Global Food Security 44 (2025) 100827

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Innovation and technology for achieving resilient and inclusive rural transformation

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A R T I C L E I N F O

Keywords:
Technology
Innovation
Agrifood systems
Employment
Inclusion
Rural transformation

A B S T R A C T

This paper examines the shifts needed in the development, adoption and scaling of innovation and technology to achieve resilient and inclusive rural transformation across farming systems and value chains. It analyzes opportunities for innovations to generate rural employment, improve smallholder farmer livelihoods, alleviate malnutrition and address the impacts of climate change. The paper identifies five key levers of change that include: (i) a renewed focus on long-term investment in participatory, equity-sensitive and gender-responsive agricultural R&D, (ii) ensuring that marginalized voices are heard, (iii) promoting equitable access to technology, (iv) leveling the playing field by curbing corporate dominance while encouraging private sector support for small- and medium-scale agrifood enterprises, and (v) prioritizing rural employment amid automation and evolving value chains.

1. Introduction

The world is facing converging crises, with global hunger on the rise and climate change exacerbating vulnerabilities, particularly for the rural poor who have low adaptive capacity (FAO, 2024a; Hallegatte and Rozenberg, 2017). To address these formidable challenges, the prevailing model of rural transformation, situated within a larger framework of economy-wide structural transformation, has prioritized an agricultural productivity-led approach measured by economic growth, efficiency and enhanced market integration (Barrett et al., 2017; de Janvry and Sadoulet, 2020). This paper argues that although this model remains relevant, both the approach and the role of innovation and technology within it need to be reconsidered to improve resilience of agrifood systems and more effectively address rural poverty, food insecurity and malnutrition.

Innovation and technology have played a pivotal role in driving productivity gains but also contributed to negative externalities. The Green Revolution, fueled by public investments in biotechnologies, irrigation and mechanization with intensive use of synthetic fertilizers and pesticides, prioritized increasing agricultural productivity (Gollin et al., 2021), saving as many as one billion people from starvation. But it also led to unintended environmental, equity and health consequences partially offsetting the productivity gains. The emphasis on increasing yields of a few staple crops contributed to reduced agricultural biodiversity. Lax regulations and generous subsidies resulted in the overuse of fertilizers and pesticides, damaging soils and polluting waterways. Productivity gains were uneven, with limited success in sub-Saharan Africa and North Africa, and slow growth in Latin America and South Asia.

Today, low- and middle-income countries (LMICs) continue to rely on agricultural productivity as a primary driver of economic growth, but climate change and depletion of natural resources are negatively impacting productivity (Zhao et al., 2017). Further, a narrow focus on productivity has often overlooked critical aspects such as nutrition, equity and environmental sustainability (Ambikapathi et al., this issue, Lipper and Cavatassi, 2024; Meybeck et al., 2024). The traditional productivity-driven model must be rethought, emphasizing not just agricultural productivity increases, but also adopting a systems approach that spans production to consumption and recognizing the synergies and trade-offs among the key objectives of agrifood systems (Davis et al., 2024). The sector must adapt to climate change, build resilience and reduce greenhouse gas (GHG) emissions to meet the Paris Agreement Goals, while ensuring access to healthy diets and addressing power dynamics, i.e. a joint agenda of food security and nutrition and climate actions without aggravating inequalities (FAO, 2023a). However, achieving these interconnected goals presents significant challenges and complexities.

In this context, the promise of technologies and innovations to boost

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https://doi.org/10.1016/j.gfs.2025.100827
Received 22 March 2024; Received in revised form 18 December 2024; Accepted 13 January 2025
Available online 26 January 2025

livelihoods, improve nutrition and enhance climate resilience, particularly those offering multiple co-benefits, is immense. That said, optimistic outcomes do not emerge on their own and the sole existence of a solution does not guarantee its adoption, sustained use and desired impact. If innovation and technology are truly to be a significant enabling factor for resilient and inclusive rural transformation, where "*everyone in rural areas of the world is able to achieve a decent living and to consume diets that are healthy, nutritious and diverse, within planetary boundaries and managing climate change challenges*" (Davis et al., this issue), it is essential to ensure they are accessible, affordable and relevant to the specific needs of marginalized and vulnerable communities. Achieving systemic change requires a fundamental shift in how appropriate technologies and innovations are developed and adopted, bundling mutually reinforcing innovations, incorporating local and traditional knowledge, and supporting these efforts with ancillary policy, social and institutional reforms (Herrero et al., 2021). Efforts to promote resilient and inclusive rural transformation will also need to prioritize human rights, equitable income distribution, and women's empowerment.

This paper explores how technology and innovation can more effectively contribute to achieving resilient and inclusive rural transformation across farming systems and value chains. Section 2 provides a framework to analyze entry points for technology and innovation. Using a gender and equity lens, it also presents illustrative examples that demonstrate how technologies and innovations can help marginalized and vulnerable communities attain decent livelihoods, while consuming healthy diets, and responding to climate change challenges. Section 3 addresses potential risks, concerns and challenges associated with these technologies and innovations. Building on the insights from this section, Section 4 outlines five key levers of change so that technology and innovation foster resilient and inclusive rural transformation. Finally, section 5 draws conclusions that synthesize the key findings and implications for policy and practice.

For the purposes of this paper, technology is defined as the application of science and knowledge to develop techniques to deliver a product and/or service that enhances the sustainability of agrifood systems, while innovation consists of doing something new and different whether solving an old problem in a new way, addressing a new problem with a proven solution, or bringing a new solution to a new problem (FAO, 2022a). An innovation system includes the interconnected networks of actors from academia, private sector, civil society and government, working together to create a suite of technological, social, policy, financial and institutional innovations that collectively influence the transformation of agrifood systems (Klerx and Begemann, 2020).

2. Technologies and innovations as catalysts for resilient and inclusive rural transformation

To foster resilient and inclusive rural transformation, several factors must be considered, such as where value added is generated in agrifood systems, how it is distributed across stakeholders, and the degree of diversity along value chains. Understanding the value generated across different segments of agrifood value chains - primary production, processing, transport and storage, and wholesale and retail - is important since it determines the distribution of money within each segment. The stakeholder composition also varies substantially across the different segments. For example, wholesale and retail tend to be more concentrated than primary production. Furthermore, inclusiveness will depend on how money flows to different actors within a segment, and in turn it remunerates labor. Ensuring diversity of actors and responses is essential to build resilience of agrifood value chains. Diversity provides a network for learning and transformation, for preventing risks and buffering shocks, and for ensuring agility in responses to varying needs and opportunities.

Different bundles of innovations and technologies may contribute in a comparable way to the objective of improving the livelihoods of small-scale producers and other agrifood system actors, including small and medium enterprises (SMEs) and those looking for off-farm employment. In general, achieving these goals will require technologies and innovations that increase incomes through higher productivity, generate employment in strategic segments of value chains, and enhance resilience of value chains. Naturally, it is important to consider whether access to technology and innovation is the most effective way to improve living standards and alleviate poverty or if there should be greater emphasis on investments in the non-agricultural sector.

