frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 09 May 2023
DOI 10.3389/fsufs.2023.1108949

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Land, Livelihoods and Food Security, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 26 November 2022
ACCEPTED 23 February 2023
PUBLISHED 09 May 2023

CITATION
Prasad PVV, Bhatnagar N, Bhandari V, Jacob G, Narayan K, Echeverría R, Beintema N, Farah Cox P and Compton J (2023) Patterns of investment in agricultural research and innovation for the Global South, with a focus on sustainable agricultural intensification. *Front. Sustain. Food Syst.* 7:1108949. doi: 10.3389/fsufs.2023.1108949

Patterns of investment in agricultural research and innovation for the Global South, with a focus on sustainable agricultural intensification

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This study is the first attempt to determine global investment patterns for research and innovation in agriculture systems for the Global South, and specifically for innovation funding targeted at sustainable agricultural intensification. We analyzed and modeled patterns of funding from governments in the Global South, development partners, private companies, and private equity and venture capital funds, using primary and secondary sources of data spanning 2010 to 2019. We ascertain the key providers and recipients of innovation funding and how it is shared out between different topics and value chains. Results showed that about $60 billion of funding (ranging from $50 to $70 billion) goes toward agricultural innovation for the Global South each year, with 60–70% of it coming from these countries' own governments (and the government of China accounting for as much as all others combined). This $60 billion investment represents just 4.5% of Global South agricultural output. Furthermore, <7% of the total funding was found to have detectable environmental intentions, and less than 5% had both social and environmental intentions. Adopting a standard for transparent reporting and measurement could potentially lead to swift changes in funding patterns toward sustainability goals.

KEYWORDS
innovation, investments, agriculture, sustainable intensification, Global South, research

1. Introduction

The countries of the Global South face monumental agricultural challenges in the coming decades. They will have an estimated 31% more people to feed by 2050—which will be around 86% of the world population (United Nations, 2022). The total population in the Global South will put severe constraints on resources and carbon budgets. For instance, China will face the daunting task of feeding 22% of the world population with 7% of the world's arable land (Chaudhury, 2020), while India will need to feed 20–25% of the world's population with only 4% of the world's freshwater (World Bank, 2022). However, in year 2022, the rate of population increase declined in China and population decreased for the first time over many decades, and this trend may continue. While population of India will continue to rise although at slightly slower rates. Additionally, adequate livelihoods will need to be found for millions living in rural areas who will face shrinking land sizes and incomes. Significant innovation in sustainable agricultural intensification (SAI) will be necessary to meet food demand while avoiding environmental and socio-economic disaster (Steensland, 2021).

A thorough understanding of funding trends in agricultural research and innovation (hereafter shortened to "innovation") is critical to guide future funding decisions and help in the sustainable achievement of food goals. However, funding data were scattered, definitions of sustainability and innovation were not consistently applied by different actors, and consequently, a global view of these funding patterns is missing. While many stakeholders within the agricultural innovation system align on the need to switch to sustainable agricultural practices and on the need for increased funding on this topic, further effort is hindered due to a poor understanding of the current funding patterns for innovation. While there have been some successful efforts to track funding for agricultural research (for example Dehmer et al., 2019; OECD, 2019; Beintema et al., 2020) this is mainly focused on science and technology and there is little or no information available on other important aspects of innovation, for example in finance and business practices (FAO, 2022). Moreover, global data are fragmented and not based on a common framework and definitions. Consequently private, public and philanthropic investors in innovation might be trading off sustainability in the future for short- to medium-term gains in agricultural productivity using unsustainable methods. Further, even wellintentioned stakeholders and investors might be underfunding in SAI innovation or might have a misplaced assessment of sectors and themes that need more funding.

Such is the backdrop for this effort to reach a baseline estimation of SAI innovation funding intended for the Global South. This article outlines the key findings from a working paper (Dalberg Asia, 2021a) commissioned by the Commission on Sustainable Agriculture Intensification (CoSAI; https://www.iwmi.cgiar.org/archive/cosai/), an independent international commission supported by Consultative Group for International Agricultural Research (CGIAR), a global agrifood research network. The assessment covers funding into different categories of SAI innovation activity, globally, by the public sector, private sector, philanthropic and development donors, as well as and private equity and venture capital[1] (PE/VC). We assess the total funding being made annually into agricultural innovation by these actors; the total funding being made in SAI innovation as a subset of agricultural innovation; and how this funding is split between regions, value chains and categories of innovation. Our findings present an opportunity for future updates to revise these estimates as new data becomes available.

1 Private equity (PE) refers to funding from institutional and/or individual investors in return for an equity stake in potentially high-growth investments and companies not quoted on a stock exchange. Venture capital (VC) is a subset of PE that supports early-stage, high potential start-ups, taking higher investment risks and seeking commensurate returns.

