Food System Innovations and Digital Technologies to Foster Productivity Growth and Rural Transformation

**Rui Benfica, Judith Chambers, Jawoo Koo, Alejandro Nin-Pratt,
José Falck-Zepeda, Gert-Jan Stads, and Channing Arndt**

1 Introduction

Food systems are a powerful lever for countries to overcome poverty, hunger, and malnutrition. In the next few decades, low- and middle-income countries (LMICs) will need to respond to numerous challenges, including rising food demand, shifts toward healthier diets, deleterious climate change effects, and the need to preserve biodiversity. Accelerated efforts to raise agricultural yields (Alexandratos and Bruinsma 2012) and increase productivity in agricultural value chains are needed, especially for vulnerable populations in LMICs. Innovations in food systems, facilitated by improved technology for more precise breeding and input use efficiency, the enabling of policy and regulatory environments, increased investments, and enhanced individual and institutional capacities (Fuglie 2018) in research development and delivery can significantly contribute to those goals.

Currently, many LMICs lack the capacity to innovate and/or benefit from global developments in agricultural innovations and digital technologies. Several factors are at play. First, while advanced and high-middle-income countries use R&D investments to catalyze technological and economic transformation (Ruttan 1982), many LMICs lag in both investment and human/institutional capacity (Beintema et al. 2012). Second, many countries are constrained by the inherent characteristics of their agrifood system operating environments, which are mostly rural, remote, and dominated by small farms, making it hard for innovations to take hold. They are

R. Benfica (✉) · J. Koo · A. Nin-Pratt · J. Falck-Zepeda · G.-J. Stads
International Food Policy Research Institute (IFPRI), Washington, DC, USA
e-mail: R.Benfica@cgiar.org

J. Chambers
Program for Biosafety Systems, IFPRI, Washington, DC, USA

C. Arndt
Environment and Production Technology Division, IFPRI, Washington, DC, USA

J. von Braun et al. (eds.), *Science and Innovations for Food Systems Transformation*,
https://doi.org/10.1007/978-3-031-15703-5_22

hampered by limited infrastructure density (roads, telecommunications, weather stations, energy grid, etc.); poorly developed markets and value chains; and inadequate financial services. They also lack efficient mitigation systems to address risks arising from climate change, global trade, and invasive species. Finally, they lack supportive enabling policies and regulations to facilitate the discovery, development, and delivery of food system and digital innovations.

Promising advancements in bioscience and digital technologies offer opportunities to address the innovation challenges and close the productivity gap for LMICs. Applications of biotechnology research have led to more precise introduction and enhancement of essential traits in crops, animals, and micro-organisms. The CRISPR-Cas9 genome editing system has become a viable tool for targeting specific genomic changes (Es et al. 2019), producing results similar to those achieved through conventional plant and animal breeding methods, but with more efficient, timely, and cost-effective R&D trajectories (Gao 2018). Likewise, digital technologies are contributing to accelerated food system transformation, optimizing management decisions (Basso and Antle 2020), facilitating information flows across food-land-water systems (von Braun et al. 2017), and facilitating regional and global trade (Jouanjean 2019).

Accordingly, this brief focuses on agricultural bio-innovations and digital technologies as important drivers of food system transformation over the next decade, and outlines elements relevant for all types of innovation to succeed. Taking a systems landscape perspective, it highlights R&D and economic viability, and environmental and social effects, while addressing enabling factors, such as R&D investment, institutional and human capacity, infrastructure, and the variety of socioeconomic, regulatory, and political economy factors that affect development, delivery, and adoption pathways for new technologies.

1.1 Agricultural Bio-Innovations

Agricultural bio-innovations comprise a broad suite of technologies, including conventional and marker-assisted breeding in crops, livestock, fish, and microorganisms, as well as biofertilizers and precision agriculture. Newer improvement techniques include genetic modifications (GM) and new breeding techniques (NBTs) such as genome editing. These confer protection from pests, diseases, and weeds, and offer other novel uses and applications that address environmental conditions and climate change effects.[1] This paper highlights crop bio-innovations, as these have advanced significantly but are still facing challenges that could

---

[1] New bio-innovations also revolutionized livestock and fish breeding, including aquaculture and embryo transplantation (Belton et al. 2020). Genome editing and other biotechnology-based livestock transformation technologies have vast potential to help address human and animal needs, as well as environmental challenges. R&D areas under development in the livestock sector include disease models, xenotransplantation, vaccine production, enhanced animal breeding and

constrain their use and viability. Some of those challenges are also relevant for other bio-innovations.

Historically, investments in crop improvement research, dominated by conventional breeding, have led to gains in agricultural productivity. In a comprehensive assessment, Evenson and Gollin (2003) documented high growth rates in the productivity of most cereals. Their analysis suggests that at least half of all total factor productivity (TFP) gains between 1960 and 2000 were attributable to crop genetic improvements. They also found that countries without genetic improvements were less likely to realize TFP gains from other sources (Evenson and Gollin 2003). A study by Lantican et al. (2015), covering three-quarters of the world's wheat area, shows that genetic improvement contributed to an increase in wheat yields from 2.5 tons/ha (hectare) in 1995 to 2.8 tons/ha in 2015, an increase of 0.6% annually. In the case of maize, Krishna et al. (2021) find that genetic improvement efforts in 10 major maize-producing countries in Africa[2] increased yields from 1.4 tons/ha in 1995 to 1.7 tons/ha in 2015, an average annual increase of 1.0%.

Despite this, in the absence of infusions of new technology, conventional breeding has limited the potential to address increasing demand for food and biomass or to mitigate agro-environmental challenges in a timely manner (Gao 2018). Recent biotechnology applications offer multiple benefits to LMICs, given the array of biophysical, climate, and socioeconomic challenges these countries face. However, their adoption varies across developing economies. Differences in R&D capacity, delivery, adoption, and benefits often reflect disparities in the socioeconomic and political factors that affect public perceptions, and in the prevailing policy and governance environments. If such factors are limiting, they can restrict the technology frontier and constrain farmers' access to potential solutions.