Fig. 1 expresses these linkages, and in a stylized manner, presents potential actions to drive resilient and inclusive rural transformation providing entry points for technology and innovation in different segments of agrifood value chains. It emphasizes that these value chain segments differ in terms of value-added generation (the size of the arrow for a value-chain segment is a stylized representation of results in Yi et al., 2021), number of actors (number of bubbles within a segment), scale of operations of individual actors (size of a bubble), diversity of actors, as well as employment generation potential. Fig. 1 is stylized in the sense that the number of actors and their scale of operations will differ across agrifood systems types. It does however capture some aspects that apply in general, such as households being much more numerous than processors or wholesalers. That being said, the agrifood system represented in Fig. 1 is one where there is concentration in input markets, some in food processing, and also in wholesale and retail trade, characteristic of modernizing or industrial systems (Marshall et al., 2021). When assessing technology and innovation, one should take this into consideration as well as how a specific intervention may affect specific actors (e.g. SMEs vs. large-scale operations) within each segment. Fig. 1 also lists enabling factors, such as governance, institutions, coordination among stakeholders and power relations that all play a role in shaping the actions within value chains and the associated outcomes.

In the following sections, these entry points along value chains are addressed. An exhaustive listing of relevant technologies and innovations is beyond the scope of this paper and a few indicative examples are provided, focusing on two aspects, namely gender and equity considerations, and technologies and innovations that can simultaneously deliver multiple co-benefits.

2.1. *Farming forward: boosting livelihoods and reducing inequity*

Fig. 1 portrays, in a schematic form, that there are many small landholdings with a limited number of large ones, and that production captures only a relatively small part of consumer expenditure on food (relative size of the arrow). Small farms, which make up 84 percent of the world's farms and produce roughly 35 percent of the world's food (Lowder et al., 2021), face persistent poverty and inequality, with their labor productivity and incomes lagging behind those of large-scale producers. Women farmers are further disadvantaged, earning less than men (The Sustainable Development Goals Report, 2024). Although increased agricultural productivity can boost small-scale producer incomes, global total factor productivity growth slowed between 2011 and 2020, especially in low-income countries (Steensland, 2022).

The range of technologies and innovations that can help small-scale producers improve efficiency and productivity is extremely broad, encompassing varieties developed through conventional breeding and genetic modification (Lidder and Sonnino, 2012) as well as agroecological approaches (HLPE, 2019). The adoption of improved cultivars has significantly boosted yields and economic outcomes, with drought tolerant maize benefitting the poorest households in sub-Saharan Africa. For rice systems, NERICA varieties have proven effective in the region, especially for women farmers, while stress-tolerant rice varieties have shown promise in Asia, delivering greater benefits to farmers in flood-prone regions (Jain et al., 2023). In LMICs, adoption of genetically modified (GM) crops by farmers, on average increased crop yields by 29 percent, reduced the use of chemical pesticides by 42 percent, and

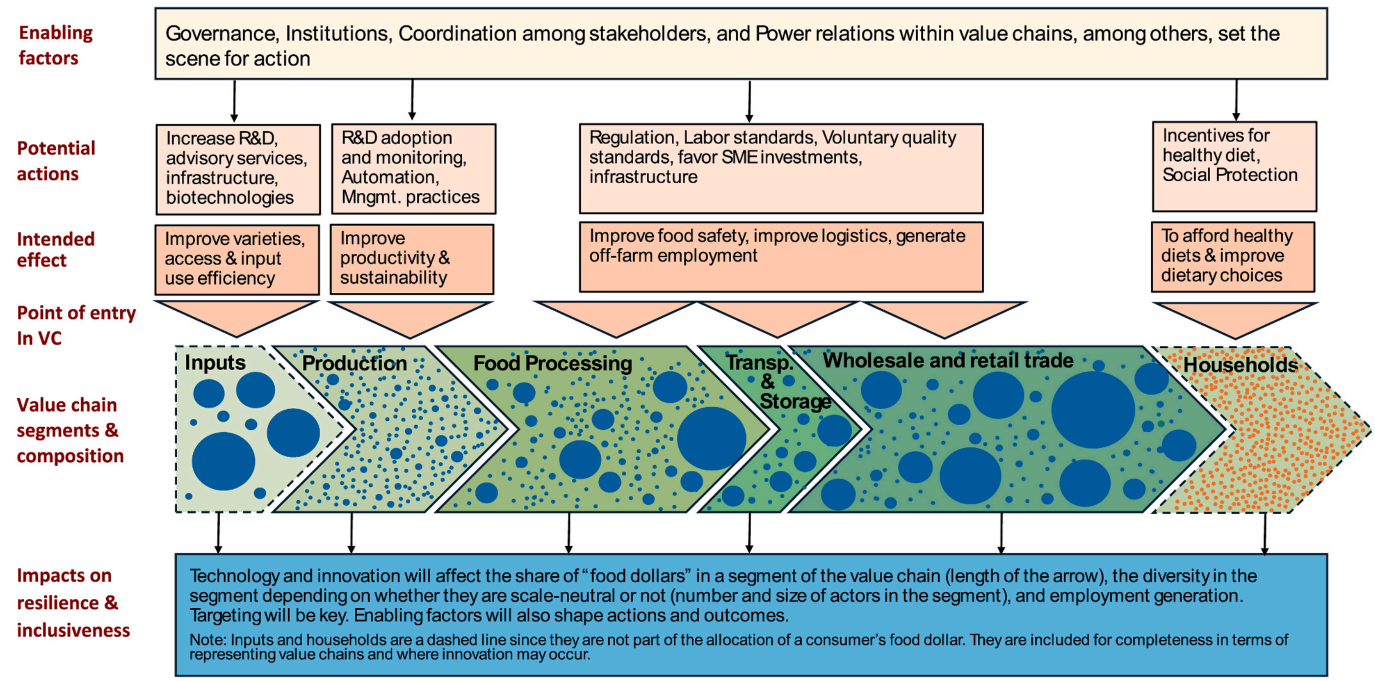

Fig. 1. Entry points for technologies and innovations for resilient and inclusive agrifood system transformation: A systems perspective
Source: Authors' elaboration.

increased profits by 78 percent (Qaim, 2020). Cultivation of GM cotton, in particular, has been reported to significantly increase yields, with the largest gains in low-income, warmer countries where pests and weeds are more prevalent (Hansen and Wingender, 2023). However, knowledge gaps related to their environmental impacts as well as the complex political economy surrounding GM crops have created barriers to their widespread adoption (see section 3.1).

Agroecological approaches can boost productivity, profitability and biodiversity (Benzer Kerr et al., 2023). In India, the Andhra Pradesh Community-Managed Natural Farming programme, the largest transition to agroecology globally involving farms averaging less than 2 ha, led to greater crop diversity, an 11 percent increase in yields, 49 percent net income increase, enhanced social capital, improved health and reduced health costs (GIST Impact Report, 2023). While reducing inputs can benefit the environment without affecting crop yields, in many LMICs (especially in Africa), external inputs are essential due to nutrient scarcity and highly weathered soils (Falconnier et al., 2023; Giller et al., 2021). Additionally, approaches that aim to reduce the use of chemical herbicides or promote no-till techniques may necessitate manual removal of weeds. Since women often perform more labour-intensive tasks in agriculture, this can increase drudgery.

