contribute to a resilient agricultural sector.

6.8 Farmer-to-Farmer Learning Exchanges

Peer-to-peer learning exchanges are effective in encouraging the adoption of innovative practices. Through shared experiences, farmers can motivate their peers to adopt new techniques, overcoming scepticism and resistance to change. Ag-tech start-ups can facilitate these exchanges by creating platforms for knowledge-sharing, accelerating the spread of innovations.

6.9 Promoting Local Food Systems through Agri-Inputs and Services

Revitalizing local food systems and promoting nutrient-dense crops is essential for current and future food and nutrition security. Digital innovations can help reduce production and marketing costs for local foods, facilitating market creation and access for small-scale producers.

6.10 Policy Support and Data Utilization

Robust policy support is essential for fostering innovations in agri-inputs and services. Policies must create an enabling environment that encourages investment in agricultural innovation and supports scalable models. Real-time data from agri-tech start-ups and other stakeholders can serve as inputs for responsive policies, guiding farmers on operations and market dynamics and enhancing their decision-making.

Finally, the paper concludes that innovations in agri-input and service markets, such as digital technologies, AI, regenerative agriculture, and emerging carbon and green credit markets, offer promising avenues for enhancing resilience, profitability, and environmental sustainability in agriculture. Digital and precision agriculture technologies will continue transforming farming, making it more efficient and sustainable. Strategic policy interventions and robust support systems are essential to realize these benefits fully. Policymakers must prioritize aligning agricultural innovations with emerging priorities such as climate resilience and gender-nutrition-sensitive food systems. Strengthening convergence among NARES, agri-tech Start-ups, industry, FPOs, and SHGs is crucial to sustainable agricultural development.

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