Consequently, more emphasis should be put on interventions that address the mix of research and enabling policy factors necessary to realize the pro-poor benefits of bio-innovations. To illustrate this consideration, we focus on genome editing, specifically CRISPR-Cas9, given its transformative potential and the urgent need to develop the enabling R&D and policy trajectories required for impact.

CRISPR-Cas9 uses targeting technologies that can produce new varieties that resemble "nature-identical" variants (Gao 2018). These varieties may be more resistant to disease, poor environmental conditions, and climate change; include desired agronomic and nutritional traits; and require fewer inputs. Compared to other methods, CRISPR-Cas9 is more targeted, faster, more efficient, more and cost-effective, making it a viable technology choice for revenue-stressed countries. Additionally, regulators who have evaluated the science recognize the need to examine those technologies and make decisions on a case-by-case basis, as gene editing can generate products that do not result in transgenic events, and thus do not necessarily require regulatory scrutiny. All of this makes CRISPR-Cas9 agricultural

---

improvement, and bioreactors (Zhao et al. 2019). Some livestock technologies have been already deployed commercially (Perisse et al. 2021; Yum et al. 2018).

[2] Benin, Cameroon, Ghana, Guinea, Madagascar, Mali, Rwanda, Senegal, Uganda, and Zambia.

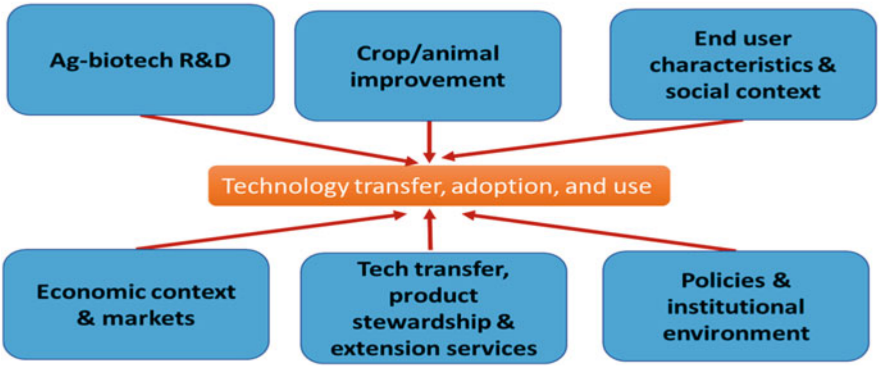

Fig. 1 The enabling environment for technology transfer, adoption, and use. (Source: Based in part on Falck-Zepeda 2021)

applications attractive investment options for global public goods research (Gao 2018; Pixley et al. 2019). Despite these advantages, however, poor enabling environments could still limit the value of and access to CRISPR-Cas9 agricultural bio-innovations for resource-poor farmers, traders, and consumers. Figure 1 illustrates the complex relationships among the factors required for the successful adoption and diffusion of bio-innovations.

The elements shown in Fig. 1 help determine whether a technology will succeed, including decision-maker support through enabling policies, economic benefits and functioning markets, and effective extension services. Some elements may be more relevant to genome editing bio-innovations, depending on the context in which these technologies operate. A discussion of factors most relevant to genome editing follows.[3]

- **Intellectual property (IP) considerations.** Evolving trends in IP rights and restrictions related to genome editing may drive technology access across organizations and influence the reach of public goods R&D efforts. Results of an analysis triangulating patents, published research, and public news searches reveal some important findings (Martin-Laffon et al. 2019; IPStudies 2019, 2020; Brinegar et al. 2017; Zambrano et al. 2021). First, globally, the public sector leads in the foundational CRISPR-Cas9 IP landscape. China leads in published research and patent filings, followed by the United States. Public institutions lead in both areas in China, while in the United States, the public sector dominates research, but the private sector dominates patent filings. Second, research and patent filings are dominated by rice, driven by China, with additional research focused on 17 other crops/plants across 24 countries. In the United States, the patent landscape is notable for its growing and diversified set of commodities and institutions. Third, foundational patent-holders are explicitly

---

[3] These likely apply to crops, animals, fish, and microorganisms.

licensing their proprietary positions and providing incentives for strategic alliances that promote access to IP-protected R&D inputs. In that context, international and national agriculture research organizations (IARCs and NAROs) have successfully negotiated licensing agreements for CRISPR-Cas9. Finally, more private sector licensors of genome editing technologies are negotiating multiple-partner IP licenses for the development of agricultural and industrial applications. Major biotechnology firms are negotiating licenses with several CGIAR centers, small private firms, and start-ups.

This evolving IP landscape points to the critical need to ensure and secure continued development of novel, productive mechanisms to facilitate IP access for pro-poor innovations to guarantee freedom to operate technology product development and deployment. Despite the positive trends in licensing for public good genome editing technologies, the CGIAR centers, IARCs, and NAROs still lack sufficient capacity to ensure and self-determine their equitable access to these technologies.