Digitalization and automation are already transforming farms, both small and large. Data on weather patterns, crop yields and market prices can be used to optimize farm management decisions. For example, GARBAL, a text message service in the Sahel region, facilitates access to geo-data information on herd/livestock mobility, agro-meteorological data and livestock prices. Gender-responsive advisory services have the potential to overcome entrenched gender norms and rectify the information asymmetry experienced by women, creating a higher demand for innovative technologies (FAO, 2023b).

Precision agriculture integrates technologies, such as crop and soil sensors, satellite navigation and positioning technology, drones with advanced optics and Internet of Things (IoT), to optimize agricultural output and profitability, preserve resources, detect nutrient deficiency and pest and disease infestation, monitor livestock and reduce pesticide and fertilizer use (Fernando et al., 2020; Zhang et al., 2021). In India, an AI-based sowing application enabling smallholder farmers to receive precision agro-advisories for a host of crops resulted in 10–30 percent higher yields (Manfre and Laytham, 2018). In low-income countries, mechanization tailored to small-scale producers, such as two-wheeled tractors, can be a cost-effective solution (Daum and Birner, 2020), alongside institutional solutions like machinery rental markets and cooperative exchange to further enable smallholder access to mechanization (FAO, 2022b).

Often demand for these technologies arises from changes occurring downstream in value chains. Barrett et al. (2022a) provide examples of studies on technology transfers through value chain innovations that generate productivity increases not just for the product itself but also for other farm level activities, highlighting the importance of taking into account innovations downstream that may affect farmer livelihoods.

2.2. *Reimagining value chains: creating jobs and empowering the vulnerable*

As highlighted in the previous section, and illustrated in Fig. 1, the bulk of value addition occurs beyond the primary production segment of value chains. Therefore, how this added value is distributed across actors in the downstream segments is key. Relative to other sectors, agrifood systems are unique in their scale of reliance on SMEs. Midstream SMEs have an important role in generating off-farm employment and establishing connections between small farms and growing urban food markets (Reardon et al., 2021). For example, in Ethiopia the transition from traditional wooden plates to modern electric ones for enjera processing significantly increased the capacity of SMEs, improved the quality of the product, and resulted in a notable rise in employment opportunities within the sector (Minten et al., 2016). In India, the proliferation of SME cold storages for potatoes resulted in rural brokers being bypassed and urban wholesalers purchasing potatoes directly from farmers at these storage facilities, despite formal regulations prohibiting such practices (Reardon et al., 2021).

Enabling factors such as governance, institutions and coordination among stakeholders play an important role and can be changed. For example, innovations along value chains may be on the contractual and institutional front. Contract farming, involving agreements whereby firms vertically coordinate upstream with farmers to deliver particular commodities, can affect farmers, and the people working for wholesalers, processors, logistics service providers, and retailers. Most studies suggest that pre-harvest coordination between growers and downstream intermediaries boosts smallholder incomes and related food security (Barrett et al., 2022a).

E-commerce platforms allow producers to sell directly to consumers, increasing their profit margins, and can improve the efficiency of the supply chain, reduce waste, promote market access and enhance financial inclusion (UNGA, 2023). For small-scale producers and middle-of-the-value-chain actors, such relationships may redistribute power and lead to more equitable outcomes. COVID-19 further boosted the growth of e-commerce - from 30 percent to 70 percent annually in India, 10 percent to 20 percent in China, and 20 percent to 50 percent in Nigeria (Diao et al., 2023). Over the past two years, e-commerce in LMICs has experienced advancements and diversification, allowing retailers of varying sizes and consumer segments to participate.

Access to finance can be promoted through novel collaboration models among stakeholders in agricultural value chains. In Mali, Senegal and Tanzania, MyAgro sells agricultural inputs and tools to small-scale producers, offering a mobile savings solution alongside to support their financial needs. Approximately 115 000 farmers in the three countries own a MyAgro account and have experienced an average harvest yield increase of 176 percent per hectare (Benni, 2023). Through the eVuna agritech platform in East Africa that enables farmer access to buyers, inputs, credit, and information, over USD 1 million in credit has been generated, boosting smallholder productivity by 80 percent and increasing incomes by an average of USD 600 per farmer (AGRA, 2024).

Distributed ledger technologies, including blockchain applications, are being implemented in supply chains for a new basis of trust for business transactions, greater transparency in monitoring and enforcement of sustainability standards for fairer compensation, traceability, land registries and to provide digital identities for rural communities (Tripoli and Schmidhuber, 2020; Meemken et al., 2024). Together with Geographic Information Systems, blockchain can bolster data collection efforts and contribute to monitoring and ultimately preventing child labour in agrifood value chains (Termeer et al., 2023).

2.3. From feeding to thriving: improving nutrition and human health

In recent years, there has been a shift from a 'food security' only approach to a 'nutrition security' approach. Such a shift can be brought to fruition through a combination of the supply of nutritious food, generating sufficient incomes to afford a healthy diet, as well incentivizing consumer demand for healthy foods. As an example on the supply side, HarvestPlus has facilitated the release of numerous biofortified varieties of staple crops, focused primarily on addressing vitamin A, iron, and zinc deficiencies. An estimated 330 million people are growing and consuming these crops across Africa, Asia and Latin America and the Caribbean. Gene editing can significantly reduce lengthy breeding processes to enhance the nutritional composition and climate resilience of crops, especially for neglected and underutilized species (FAO, 2022c).

On the consumer end, e-commerce can enhance dietary diversity and quality among rural households through better food accessibility (Shen et al., 2023). Social innovations like direct transfer payments can offer financial incentives to encourage the consumption of healthy foods and can be particularly effective when paired with taxes aimed at reducing the affordability of foods high in fats, sugars and salt. Fiscal policies to promote healthy diets, for example taxes on sugar-sweetened beverages can reduce intake. In Tonga, taxing unhealthy foods effectively shifted consumption habits, though some consumers opted for untaxed alternatives, yielding no significant health benefits (Loring et al., 2023). However, such policies often impose greater economic burdens on the poor, indicating the need for targeted support to those in need. School feeding programs are another example of innovation in an institutional setting that can lead to long-term benefits on nutrition.

Policy innovations that shift priorities towards the application of more sustainable agricultural practices and target overweight and obesity in addition to undernutrition can trigger important changes. While agricultural intensification has not been uniform across the globe, calorie-rich crops have been incentivized to be produced. The production of nutrient-rich foods can be increased by gradually shifting away from current production and consumption patterns, towards higher supplies of fruits and vegetables. Repurposing fiscal subsidies can make healthy diets affordable, but there is a risk of aggravating inequality if small-scale producers lack the resources to specialize in the production of nutritious foods. Social protection policies might then be essential to alleviate potential trade-offs (FAO, IFAD, UNICEF, WFP and WHO, 2022), concurrently with the promotion of alternative livelihoods for those negatively impacted such as small-scale producers who lack the resources to specialize.

2.4. Future-proofing: building resilience to shocks

Approaches to building resilience need to be tailored to the wide range of shocks agrifood systems face, and ensuring diversity of actors and responses is crucial. For example, crops and livestock bred for climate resilience can help small-scale producers continue to produce food in a changing climate. Similarly, the System of Rice Intensification (SRI), a set of practices to enhance the productivity of irrigated rice while using fewer resources and minimizing environmental impacts, has been linked to significant yield increases across various countries in Asia. These gains have ranged from 17 to 64 percent, with poorer farmers on smaller landholdings and during years with suboptimal weather often experiencing larger benefits (Jain et al., 2023). Setting up improved climate forecasts and pest/disease early warning systems can help de-risk agrifood systems, reducing the sphere of "unknown unknowns". In Benin, SMS forecasts resulted in estimated benefits of USD 104–356 per farmer per year, while improving monsoon seasonal rainfall forecasts in India to at least average accuracy levels could yield over USD 3.2 billion in benefits for farmers over five years (Innovation Commission for Climate Change, Food Security and Agriculture, 2023).

Concurrently, food systems are responsible for 34 percent of total anthropogenic GHG emissions and climate change is amplifying the already large environmental impacts of agriculture (Yang et al., 2024). Alternative fertilizer sources, and synthetic and biological nitrification inhibitors can increase nutrient use, while curbing GHG emissions. Climate-smart agricultural practices, such as soil carbon enhancement, biochar application and expansion of silvo-pastural systems have been projected to create a significant global carbon sink by 2050, with the largest contributions expected from LMICs (Frank et al., 2024). Financial innovations such as carbon credits can help disincentivize deforestation, though the majority of voluntary carbon markets operate in middle-income countries, not low-income countries (OECD, 2021).

Diversification across cropping and animal systems, income sources, markets and trade and in well-connected food supply chains is essential for building resilience (Elouafi et al., 2022). Evidence from multi-country studies indicates that agricultural diversification strategies provide social and environmental benefits, with multiple diversification strategies resulting in more favorable outcomes (Rasmussen et al., 2024). In Brazil, by matching institutional food procurement with local agroecological production, the National School Feeding Programme supported transitions on family farms from low agrobiodiversity, input-intensive systems to highly-diversified farming systems. As a result, smallholders increased their autonomy and resilience through market integration, diversified income, and enhanced dietary diversity (Valencia et al., 2019).

Additionally, technology and innovation can improve resilience if they support diversity in value chains, for example by enabling a mix of traditional, transitional, and modern food supply chains, as each plays a role in buffering against different types of shocks. Transitional and modern supply chains, with their broad reach, can quickly respond to local disruptions and typically have the financial strength to sustain periods of instability. At the same time, traditional local value chains, particularly those involving small-scale producers, can be nimble in adapting to demand shifts, as seen during the COVID-19 pandemic (FAO, 2021).

At the consumer end, the digitalization of social protection delivery brings several advantages, including cost reduction, enhanced accuracy and transparency of data, and improved monitoring. For vulnerable and marginalized populations, digitalization can streamline access to multiple benefits and services. It reduces travel time, transportation costs, and provides easy access to program information. Moreover, digital social protection can empower women by granting them greater control over received benefits when they are prioritized as primary recipients, and mitigate women's exposure to harassment and violence during long-distance travel for registration and benefit collection (Burattini et al., 2022).

3. The flip side: potential risks, concerns and challenges

While technology and innovation hold significant transformative potential to alleviate poverty and inequality in agrifood systems, they have pros and cons in terms of how they affect resilience and inclusiveness of rural transformation, and several challenges obstruct their effective implementation. This section highlights a few critical ones, noting that additional institutional, policy and socio-cultural barriers can stifle innovation and impede equitable access and adoption of appropriate technologies and innovations.

3.1. GM crops and Gene editing: risks and ethical dilemmas

Concerns and risks regarding GM organisms relate to benefit sharing, privatization of agricultural research, market concentration, biosafety, food safety, risk assessment and mitigation, and the corresponding regulatory and Intellectual Property Rights ramifications. Small-scale producers face specific challenges, including the higher costs of GM seeds and inputs, lack of reliable and valid information for growing GM crops, reduced participation in breeding efforts and potential negative impacts on traditional knowledge and rural practices of seed-keeping and exchanging. Notably, the widespread adoption of GM crops thus far has been restricted to only two traits, herbicide tolerance and insect resistance, in four commercial crops with mostly positive impacts on yields and varying effects on the environment and human health (Noack et al., 2024). The concept of social license, illustrated by the resistance to Golden Rice in Southeast Asia, remains central to the GM crop debate. Despite being promoted as a solution to vitamin A deficiency, Golden Rice faced protests over safety, environmental concerns, and corporate power, leading to a revoked production permit in the Philippines earlier this year (Table, 2024).

Gene-edited crops exhibit greater diversity in both varieties and traits compared to GM crops, as well as in the institutions involved in their development. Gene editing enhances breeding accuracy and efficiency, reducing costs and accelerating processes (FAO, 2022c). To benefit small-scale producers, it must be integrated into existing plant and animal breeding systems, all within a conducive regulatory and policy environment. The potential for impact will depend not only on the technology's inherent characteristics, but also on access patterns and who owns and controls it.

3.2. The digital divide

Digital technologies, while expanding across agrifood systems, risk intensifying disparities, by excluding those who are not digitally connected. People in rural areas are adopting fewer digital technologies than those in urban areas. Affordability remains a significant barrier to Internet access, with 2.6 billion people still not online. Individuals in low-income countries, who stand to gain the most from broadband access, pay the highest price for it relative to their income. The gender gap in low-income countries is even more worrying, with only 20 per cent of women connected to the Internet compared to 34 per cent of men (ITU, 2023). Furthermore, the willingness to use digital technologies is shaped by various context-specific and dynamic factors that are often harder to evaluate than availability and affordability (Porciello et al., 2022).

Digital technologies have varying investment, infrastructure and skill requirements. In contrast to 74 to 80 percent of farms of larger than 200 ha in size, only 24 to 37 percent of farms of less than one ha in size are served by 3G/4G services (Mehrabi et al., 2021). Additional issues relate to privacy concerns, data ownership, intellectual property monopolies, access and control rights, poor digital literacy, and potential loss of traditions and cultural heritage (Finger, 2023; Foster, 2023). For example, when considering precision agriculture, one should take into account that it could be challenging to ensure in small-scale agriculture in LMICs. Efficiency gains can lead to increased machinery and associated energy use and accelerate the depletion of natural resources through the so-called rebound effect. Another major concern is the challenges that digital technologies (particularly AI and big data) raise in terms of regulation, appropriate safeguards and ethics (ECOSOC, 2024).

3.3. Navigating change: automation, value chain modernization and rural employment

Fig. 2 represents a simplification of agrifood systems showing backward and forward linkages agricultural production (subsistence, family commercial and corporate commercial farms) has with upstream and downstream activities. At the bottom, the major types of labour used at each stage are included, as are the expected employment impacts from agricultural automation and modernization of agrifood value chains (shown with upward and downward arrows). This is meant as an illustration of the type of analysis that is needed to prioritize policies and investments for technologies and innovations.

The impact of agricultural automation and modernization on employment extends beyond the farm. Automation not only displaces workers doing automated tasks but also creates jobs in operating and maintaining new machinery. In contexts with scarce rural labor, agricultural automation can stimulate employment by enabling production expansion and creating storage, processing and transport jobs. However, if heavily promoted where rural labor is abundant, agricultural automation can displace workers and depress wages, especially for poorer and less skilled workers. Two additional points: first, new automation-enabled jobs require new skills, challenging workers displaced by automation. Second, if automation technologies are not scale-neutral, they can push small-scale producers and processors out of business.