- **Regulatory considerations**. The costs of regulatory delays in the approval of innovations may reduce access to potentially valuable technologies and affect market entry, and thus the realization of potential benefits. Feasible regulatory frameworks are those that consider evidence-based scientific approaches balancing safety, time, and costs, and that are both risk-proportional and fair (Arndt et al. 2020; Falck-Zepeda et al. 2016), generally leading to valuable technologies being approved for potential producer use. Without this solid foundation for decision-making, regulatory frameworks could create large opportunity costs, as an examination of regulatory delays associated with GM crops has demonstrated.[4] In the face of a similar regulatory environment, these opportunity costs could be even higher for genome editing, given the expanded licensing and R&D efforts across a growing array of food-security-relevant traits and crops (Chen et al. 2019). Conversely, the wider range of applications for genome editing, combined with lower development costs and enabling policy factors, implies greater potential for positive economic benefits. In fact, given that potential, the opportunity costs of excluding genome editing from the technology options available to improve agricultural productivity are quite significant (Wesseler and Zilberman 2014; Wesseler et al. 2017).
- **Socioeconomic and political economy issues.** It is widely recognized that socioeconomic and political economy factors can promote or prevent the successful deployment of bio-innovations. Current research indicates that GM crops can potentially address critical biotic and abiotic constraints in agriculture and livestock production efficiently but lack broad-based public acceptance (Ahmed

---

[4] The cost of regulatory delays for GM crops is well documented (Wesseler et al. 2014; Smyth et al. 2016). Costs of regulatory delays in livestock and fisheries sectors are also significant (Van Eenennaam et al. 2021).

et al. 2021; Gouse et al. 2016; Chen et al. 2019).[5] NBTs, including CRISPR-Cas9, risk facing the same impediments to adoption as GM crops, though many NBTs will not include foreign DNA. Extrapolation of results from economic impact assessments for conventional and GM-assisted plant breeding suggests that returns from genome editing technologies may be significant, with important implications for LMICs. It is therefore critical to develop science-based regulatory guidance that promotes the use of this technology to address the needs of the poor.

1.2 Digital Technologies in Agricultural Value Chains

Digital innovation is transforming lives worldwide. We work, learn, communicate, shop, and entertain online. More than half of the world's population uses the Internet, with the 4G mobile network now covering about 85% of the global population (ITU 2020). Digital technologies catalyze development and accelerate economic growth. The digital economy is now equivalent to 15.5% of global gross domestic product (GDP) and has grown 2.5 times faster than global GDP over the past fifteen years (Huawei and Oxford Economics 2017). The agriculture sector is no exception. For family farmers in Africa, digital technologies revolutionize livelihoods by overcoming isolation, as they connect farmers to markets and financial institutions, speeding up change through digital extension and taking success to scale by using granular data to better target innovations (Annan and Dryden 2015). Research shows that innovative applications of digital technologies in agriculture enable more productive, efficient, resilient, and sustainable food systems (Basso and Antle 2020).

Digital technologies in agriculture leverage digitally collected data and analytics to guide decisions along agricultural value chains. *Farmers* can access high-frequency, high-resolution data to make customized decisions. *Traders* can predict food supply and demand dynamically and connect producers and markets at the right time with the right volume. *Policymakers* can make informed decisions related to investments, smart subsidies, and risk management. The following are examples of promising digital applications that address challenges along agricultural value chains:

- **Remote sensing.** The rapid technological improvement of remote sensing makes the precise and timely monitoring of agriculture and natural resources possible, providing actionable information for farmers, traders, and policymakers. For large areas (for example, a country or region), satellite remote sensing can be used to manage food-land-water systems in an integrated and efficient way (Sheffield et al. 2018), including monitoring potential risks to crop yields

---

[5] Projections of potential for technologies already advanced in the regulatory pipeline include: Dzanku et al. 2018; Kikulwe et al. 2020; Phillip et al. 2019; Ruhinduka et al. 2020; and Yirga et al. 2020.

(Burke et al. 2021), flash floods (Liu et al. 2018), landslides (Casagli et al. 2017), and locust infestations (Piou et al. 2019). Crop and livestock insurance providers increasingly rely on information from remote sensing to profile the risks and damages to production (Benami et al. 2021). When used in small areas, unmanned aircraft vehicles (UAVs or drones) can capture very high-resolution imagery on demand and provide farmers and extension services with useful and timely monitoring information.

- **Connected sensors.** Low-cost, Internet-connected sensors can directly monitor crop and environmental field conditions with speed and precision. These data help farmers make real-time informed and customized management decisions. Antony et al. (2020) conducted an extensive review of the literature and expert interviews on the use of Internet of Things (IoT) devices for smallholder agriculture, including automated solar-powered drip irrigation for vegetables, water-level sensors in rivers for flood alerts, automatic climate control systems, and in-field multiparameter sensors to monitor real-time crop conditions, providing extension agents with information to advise farmers.
- **Artificial intelligence.** As large amounts of data from multiple sources become available in real time, artificial intelligence (AI) helps combine data streams from multiple sources, analyzes them quickly, and generates timely, actionable insights. In addition to processing remote-sensing and IoT data, AI could revolutionize farm mechanization in the near future, with the use of agricultural robots that can apply fertilizer, remove weeds, and harvest crops (Torero 2021).
- **Digital advisory services.** Resource-poor farmers often lack access to information and advisory services at times of critical need. While developing country extension services are improving, with the number of extension agents now exceeding one million, insufficient and unsustainable financing for extension services remains an information constraint (Davis et al. 2020). Through digital channels (for example, mobile phones, interactive voice response, and the Internet), farmers and extension agents can directly access timely agricultural information customized for individual farmers' needs.

  Many private companies offer subscription-based information services through mobile phones. In sub-Saharan Africa, CTA (2019) identified 390 digital agriculture services, of which 15 reached more than one million farmers. There is evidence of some positive impacts. Fabregas et al. (2019) conducted a meta-analysis of studies in sub-Saharan Africa and India, finding that farmers who subscribed to digital services increased their adoption of recommended agro-chemical inputs by 22% and their yields by 4%. CTA (2019) analyzed 50 impact studies in sub-Saharan Africa and found that subscribers' income increased by 20–40%. In Ethiopia, video-mediated extension was shown to reach wider audiences, enhancing agricultural knowledge and the uptake of technologies compared with conventional approaches (Abate et al. 2019).
- **Digital financial services.** Farmers often use cash in financial transactions, and are excluded from credit, savings, and insurance services. The World Bank (Demirgüç-Kunt et al. 2018) reports that, globally, 1.7 billion adults (31%) do not have accounts at financial institutions or through mobile money providers.