However, automation and value chain modernization do not occur in isolation. They are often concurrent with a mix of R&D, with the right enabling digital infrastructure, legal, regulatory and cultural environment. It is the optimal combination of these elements that creates the potential for automation and value chain modernization to enable sustainable and inclusive rural economic development. The aspect that poor households may benefit through employment effects in the downstream segments of the value chain that are modernizing is often underappreciated (Barrett et al., 2022a). Although beyond the scope of this paper, rural and urban employment opportunities will also depend on development in other economic sectors and how these interact with agrifood value chains.

3.4. Power dynamics and corporate consolidation

In the agrifood sector, vertical and horizontal consolidation of multinational agribusiness firms has led to corporate concentration with a handful of firms controlling a significant portion of the market, exercising political power and exerting a significant influence on the

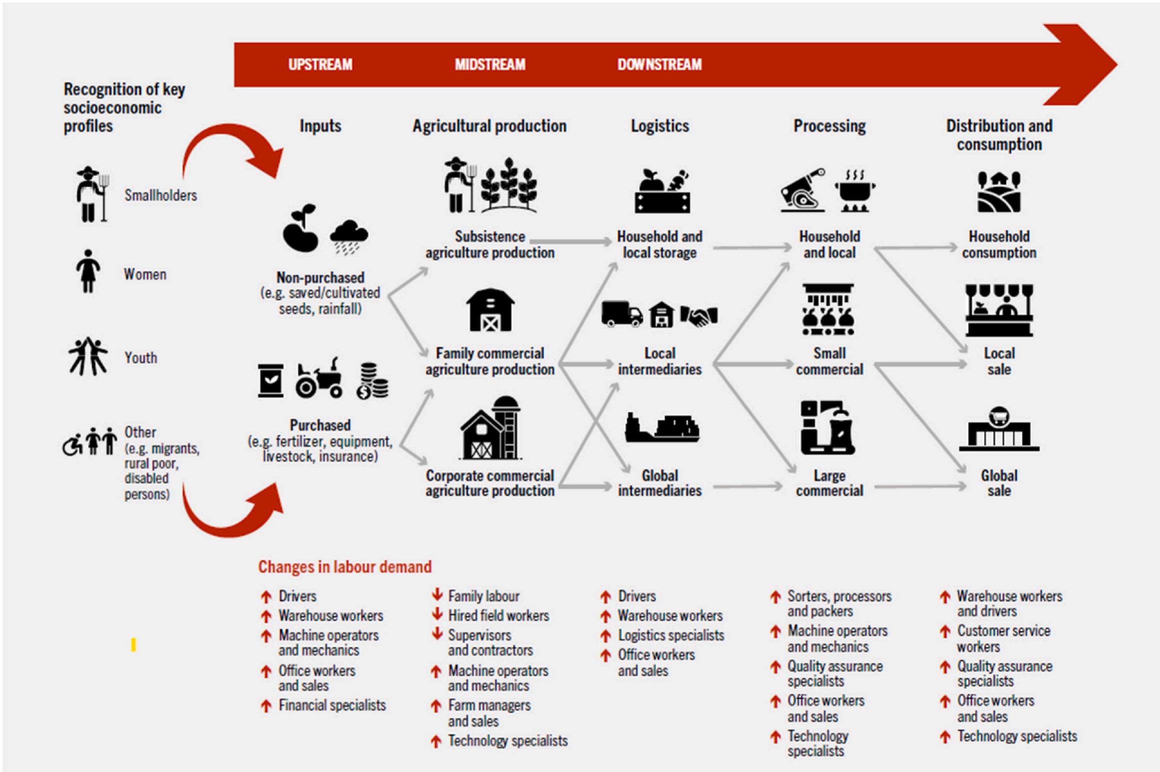

Fig. 2. An agrifood systems approach to automation impacts on employment
Source: FAO (2022b).

governance of agrifood systems (see Fig. 1). For seeds and pesticides, just four giant firms control 60 percent of the global seed market and 70 percent of the global agrochemical market (Clapp, 2022). For farm machinery, four firms account for around 40 percent of the USD 115 billion market. Similarly, there is clear evidence of consolidation within the food retail sector, commodity trading, and industrial food and beverage companies.

While mergers can allow economies of scale in resources allocated to R&D and boost innovation, consolidation can exacerbate existing power imbalances and lead to reduced competition, affecting prices and consumer choice, excluding SMEs from markets and limiting the diversity of approaches in agricultural R&D. Vertical integration, across different parts of the agrifood value chain as exemplified by the merger of seed and agrochemical companies, can lead to tighter product complementarity and influence product availability in markets. By gaining greater control over disruptive technologies like big data and AI, large corporations can further strengthen their market dominance, creating a self-reinforcing cycle of data accumulation, capital growth and expansion (FoEI, 2019).

Moreover, evidence from a range of sectors suggests that economies of scale rarely result in transformative innovation; in fact there seems to be strong negative correlation between high levels of market concentration and innovation (USFTC, 2003). Highly concentrated markets tend to focus on defensive R&D (intended to protect existing products or technologies, instead of fueling new ideas; IPES, 2017). The high volume of private R&D spending in the agrifood sector emphasizes a narrow range of crop and livestock species, technologies and approaches, detracting from research on neglected and underutilized species and/or social innovations. High-tech and relatively high-cost proprietary technologies create technological 'lock-ins' with negative environmental and social consequences (Clapp, 2021). Private R&D also limits low-cost and more accessible innovations for small-scale producers in LMICs, favoring investments with high returns.

Finally, multinational corporations can have a profound impact on science and public discourse, for example through funding academic research aligned with corporate interests and sponsoring industry-authored articles in journals (IPES-Food, 2023).

3.5. Data deficiencies and knowledge gaps

Up-to-date tracking, monitoring and assessment of technology and innovation is complex and there is a gap in their effective use, characterized by challenges of context-specificity, appropriateness, accessibility and affordability. Evidence on the potential unintended or indirect impacts of adopting improved practices or new technologies is limited. There is lack of information on the levels and patterns, including the full array of innovations needed for agrifood system transformation. When available, data is scattered, fragmented and difficult to synthesize. The data and analysis deficiencies are particularly severe for innovations that do not originate from formal research systems, including social, institutional and policy innovations, as well as discoveries that are based on Indigenous Peoples' knowledge or informal experimentation by small-scale producers (FAO, 2022d).

Most research on agricultural practices and technologies for smallholder systems is on plot-level trials, typically conducted under ideal management conditions. However, these results do not always reflect real-world farmer practices, which can vary significantly. There is a geographical and crop bias, with an overrepresentation of studies on maize in sub-Saharan Africa and insufficient attention on fruits and vegetables. The majority of studies focus on crop yield, which is only one aspect of total factor productivity, few address environmental outcomes and none couple these outcomes with yield or economic ones (Jain et al., 2023). Other methodological shortcomings relate to reliance on small, nonrepresentative samples and short time frames (Doss, 2006).

Lastly, the relationship between Intellectual Property Rights (IPR) and technological innovation in agrifood systems is complex, with limited understanding of how IPR influence innovation dynamics, especially the balance between encouraging innovation and stifling competition (Amentae et al., 2024). Knowledge about how IP frameworks can protect traditional knowledge, especially in the context of biopiracy, is also insufficient (Rotzin, 2024).

4. Key levers of change for technologies and innovations to contribute to resilient and inclusive rural transformation

Having recognized both the potential and the challenges that technology and innovation face in driving resilient and inclusive rural transformation, it is essential to consider what levers of change are needed and who must act to push progress forward. Achieving meaningful impact requires identifying the critical steps that enable technologies and innovations to move effectively from conceptualization to widespread use, particularly in resource-constrained and marginalized settings. Simultaneously, enabling factors (see Fig. 1) such as governance, institutions, power dynamics, and coordination among stakeholders will play a crucial role in either accelerating progress or hindering the diffusion and adoption of technologies and innovation.

Ensuring that innovation and technology address the specific constraints faced by vulnerable populations will require stronger measures to promote agency and equity among agrifood system actors. Such change requires not just finding the right entry points in a value chain, but actually addressing significant barriers, including market and government failures, lack of or restrictive policies, unfavorable regulation, limited human competences and financial resources, return on investment uncertainty, weak infrastructure, and risk perception, among others (Campuzano et al., 2023). From a pragmatic perspective, such a transition will not be straightforward and is likely to face political and cultural challenges. Agrifood system policies of the kind envisaged here have redistributive impacts and involve sensitive issues, making them highly political. Consequently, they frequently encounter resistance from influential lobby groups and vested political coalitions (Sutton et al., 2024). Multistakeholder engagement, often involving conflicting interests and values, to address potential trade-offs and develop acceptable strategies is indispensable for fostering political support.

Here we focus on five specific levers of change that are particularly important for traditional and transitional agrifood systems prevalent in LMICs (FAO, 2024b), namely long-term investment in agricultural R&D for small-scale producers, engaging marginalized voices as part of value chain development, equitable access to technology, providing a level playing field along value chains, and prioritizing rural employment as agriculture automates and value chains evolve.

4.1. Long-term investment in agricultural R&D in support of small-scale producers

Investing in agricultural research is a highly effective strategy for reducing poverty and hunger as well as addressing the impacts of climate on agrifood systems (IFPRI, 2022). It can significantly boost productivity, leading to more affordable food prices, which are key for poverty reduction especially in low-income countries. Economic growth in the agrifood sector has been found to be two to four times more effective at reducing poverty than growth originating in other sectors (World Bank Group, 2015). Compared to investments in irrigation, soil conservation and farm subsidies, or even in health, education, and roads, agricultural R&D expenditures have consistently ranked among the top performers in reducing poverty (Mogues et al., 2015). Over the last six decades, crop technologies developed by CGIAR and national agricultural research systems have led to an estimated cumulative economic impact of USD 1334 billion (Fuglie and Echeverria, 2024).

Global investment in public agricultural R&D doubled between 1981 and 2016, with nine countries investing more than 1 billion dollars in 2016 (measured in inflation-adjusted, purchasing power parity (PPP) dollars; ASTI, 2020). China, India and Brazil accounted for more than half of LMIC spending in 2016, while the proportion of global public agricultural R&D expenditure across all African countries has remained constant at approximately 5 percent (Stads et al., 2023). Relatively low investment in R&D has been attributed to incomplete markets, price distortions, appropriability problems, long time lags between investments and farm level benefits, and the "abstract" nature of research and innovation compared to more concrete expenditures in physical infrastructure (James et al., 2008).

Moreover, there is a deficit in public spending compared to the private sector. Between 1990 and 2014, private spending on agricultural R&D worldwide more than tripled from USD 5.1 billion to USD 15.6 billion surpassing public R&D (see Fig. 3), though concentrated on a relatively small number of commodities. While venture capital in agrifood technology dropped to its lowest in six years in 2023, agrifoodtech startups still mobilized USD 15.6 billion (AgFunder, 2024). Investment in farm robotics, mechanization and equipment has grown steadily over the past five years, whereas investment in agricultural biotechnology fell 34 percent from 2022.

Only about 4.5 percent of LMICs' agricultural output value is spent on agricultural innovation per year (USD 50–70 billion), with national governments contributing around 70 percent of total spending (Dalberg Asia, 2021). Most investment is focused on improving productivity and economic outcomes rather than environmental or social aspects. The research and innovation investment gap to achieve SDG2 and reduce GHG emissions to a level consistent with the Paris Agreement target has been estimated to be USD 10.5 billion per year for the Global South (Rosegrant et al., 2022).

It has been proposed that governments allocate at least 1 percent of their nations' GDP that relates to food systems to food related research (von Braun et al., 2021). Transformative impacts of technology and innovation often take decades to materialize, highlighting the need for long-term investments in cost-effective innovations that go beyond farm-level productivity, using a holistic agrifood system lens that recognizes the multiple interdependencies and interrelations among the actors, supply and consumption, as well as between development objectives. Investment in R&D for off-farm components, i.e. along the entire value chain (for example improved food preservation and cold chains to reduce post-harvest nutrient loss) is vital. Additionally, it is important to recognize that small-scale producers have significantly evolved over the past few decades, becoming more engaged in markets and commercialization while intensifying and diversifying their farming practices. As a result, public R&D needs to reorient and align much more closely with these changes in demand and ensure that research strategies adapt accordingly (Reardon et al., 2019).

Greater investment by research funders is needed in equity-sensitive and gender-responsive public R&D to address the unique challenges faced by women and marginalized rural communities. This investment should focus on areas where private research incentives are low, prioritizing innovations beyond major staples and commercially significant commodities, particularly neglected and underutilized species, to promote agrifood system diversification and social equity. Simulation results have indicated that repurposing a small portion of government spending on agriculture towards targeted expenditures on R&D and incentives for the adoption of innovations could reduce poverty, lower the cost of healthy diets, and reduce the amount of land needed for agriculture, although rapid repurposing of subsidies can lead to negative short-term effects (Gautam et al., 2022).