Common reasons include not having enough money, physical distance from financial institutions, and documentation requirements. Digital financial services (DFS) can address those constraints, provided that an active mobile phone is available to use as an entry point for financial inclusion. Evidence points to positive DFS impacts on rural households. In Kenya, Kirui et al. (2013) report that use of mobile money in rural areas increased input use by 95%, agricultural commercialization by 37%, and annual household incomes by 71%. Suri and Jack (2016) estimate that the M-PESA mobile money service in Kenya helped 194,000 households escape poverty and diversify income sources. Evidence from India suggests that picture-based insurance, which verifies insurance claims using smartphone images of insured plots, minimizes asymmetric information and claim verification costs while reducing risk compared to index-based insurance (Ceballos et al. 2019).

- **E-commerce.** Unlike traditional agricultural value chains involving multiple intermediaries, e-commerce allows farmers to directly connect with buyers, and so increase income. Agricultural e-commerce is at an early stage in LMICs, yet, although comprehensive impact evidence is unavailable, its potential is undeniable. By shortening supply chains, e-commerce can also reduce food waste and benefit consumers with fresher produce (GSMA 2019). During the COVID-19 pandemic, e-commerce has been pivotal in connecting farmers to markets and consumers to fresh foods (Reardon et al. 2021).

Like bio-innovations, digital technologies in LMICs face important policy challenges related to data ownership and user rights that require well-defined guidelines in terms of IP frameworks and regulations.

2 Agricultural R&D Enabling Investments and Capacities

The rise of biological and digital technologies offers viable options for LMICs, but also raises concerns about their preparedness to take advantage of these opportunities and to foster an appropriate enabling environment to support product development, deployment, and adoption.

Public agricultural R&D investment is a recognized major engine for promoting food system innovations; this investment funds socially valuable research that can potentially lead to private innovation for local benefits. In recent decades, support for public agricultural research in high-income (HI) countries has stagnated, while private agricultural research spending has increased, reshaping the structure of the global agricultural research system (Fuglie and Toole 2014). Global agricultural R&D investments have shifted from HI countries toward large middle-income economies (Brazil, China and India), which have grown in importance as agricultural producers and research leaders. Meanwhile, most low-income countries continue to lag significantly in agricultural R&D investments and human and institutional capacity, having thus experienced limited agricultural productivity growth.

Table 1 Countries grouped by level of development of their agricultural research systems, 2016

Key indicators	Lagging	Average	Advanced	Brazil, China, & India
Number of countries	55	50	15	3
Total R&D investment (million 2011 $)	17,679	83,170	212,256	202,615
Average R&D investment (million 2011 $)	9	46	393	1876
Share of R&D investment among LMICs	3%	16%	41%	39%
Annual agricultural TFP growth, 2000–2016 (%)	0.7%	1.0%	1.3%	2.6%
Published articles per FTE researcher	0.1	0.4	0.7	1.3
H index (quality and influence of publications)	26	72	160	266
Share of total population among LMICs	11%	26%	14%	50%
GDP per capita (2011 $)	5405	5146	11,832	11,419
Number of people living on under $1.9/day (million)	111	238	80	366

Source: ASTI (2021), SCImago (n.d.), USDA-ERS (2021), and World Bank (2021). These are gaps in investment, human capital, and institutional capacity.

To fully benefit from the range of bio-innovations and digital technologies, LMICs require focused efforts to close the gaps in R&D. Only 18 LMICs possess agricultural research systems comparable to HI countries in quality and productivity (Table 1).[6] Overall, countries with *lagging* research systems account for only 3% of total R&D investment in LMICs. Their investments are significantly smaller and less productive than those in countries with *average* or *advanced* systems. Moreover, LMICs with *lagging* research systems also show considerably slower agricultural productivity growth. Similarly, LMICs with *average* research systems trail those with *advanced* research systems in terms of R&D investment and long-term agricultural productivity growth. Given their modest share in global agricultural R&D investments and over-representation in global extreme poverty, evidence suggests these *lagging* and *average* countries could make enormous progress if R&D efforts were to be stepped up. Three main R&D gaps differentiate LMICs with *lagging*, *average*, and *advanced* agricultural research systems.

- **The R&D investment gap.** A country's agricultural R&D investment capacity depends on factors beyond the size of its agricultural GDP. The overall size of the economy, its income level, and the availability of relevant technology spillovers from other countries also play important roles. When comparing R&D investments of a given country with those of countries with similar characteristics, it is

---

[6] We used the country's H index of agricultural science and biology publications from SCImago (n.d.) to classify countries by quality and productivity of the agricultural research system.

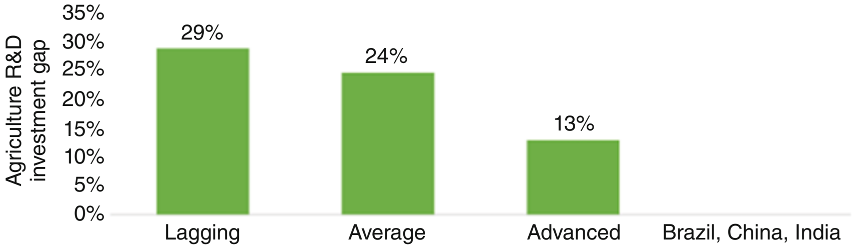

Fig. 2 Agricultural R&D investment gap, as a percentage of R&D investment by country group, 2014–2016. (Sources: ASTI (2021) and World Bank (2021). Note: The Lagging group includes 53 countries; Average 50; Advanced 15. Eastern European and former Soviet countries were excluded)

possible to determine attainable R&D investment based on relative investment differences. The ASTI intensity index (AII) does precisely this by quantifying the gap between a country's agricultural research investment and its potential, based on country comparisons (Nin-Pratt 2016). Use of the index shows that the investment gap is much higher in countries with *lagging* and *average* agricultural research systems than in countries with *advanced* systems (Fig. 2). Economic development, the quality of institutions, and political constraints are major factors determining governments' revenues and spending capacity. Total government spending in the *lagging* group was only $0.7 per person in 2011, compared to $1.95 in the *advanced* group. Only 3–6% of total government spending in LMICs is for agriculture, and only a fraction of that is allocated to R&D. These findings underscore the need to reconsider the generalized recommendation to "increase R&D investment in LMICs" and examine the unique development challenges faced by countries with weaker R&D systems.