However mere advocacy for greater investment and improved allocation of funds, without tackling the underlying complexities of funding mechanisms and institutional capacities in countries, is insufficient. While larger LMICs may possess the necessary economies of scale to make strategic investments and innovate, smaller ones often lack the capacity and resources. To enhance agricultural research productivity, policies should optimize resource use and mitigate the challenges associated with small-scale research operations (Nin-Pratt and Stads, 2024). It is crucial to strengthen universities and research institutions and increase coordination among national, regional and global research organizations. Collaborative efforts should align local and global

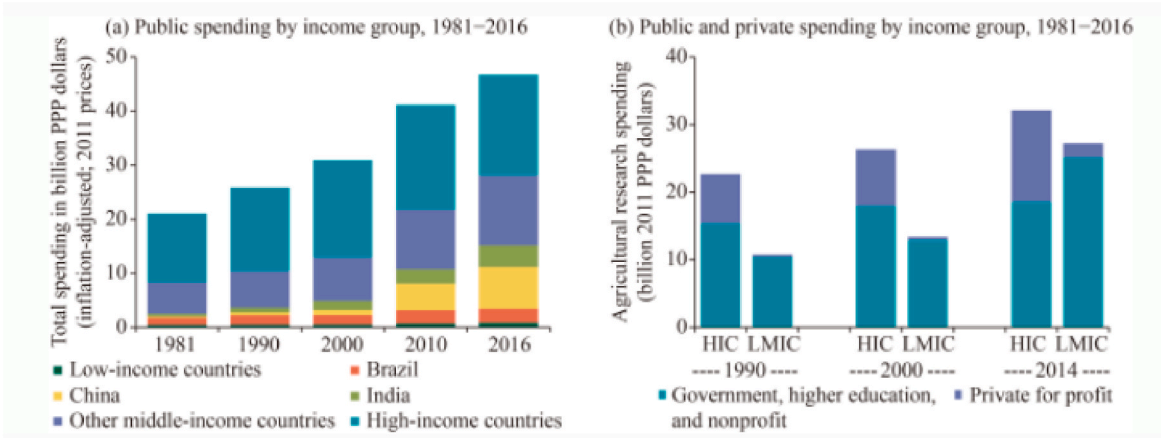

Fig. 3. Long-term trends in public (a) and public and private (b) agricultural research spending by income group
Source: Stads et al. (2023).

agendas and avoid creating competing structures, relying on flatter governance and subsidiarity principles (Tomich et al., 2019).

4.2. *Engaging vulnerable and marginalized voices as part of value chain development*

Despite making up the majority of agrifood system stakeholders and being heavily dependent on agrifood value chain activities for their livelihoods, the interests of small-scale producers, women, and other marginalized groups are often overlooked. Engagement with these stakeholders is key in terms of how to improve their livelihoods both from primary production and from capturing some of the value addition opportunities along the value chain.

Most (published) research is not relevant to the needs of small-scale producers, is focused on how technologies work in isolation and often conducted without farmer involvement and participation (Laborde et al., 2020). Effectively aligning agricultural research with the needs of small-scale producers will require taking into account the heterogeneity of contexts in terms of scale and farming systems, and leveraging local and traditional knowledge. Additionally, many technologies and innovations are developed by and most appropriate for high-income countries, creating a mismatch that limits technology transfer to LMICs (Moscona and Sastry, 2022). Technologies and innovations must therefore either be customizable or profitable across contextual conditions or accompanied by complementary inputs and resources to ensure their effectiveness.

Researchers and technology developers should establish inclusive dialogue and actively engage with affected communities to develop a shared vision, foster understanding of technological advancements (such as GM crops) and ensure legitimate social acceptance that aligns with local values (Kettenburg et al., 2018). Empowering less powerful actors through co-creation of knowledge and adapting technologies to their environments is critical. This shift towards co-innovation demands changes in research methodologies, governance and capacity-building for inclusion. An enhanced focus on transdisciplinarity, authentic participatory research and dialogue that leverages local knowledge, as well as investments in demand-driven extension and rural advisory services, are key for bridging the gap between research and its practical application. For example, the Science and Technology Backyards in China connect scientists and small-scale producers, local government, and private enterprises, and have been instrumental in facilitating information exchange and developing bottom-up innovations (Jiao et al., 2019). However, efforts to include some groups may inadvertently overlook others (McCampbell et al., 2021).

LMIC knowledge, experiences, and perspectives are underrepresented. The global distribution of scientific capacity is highly uneven, and only 16 percent of articles in high-profile development journals are authored by researchers exclusively based in LMICs (Amarante et al., 2021). Additionally, much Indigenous Peoples' knowledge remains undocumented and not integrated with science-driven technology and innovation development. Women continue to have a smaller footprint in the research landscape. Thus, inclusive agricultural R&D requires integrating diverse perspectives of LMIC researchers, fostering international partnerships, and aligning efforts to strengthen research capacity in LMICs.

Innovation along value chains can enhance the livelihoods of vulnerable populations by engaging them in downstream activities such as processing and packaging of higher-value goods, creating income and employment opportunities. The labor-intensive nature of processing offers a vital entry point for SMEs, especially in low-income regions. In Africa and South Asia, the innovation brought about by rapid expansion of midstream value chains driven by SMEs presents untapped potential for inclusive economic development, though it remains underexplored by researchers and policymakers (Vos and Cattaneo, 2021). Leveraging this type of innovation through engagement of vulnerable populations is key for rural transformation and improving incomes with activities beyond the farmgate.

4.3. *Equitable access of marginalized populations to technologies and innovations*

To increase the likelihood of adoption and scaling, governmental institutions must address the economic and behavioral constraints that impede uptake. Enhanced awareness of new technologies together with the relevant insights about the returns to the technology through expanded extension and education activities attuned to their information needs and social networks can be a major leverage point for empowering small-scale producers and increasing adoption rates (Suri et al., 2024). Interventions to strengthen and diversify value chains can improve the reliability of input quality, lower information costs about market conditions and prevailing prices, and enhance returns on financial intermediation (Bridle et al., 2020).

Caution is needed with high-tech, production-focused solutions that may be seen as 'silver bullets.' Instead, a balanced perspective is required, integrating the benefits of technologies and innovations with the principles of social justice, equity and community empowerment (Loken et al., 2024). A portfolio approach that facilitates the bundling of co-designed and contextually appropriate technologies with complementary and synergistic financial, social and institutional innovations can enable Pareto improvements and obviate trade-offs, with one innovation compensating for the adverse effects of another (Barrett et al., 2022b). For example, the success of rinderpest eradication cannot be solely attributed to the vaccine; global scientific collaboration, efficient cold chain distribution systems, community involvement, political support, awareness initiatives, and internationally coordinated vaccination efforts, together with unrestricted IPR related to the vaccine were pivotal (Roeder et al., 2013). Similarly breeding breakthroughs produced high-yielding orange-fleshed sweet potato (OFSP) varieties with enhanced beta carotene, improved drought tolerance and local adaptability. But these advances had to be combined with efforts to improve access, raise awareness of OFSP's health benefits, and promote its consumption and value chain development (Lidder and Dijkman, 2019).

Technologies impact various social groups differently, even within the same geographical or agroecological context, potentially creating winners and losers. Additionally, small-scale producers, women and other social groups are not homogeneous; various identities and categorizations intersect, creating overlapping systems of discrimination or disadvantage. Human rights-based monitoring of technology- and innovation-based interventions, including the collection of disaggregated data, is therefore essential to ensure that the benefits are measured against effects on marginalized populations over time, and to evaluate effectiveness compared to other approaches. To improve the welfare of small-scale producers and vulnerable agrifood system actors, the impact of technology adoption on well-being should encompass not only economic indicators like income and productivity, but also social and environmental metrics, as well as value judgments such as happiness necessitating the use of qualitative approaches (Abdul-Majid et al., 2024). Understanding the factors behind the success or failure of innovations in specific contexts, considering farmers' behavior and employing best-practice methods to accurately evaluate different technologies should be prioritized (Stevenson et al., 2023). A diverse set of metrics is essential to address various types and objectives of innovation across different stages and scales, incorporating multiple stakeholder perspectives and resource levels for measurement.