- **The human capital gap.** Even more significant than the investment gap is the human capital gap affecting the quality, scope, and potential of research systems in LMICs. This gap limits their participation in the emerging opportunities presented by bio-innovations and digital technologies. Despite an increase in the number of PhD-qualified agricultural researchers in developing countries since 2000 (ASTI 2021), the composition of researchers by degree differs significantly—countries in the *lagging* group are clearly disadvantaged, with only 17% of their agricultural researchers holding PhD degrees, compared with 75% in Brazil, China and India, and 27% in countries with *advanced* systems (Fig. 3). Although researchers in the *average* group of countries hold higher qualification levels, a very large portion of their PhD-qualified researchers is set to retire in the coming decade, a situation that is particularly severe in sub-Saharan Africa.
- **The institutional capacity gap.** The suboptimal quality of institutions causes inefficiencies and results in the underperformance of agricultural R&D systems, especially in *lagging* and *average* countries. Some of these inefficiencies may emanate from decisions made within countries (for example, centralized versus

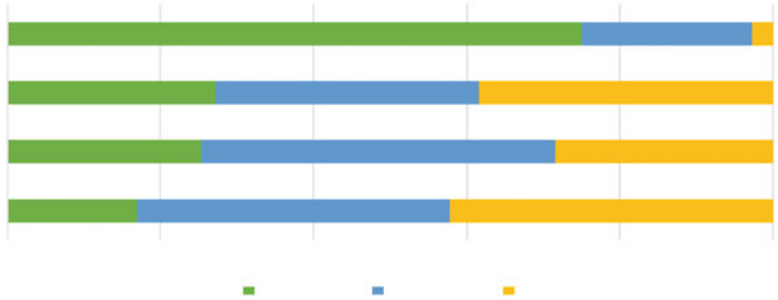

Fig. 3 Researchers with PhD, MSc, and BSc degrees as a share of total full-time equivalent (FTE) researchers. (Source: ASTI 2021)

decentralized systems); others are structural in nature. For countries with relatively small economies and/or agriculture sectors and a limited supply of researchers, overall development of their agricultural research system is constrained by the size of research teams and the capacity to develop a critical mass of diverse and relevant research platforms. The situation for research systems in these countries will likely worsen with the increasing demand for research-oriented responses to address climate change-related challenges.[7]

3 Actions and Solutions for Enabling Food System Innovations

This analysis proposes a way forward to advance agricultural research and accelerate the scaling and adoption of bio- and digital innovations for food systems by closing critical gaps and promoting the necessary investments, policies, and regulations through actions at the global, regional, and national levels. Synergistically, those efforts will help accelerate agricultural productivity growth and food system transformations, as well as the achievement of the Sustainable Development Goals (SDGs).

At the **global level**:

- **Facilitate LMIC engagement with global players in food system innovations to strengthen IP access and management capacity.** Given the role of IP frameworks in determining access to emerging bio- and digital innovations, it will be important to create the conditions for agricultural research entities—such as IARCs, NAROs, and national agricultural research systems—to negotiate IP agreements with global innovators and enhance their IP management capacity so

---

[7] The average number of researchers per country in the group of *lagging* research systems is below 300 full-time equivalents (FTEs), compared to 900 FTEs in the *average* group, 3700 FTEs in the *advanced* group, and more than 12,000, on average, in China, India, and Brazil.

as to ensure jurisdictional freedom to operate while fostering strategic alliances. On the crop biotechnology side, it will be important to engage with China and the United States to secure and support public good technology flows to developing countries.[8] For digital technologies, appropriate mechanisms need to be established with key global players to enable efficient and cost-effective access to data and digital applications for the relevant stakeholders in LMICs.

- **Promote North–South, South–South, and triangular cooperation to strengthen LMIC regulatory frameworks**. Building on their relatively more advanced regulatory framework development, countries in the global North, as well as emerging players such as China, India and Brazil, should use available mechanisms to support LMICs' efforts to advance their regulatory capabilities, including strengthening institutional and stakeholder capacity at different levels (Arndt et al. 2020).

To complement these global efforts, programmatic and policy actions will be needed at the **national and/or regional levels** to improve the development, delivery, and use of food system and digital innovations.

- **Adapt emerging technologies to local conditions.** Countries will need to invest in science-based participatory approaches to benefit from the range of food system innovations highlighted here that have potential to help address multiple challenges. Given the diversity among countries, adapting these technologies to local conditions—in ways that make them accessible to farmers and retain much of the gain among consumers—is challenging, especially for developing economies, smallholder farmers, and small businesses (Hendriks et al. 2021). Therefore, investments in science-based, participatory processes to map out realistic and equitable options are needed (Basso and Antle 2020).
- **Close the regulatory gaps for enabling innovations.** To minimize opportunity costs associated with regulatory delays, governments must create evidence-based regulatory environments, in a timely manner, that enable the safe use and application of bio-innovations and digital technologies by stakeholders in LMICs. This involves working with a diverse set of actors, including local and international scientists, the private sector, and others, to provide a pathway that ensures timely, secure, and equitable access. While these processes can benefit from global engagement, they should be customized to country-specific circumstances.
- **Close human capital gaps at the country level.** Training for a new generation of scientists and researchers should emphasize the development of skills needed to generate and deliver emerging and fast-changing biotechnology and digital innovations relevant to food systems, including the capacity to integrate local knowledge with modern science. Managerial capacity, business education, and multidisciplinary thinking are also critical. At the same time, work with governments and the private sector should improve the capacity of farmers, farmer organizations, and other value chain actors to adopt transformative food system innovations.

---

[8] For livestock, other players such as Argentina and Brazil are also critical.

- **Close institutional capacity gaps.** Increasing institutional capacity will require addressing limitations in organizations' capacities and strengthening institutional coordination among food system stakeholders. Efforts by regional institutions and organizations to achieve long-term reforms could provide a more efficient and cost-effective way for groups of countries to work together to target specific goals and escape the trap of lagging research systems. In this context, it will be critical to create policy environments that stimulate cooperation among agricultural R&D agencies so as to maximize synergies and efficiencies, rather than solely relying on individual country efforts. The restructured One CGIAR can play a constructive role in this regard.
- **Develop a deeper understanding of political economy factors.** These factors impact the development and deployment of food system innovations to and within countries. A more nuanced understanding of actors, agendas (both social and economic), and influence relationships may better inform the understanding of technology hesitancy and will better support targeted communications and outreach efforts to build consumer confidence and enable pro-poor technology access. Informed political will is also essential for building local, regional, and global policy platforms in support of safe and timely access to these technologies in emerging economies.
- **Strengthen communications and public acceptance of modern biotechnology innovations.** Early and enhanced communication efforts to inform decision-makers and the public are needed in order to develop a climate of transparency and trust about the safety and socioeconomic benefits of genome editing applications. This will be critical for policy development and public/market acceptance (Gao 2018). Similarly, discussions on the costs of regulatory delays and the results of losing access to important food security, productivity, and environmental solutions must be part of the policy and public dialogues.
- **Close digital infrastructure gaps in rural areas.** Although 50% of the global population has Internet connectivity, significant digital divides exist between rural and urban areas. Only 6% of rural households in Africa have Internet access, compared with 28% in urban areas (ITU 2020). Data costs remain prohibitive, and technology ownership and access are gender-divided (GSMA 2020). Croplands with severe yield gaps, climate-stressed locations, and food-insecure populations have relatively poorer service coverage (Mehrabi et al. 2021). Enabling policies and investments targeting rural households are urgently needed. Connecting all of Africa is estimated to cost $100 billion and would only be feasible with strong private sector involvement (Broadband Commission 2019). Slow progress on electrification in LMICs further limits the affordability and coverage of digital technologies. The number of people without access to electricity in sub-Saharan Africa likely increased in 2020 due to the COVID-19-related economic slowdown (IEA 2020). Research is needed to develop business cases for simultaneous investment in digital infrastructure and electrification and to provide evidence of their synergistic impact for creating value and achieving the SDGs (GeSI 2019).

- **Develop sustainable business models for digital service providers across food systems.** Most digital service providers lack viable business models and revenues. In sub-Saharan Africa, only 26% of agricultural information service providers generate enough revenue to break even (CTA 2019). Achieving profitability, interoperability and scale is essential to reaching a sustainable critical mass. This would facilitate the use of financially viable digital technologies across value chains, thus increasing the adoption of various innovations, including new bio-innovations.

Additionally, as digital information comes to play an increasingly vital role in LMICs, clear policies and secure infrastructure are needed to protect the privacy of farmers and value chain actors while ensuring transparency and inclusivity. Strengthening technology capacity and digital literacy and skills (OECD 2019) will further accelerate the prospects for the democratization of digital technologies as part of game-changing solutions to end hunger.

References

Abate GT, Bernard T, Makhija S, Spielman DJ (2019) Accelerating technical change through video-mediated agricultural extension: evidence from Ethiopia. IFPRI discussion paper 1851. International Food Policy Research Institute, Washington, DC

Ahmed AU, Hoddinott J, Abedin N, Hossain N (2021) The impacts of GM foods: results from a randomized controlled trial of Bt eggplant in Bangladesh. Am J Agric Econ. https://doi.org/10.1111/ajae.12162

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050 [2012 revision]. ESA working paper No. 12-03. Food and Agriculture Organization of the United Nations, Rome

Annan K, Dryden S (2015) Food and the transformation of Africa: getting smallholders connected. Foreign Aff 94(6):18

Antony AP, Leith K, Jolley C, Lu J, Sweeney DJ (2020) A review pf practice and implementation of the internet of things (IoT) for smallholder agriculture. Sustainability 12(9):3750

Arndt C, Chambers JA, Zambrano P, Alahmdi MI, Alatawi A, Benfica R, Edward MG, Gatehouse AMR, Moronta-Barrios F, Ahmed A (2020) Embracing innovation to meet food systems challenges: task force 10 sustainable energy, water, and food systems (policy brief). T20 Saudi Arabia 2020 THINK

ASTI (Agricultural Science and Technology Indicators) (2021) Agricultural research expenditures and human resource capacity database. International Food Policy Research Institute, Washington, DC. http://www.asti.cgiar.org/data

Basso B, Antle J (2020) Digital agriculture to design sustainable agricultural systems. Nat Sustain 3(4):254–256

Beintema N, Stads G, Fuglie K, Heisey P (2012) ASTI global assessment of agricultural R&D spending: developing countries accelerate investment. ASTI, International Food Policy Research Institute/Global Forum on Agricultural Research, Washington, DC/Rome

Belton B, Thomas R, Zilberman D (2020) Sustainable commoditization of seafood. Nat Sustain 3(9):677–684

Benami E, Jin Z, Carter MR, Ghosh A, Hijmans RJ, Hobbs A, Kenduiywo B, Lobell DB (2021) Uniting remote sensing, crop modelling and economics for agricultural risk management. Nat Rev Earth Environ 2(January):140–159