Incorporating context-specific analyses to understand demand for a given technology/innovation and considering the needs of these groups, from design to implementation, is necessary for ensuring they reap the benefits (Vemireddy and Choudhary, 2021). For example, limited access to land, financial resources, social networks and information, coupled with systemic barriers like male-centric technology design and cultural biases, restrict women's adoption rates. Policies, legislation and investments that address their disadvantages (e.g. supporting broadband Internet access for remote and rural communities, improving women's access to credit and extension, strengthening women's tenure security, promoting STEM education for female students, while also acknowledging the value of complementary soft skills) can help increase their access to technologies. Similarly, prioritizing a policy agenda to equip rural youth with the necessary skills is vital.

4.4. *Leveling the playing field by curbing corporate dominance and incentivizing private sector engagement with small- and medium-scale agrifood enterprises*

Multifaceted and targeted policies, regulatory measures, and economic and legal instruments, grounded in a people-centered and rights-based approach, are required to reduce costs and risks (such as overconcentration of market power), while creating the right incentives for inclusive agribusiness models. Curbing corporate dominance is challenging, and while most governments have anti-trust legislation in place, it is narrowly focused on price effects to consumers or efficiency concerns (IPES-Food, 2023). Given that the vast majority of mergers and acquisitions occur within countries (Keenan et al., 2023), more stringent domestic measures by national governments are necessary, including robust and effective competition laws and stricter rules for preventing industry influence in shaping research and regulatory guidance. Regional organizations can play a vital role to counter the anti-competitive conduct of multinational firms, especially in countries without competition authorities or competition laws (Buthelezi et al., 2023). Regulations regarding the use of certain innovations, especially as it pertains to data, are crucial to ensure that technologies are not misused by private sector or government actors against certain groups of the population.

At the same time, expanding access of small-scale producers and SMEs along the value chain, to finance and competitive markets is essential. Mechanisms like contract farming, farmer cooperatives, producer organizations, etc. can lower transaction costs, increase bargaining power and counterbalance market dominance by vertically integrating small-scale producers. Incentivizing private sector operations that align with the needs of LMICs implies creating shared value for both the private sector, and small-scale producers and SMEs. Beyond tax incentives and public-private partnerships, risk-sharing mechanisms such as blended finance can de-risk investments in smallholder farming, making it more attractive to private capital.

In this context, small venture capital investors—such as seed funds, startup accelerators, science venture funds, and government agencies can help to create innovation ecosystems that foster the exchange of knowledge and entrepreneurial insights. Nonetheless, while venture capital is crucial for innovation, investors often favor low-risk, fast-return opportunities, particularly in downstream segments of the value chain such as e-commerce solutions, where technologies are more mature and offer greater profit potential (Mac Clay et al., 2024). Consequently, upstream technologies are often overlooked due to higher risks and longer return timelines. A mission-oriented approach that fosters collaboration between public and private sectors can help attract more private investment into these technologies over time. Evidence suggests that establishing effective mechanisms for dialogue and collaboration, tailored to the specific country and context and ideally organized by value chain, can help address evolving challenges (AGRA, 2024).

Finally, while demand for renewable energy can create lucrative opportunities for smallholders, declining profitability in conventional farming could lower land opportunity costs, allowing energy companies to acquire land more cheaply. This is compounded by a feedback loop between renewable energy and novel non-farm food production methods. Relying solely on unregulated energy markets poses risks for rural communities, and a proactive approach to farm subsidies is needed to protect rural areas as de-agrarianized production methods impact farm profitability and land values (Barrett, 2020).

4.5. *Considering rural employment generation as a priority as agriculture becomes more automated and agrifood value chains transform*

The increasing use of automation in agriculture and transformation of agrifood value chains has been incremental, increasing labor productivity, and will likely continue to be so, but the process will not be without friction; the adoption (or non-adoption) of labour-saving technologies will create unemployment at some times and in some places. There are policy approaches that can help the positive social impacts of the increase in higher-paying, less seasonal work outweigh the negative impacts of the decrease in low-paying, seasonal employment, facilitating alternative employment opportunities for affected workers.

In general, governments must avoid excessive and too rapid automation, especially in low- and lower middle-income countries where rural labour is abundant and wages are low. This can lead to negative social impacts, especially for less skilled workers. On the other hand, government policies must also avoid creating obstacles to agricultural automation on the assumption that this will preserve jobs and incomes. This assumption is likely to be flawed because such policies make farms less competitive and unable to expand production, while the adoption of new technologies can improve wages and working conditions for farm workers.

Another area of intervention concerns building human capacity. Public efforts to build knowledge and skills of relevant stakeholders concerning agricultural automation as well as the skills needed in expanding downstream activities will be key to support scaling and ensure an inclusive process through improved labor productivity.

In parallel with building human capacity, policy support that provides public or collective goods, such as developing and maintaining infrastructure (e.g. energy and internet connectivity), will enable a smoother transition to greater automation and value chain integration, while minimizing risks of unemployment. Improved market infrastructure with a particular focus on short supply chains, local and territorial markets will be important. Small-scale producers must be supported to link directly to rural and urban consumers through online marketing platforms, producer and consumer cooperatives, etc.

5. Conclusion

The journey towards resilient and inclusive rural transformation through innovation and technology is fraught with complexities, ethical dilemmas, and the potential for unintended consequences. However, this challenge also presents an unparalleled opportunity to reimagine and reshape agrifood systems in ways that prioritize the marginalized, democratize access to technology, and foster an equitable distribution of benefits. Technologies and innovations aimed at inclusive rural transformation need to address the specific vulnerabilities and needs of the food insecure and climate-vulnerable, ensuring economic viability for small-scale systems. The future we must envision is one where innovation and technology are not seen as ends in themselves–aimed at improving efficiency–, nor do they exacerbate existing inequalities; rather they are leveraged as tools for social justice and environmental sustainability. To achieve this, a shift is needed towards a model of development that is participatory, equity-sensitive and gender-responsive. This calls for a concerted effort to dismantle the barriers that prevent small-scale producers, Indigenous Peoples, women, youth and other marginalized groups from accessing and benefiting from these advancements.

Quick technological fixes are unlikely to succeed; resilient and inclusive rural transformation will come from long-term research and innovation processes that incorporate critical inputs from local and traditional knowledge and are underpinned by supportive policies, and social and institutional reforms. Such strategic deployment will need a network of actors and an enabling environment, and must be accompanied by increased investments in equity-sensitive R&D, gender-transformative policies, and strengthened individual and institutional capacities. Good governance and strong political will is vital to ensure that vulnerable and marginalized people have access to services, rights, technologies, information, markets, and economic opportunities.

CRediT authorship contribution statement

Preetmoninder Lidder: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Andrea Cattaneo:** Writing – review & editing, Writing – original draft, Methodology. **Mona Chaya:** Writing – review & editing.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to Ben Davis, Leslie Lipper, Paul Winters and three anonymous reviewers for their insightful feedback on an earlier version of the paper. Thanks are extended to all the experts who participated in the Expert Consultation on Shaping priorities for investment in resilient, inclusive rural transformation (RITI) of 01–03 March 2023 that helped sharpen the paper.

Data availability

No data was used for the research described in the article.

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