Brinegar, K., A.K. Yetisena, S. Choi, E. Vallillo, G.U. Ruiz-Esparza, A.M. Prabhakar, A. Khademhosseini, and S.H. Yun. 2017. "The commercialization of genome-editing technologies." Crit Rev Biotechnol 37(7): 924–932

Broadband Commission (2019) Connecting Africa through broadband: a strategy for doubling connectivity by 2021 and reaching universal access by 2030

Burke M, Driscoll A, Lobell DB, Ermon S (2021) Using satellite imagery to understand and promote sustainable development. Science 371(6535):eabe8628

Casagli N, Frodella W, Morelli S, Tofani V, Ciampalini A, Intrieri E, Raspini F, Rossi G, Tanteri L, Lu P (2017) Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning. Geoenvironmental Disasters 4(1):1–23

Ceballos F, Kramer B, Robles M (2019) The feasibility of picture-based insurance (PBI): smartphone pictures for affordable crop insurance. Dev Eng 4(May):100042

Chen K, Wang Y, Zhang R, Zhang H, Gao C (2019) CRISPR/Cas genome editing and precision plant breeding in agriculture. Annu Rev Plant Biol 70(April):667–697

CTA (2019) The digitalisation of African agriculture report 2018–2019. CTA/Dalberg Advisers, Wageningen

Davis, K.E., S.C. Babu, and C. Ragasa. 2020. "Conclusions and policy implications." In Agricultural extension: global status and performance in selected countries, eds. K.E. Davis, S.C. Babu, and C. Ragasa. Part 2: performance of extension systems, chapter 9 313–331. Washington, DC: International Food Policy Research Institute

Demirgüç-Kunt A, Klapper L, Singer D, Ansar S, Hess J (2018) The global Findex database 2017: measuring financial inclusion and the fintech revolution. World Bank, Washington, DC

Dzanku FM, Zambrano P, Wood-Sichra U, Falck-Zepeda JB, Chambers JA, Hanson H, Boadu P (2018) Adoption of GM crops in Ghana: Ex ante estimations for insect-resistant cowpea and nitrogen-use efficient rice. IFPRI Discussion Paper 1775. International Food Policy Research Institute, Washington, DC

Eş I, Gavahian M, Marti-Quijal FJ, Lorenzo JM, Khaneghah AM, Tsatsanis C, Kampranis SC, Barba FJ (2019) The application of the CRISPR-Cas9 genome editing machinery in food and agricultural science: current status, future perspectives, and associated challenges. Biotechnol Adv 37(3):410–421

Evenson RE, Gollin D (2003) Assessing the impact of the green revolution, 1960 to 2000. Science 300(5620):758–762

Fabregas R, Kremer M, Schilbach F (2019) Realizing the potential of digital development: the case of Agricultural advice. Science 366(6471):eaay3038

Falck-Zepeda JB (2021) Defining an enabling environment for bio-innovation technologies and products: *quo vadis investigationis publicum*? Unpublished paper

Falck-Zepeda JB, Smyth S, Ludlow K (2016) Zen and the art of attaining conceptual and implementation clarity: socio-economic considerations, biosafety and decision-making. Estey J Int Law Trade Policy 17(2):117–136

Fuglie K (2018) R&D capital, R&D Spillovers, and productivity growth in world agriculture. Appl Econ Perspect Policy 40(3):421–444

Fuglie K, Toole A (2014) The evolving institutional structure of public and private agricultural research. Am J Agric Econ 96(3):862–883

Gao C (2018) The future of CRISPR technologies in agriculture. Nat Rev Mol Cell Biol 19(January):275–276

GeSI (2019) Digital with purpose: delivering a SMARTer2030. GeSI and Deloitte. https://digitalwithpurpose.gesi.org

Gouse M, Sengupta D, Zambrano P, Zepeda JF (2016) Genetically modified maize: less drudgery for her, more maize for him? Evidence from smallholder maize farmers in South Africa. World Dev 83(July):27–38

GSMA (2019) E-commerce in agriculture: new business models for Smallholders' inclusion into the formal economy. London

GSMA (2020) Connected women: the Mobile gender gap report 2020. London

Hendriks S, Soussana J, Cole M, Kambugu A, Zilberman D (2021) Ensuring access to safe and nutritious food for all through transformation of food systems. Paper prepared for Action Track 1, Scientific Group of the UN Food Systems Summit

Huawei and Oxford Economics (2017) Digital spillover: measuring the true impact of the digital economy. Shenzhen and Oxford

IEA (International Energy Agency) (2020) World energy outlook 2020. Paris

IPStudies (2019) CRISPR patent analytics. https://www.ipstudies.ch/crispr-patent-analytics/

IPStudies (2020) CRISPR patent analytics. https://www.ipstudies.ch/crispr-patent-analytics

ITU (International Telecommunication Union) (2020) Measuring digital development: facts and figures 2020. Geneva

Jouanjean M (2019) Digital opportunities for trade in the agriculture and food sectors, OECD food, agriculture and fisheries papers, no. 122. OECD Publishing, Paris

Kikulwe EM, Falck-Zepeda JB, Oloka HK, Chambers JA, Komen J, Zambrano P, Wood-Sichra U, Hanson H (2020) Benefits from the adoption of genetically engineered innovations in the Ugandan banana and cassava sectors: an ex ante analysis. IFPRI discussion paper 1927. International Food Policy Research Institute, Washington, DC

Kirui OK, Okello JJ, Nyikal RA, Njiraini GW (2013) Impact of mobile phone-based money transfer services in agriculture: evidence from Kenya. Quart J Int Agric 52(2):141–162

Krishna VV, Lantican MA, Prasanna BM, Pixley K, Abdoulaye T, Menkir A, Bänziger M, Erenstein O (2021) Impacts of CGIAR maize improvement in sub-Saharan Africa, 1995–2015. International Maize and Wheat Improvement Center (CIMMYT), Mexico City

Lantican MA, Braun HJ, Payne TS, Singh RP, Sonder K, Baum M, van Ginkel M, Erenstein O (2015) Impacts of international wheat improvement research, 1994-2014. CIMMYT, Sept, p 15

Liu C, Guo L, Ye L, Zhang S, Zhao Y, Song T (2018) A review of advances in China’s flash flood early-warning system. Nat Hazards 92(2):619–634

Martin-Laffon J, Kuntz M, Ricroch AE (2019) Worldwide CRISPR patent landscape shows strong geographical biases. Nat Biotechnol 37(June):601–621

Mehrabi Z, McDowell MJ, Ricciardi V et al (2021) The global divide in data-driven farming. Nat Sustain 4:154–160

Nin-Pratt A (2016) Comparing apples to apples: a new indicator of research and development investment intensity in agriculture. IFPRI discussion paper 1559. International Food Policy Research Institute, Washington, DC

OECD (Organisation for Economic Co-operation and Development) (2019) Digital opportunities for better agricultural policies. Paris

Perisse IV, Fan Z, Singina GN, White KL, Polejaeva IA (2021) Improvements in gene editing technology boost its applications in livestock. Front Genet 11:614688. https://doi.org/10.3389/fgene.2020.614688

Phillip D, Nin-Pratt A, Zambrano P, Wood-Sichra U, Kato E, Komen J, Hanson H, Falck-Zepeda JB, Chambers JA (2019) Insect-resistant Cowpea in Nigeria: an ex ante economic assessment of a crop improvement initiative. IFPRI discussion paper 1896. International Food Policy Research Institute, Washington, DC

Piou C, Gay PE, Benahi AS, Babah Ebbe MAO, Chihrane J, Ghaout S, Cisse S, Diakite F, Lazar M, Cressman K, Merlin O (2019) Soil moisture from remote sensing to forecast desert locust presence. J Appl Ecol 56(4):966–975

Pixley KV, Falck-Zepeda JB, Giller KE, Glenna LL, Gould F, Mallory-Smith CA, Stelly DM, Stewart CN (2019) Genome editing, gene drives, and synthetic biology: will they contribute to disease-resistant crops, and who will benefit? Annu Rev Phytopathol 57(August):165–188

Reardon T, Heiman A, Lu L, Nuthalapati CSR, Vos R, Zilberman D (2021) ‘Pivoting’ by food industry firms to cope with COVID-19 in developing regions: E-commerce and ‘co-pivoting’ delivery-intermediaries. Agric Econ (preprint). https://doi.org/10.1111/agec.12631

Ruhinduka RD, Falck-Zepeda JB, Wood-Sichra U, Zambrano P, Semboja H, Chambers JA, Hanson H, Lesseri G (2020) Ex ante economic assessment of impacts of GM maize and cassava on producers and consumers in Tanzania. IFPRI Discussion Paper 1911. International Food Policy Research Institute, Washington, DC

Ruttan V (1982) Agricultural research policy. University of Minnesota Press, Minneapolis

SCImago (n.d.) SJR — SCImago Journal & Country Rank [Portal]. Retrieved in May 2021 from http://www.scimagojr.com

Sheffield J, Wood EF, Pan M, Beck H, Coccia G, Serrat-Capdevila A, Verbist K (2018) Satellite remote sensing for water resources management: potential for supporting sustainable development in data-poor regions. Water Resour Res 54(12):9724–9758

Smyth SJ, Falck-Zepeda J, Ludlow K (2016) The costs of regulatory delays on genetically modified crops. Estey J Int Law Trade Policy 117(2):173–195

Suri T, Jack W (2016) The long-run poverty and gender impacts of mobile money. Science 354(6317):1288–1292

Torero M (2021) Robotics and AI in food security and innovation: why they matter and how to harness their power. In: von Braun J, Archer MS, Reichberg GM, Sorondo MS (eds) Robotics, AI, and humanity: science, ethics, and policy. Springer, Cham, pp 99–107

USDA-ERS (2021) Economic research service. US Department of Agriculture, Washington, DC

Van Eenennaam AL, de Figueiredo Silva F, Trott JF, Zilberman D (2021) Genetic engineering of livestock: the opportunity cost of regulatory delay. Ann Rev Animal Biosci 9(1):453–478

Von Braun J, Gulati A, Kharas H (2017) Key policy actions for sustainable land and water use to serve people. Economics 11(32):1–14

Wesseler J, Zilberman D (2014) The economic power of the golden rice opposition. Environ Dev Econ 19(6):724–742

Wesseler J, Kaplan S, Zilberman D (2014) The cost of delaying approval of golden rice. ARE Update 17(3):1–3. University of California Giannini Foundation of Agricultural Economics, Berkeley

Wesseler J, Smart RD, Thomson J, Zilberman D (2017) Foregone benefits of important food crop improvements in Sub-Saharan Africa. PLoS ONE 12:e0181353

World Bank (2021) World development Indicators. Washington, DC

Yirga C, Nin-Pratt A, Zambrano P, Wood-Sichra U, Habte E, Kato E, Komen J, Falck-Zepeda JB, Chamber JA (2020) GM maize in Ethiopia: an ex ante economic assessment of TELA, a drought tolerant and insect resistant maize. IFPRI Discussion Paper 1926. International Food Policy Research Institute, Washington, DC

Yum SY, Youn KY, Choi WJ, Jang G (2018) Development of genome engineering technologies in cattle: from random to specific. J Animal Sci Biotechnol. https://doi.org/10.1186/s40104-018-0232-6

Zambrano AP, Falck-Zepeda JB, Chambers J (2021, forthcoming) Intellectual property of agriculturally based gene editing technologies: follow the new leaders. IFPRI discussion paper. International Food Policy Research Institute, Washington, DC

Zhao J, Lai L, Ji W, Zhou Q (2019) Genome editing in large animals: current status and future prospects. Natl Sci Rev 6:402–420. https://doi.org/10.1093/nsr/nwz013