2. Materials and methods

Full details of the methodology can be found in Dalberg Asia (2021b). The study covers the four key categories of funders for agricultural innovation globally: (1) Global South governments (domestic budgets); (2) development partners (bilateral, multilateral and philanthropic donors); (3) private companies; and (4) private equity and venture capital (PE/VC) investors (Figure 1). Data spanning 2010–2019 was collected from industry reports; annual reports of companies; government budget and funding documents; third-party online funding data sources such as Tracxn.com and Statista.com (PE/VC), OECD.Stat (development partners) and the Bill and Melinda Gates Foundation (BMGF) grants database (BMGF, 2020); expert conversations; and credible media reports. Individual framework of analysis for funding streams or projects were identified to the extent possible, and each was tagged by innovation layer (Figure 2), value chain, funding source, funding recipient, target country, and SAI domain (see definitions below). Other tags (e.g., funding instrument, stage of innovation, target user type) were also applied where information was available, but results are not presented for these as the data were too patchy. Tagging was done manually for most data, with sampled cross-checking, but for the OECD. Stat dataset, given its size, we used word crawl algorithms along with sampled triangulation.

Once tagging was complete, we summed individual funding streams to estimate total funding and share by category. For several questions, funding data lacked comprehensiveness or granularity, and the models developed for this study use extrapolations and interpolations to compute funding values in these cases. The results highlight ranges and assumptions wherever appropriate. The reasonableness of the estimates was validated, where possible, through experts across each of the funder categories.

All values were converted to constant 2019 prices and constant 2019 US$ exchange rates. Comparisons across countries will thus differ from calculations based on purchasing power parity, such as Beintema and Stads (2019).

2.1. Definitions used for the analysis

Funding in innovation, agriculture, SAI and the Global South are constructs interpreted differently by different organizations. This study used the following definitions.

2.1.1. Funding in innovation

This includes all funding related to the creation or adoption of new agricultural technologies, practices and systems (Table 1). In addition to purely technological innovation, the study includes funding in non-technological areas such as business models, policy reforms, agricultural extension and training, process innovations,

	Total annual funding in ag innovation (2010 – 19, annualized) *(USD Bn)*	Availability of bottom-up information *How much of the universe is uncovered?*	Granularity of information *What is the resolution of information?*	Implications for our methodology *What is the methodology of estimating investments?*
1 Global South Governments (domestic funding)	35-45	• Covered 4 countries representing >90% of public spending and >50% of agricultural innovation spending	• Only high-level details available for two out of four countries	• Analyzed country budget line items to identify ag spending, and used these line items to estimate innovation spend and conduct bottom-up tagging
2 Private Companies	9-18	• Analyzed 20+ companies from 10 sub-sectors contributing >20% of investments	• Required detail available from company annual reports	• Estimated innovation spend for each company by calculating their R&D and adoption spending
3 Development Partners (Philanthropic, Multilateral, & Bilateral Agencies)	~5	• Analyzed complete OECD dataset with information on >115K projects	• Project description available but challenges found for notable proportion of projects	• Performed semi-automated tagging on OECD.stat project database for bottom-up tagging and analysis
4 Private Equity and Venture Capital Investors	1.5-2	• Analyzed investment data for 600 transactions from the Tracxn platform	• Investment amount with required description available	• Estimated total investments using AgFunder estimates and performing adjustments; Leveraged Tracxn database for bottom-up tagging to identify investment trends

FIGURE 1
Data availability and granularity across different funding sources. Source: Dalberg Asia (2021a).

and marketing funding on innovative technologies. This expanded definition allows the study to count new business models, startup funding on e-commerce platforms that promote access to agriculture inputs, and other similar examples—all important funding in agricultural innovation. On the other hand, pure subsidies to purchase existing products and services in agriculture, routine administration costs, and general infrastructure funding such as rural roads are not counted as innovation funding. Percentage values for funding other than research and development (R&D) were applied to individual funding streams on a case-by-case basis to account for funding that was judged to support adoption of innovative agricultural practices. All percentages used are listed in the detailed methodology (Dalberg Asia, 2021b).

2.1.2. Agriculture

The study includes all funding linked to on-farm food value chain activities and any off-farm processes essential to the production of a consumable food product. Since the goal of the study is to understand the Global South's preparedness for a sustainable food secure future, the analysis is limited to funding in food, including, for example, innovations related to on-farm food production, milling, milk pasteurization and urban/vertical farming. It excludes funding in cash crops such as cannabis, cotton, paper, rubber and wood, as well as innovations for food retail and in non-essential value-added categories such as milk flavoring or manufacturing of potato chips. It also excludes innovation in general areas that have indirect effects in agriculture: for example, innovation in general information technology is excluded but innovation in applications for agricultural extension or finance would be included.

2.1.3. Sustainable agricultural intensification (SAI)

It is a multi-dimensional construct with different actors adopting different definitions (e.g., Pretty, 1997; Garnett et al., 2013; Rockström et al., 2017; Mockshell and Kamanda, 2018). This study uses five agriculture sustainability domains—economic, social, environmental, human condition, and productivity—laid out in the Sustainability Intensification Assessment Framework by Musumba et al. (2017) and Stewart et al. (2018) (web version of the framework available at https://sitoolkit.com). This framework was used since it allowed the team to analyze funder intentions with variable quality data across multiple funders, while providing the flexibility to consider various definitions of SAI.

We tagged stated SAI intentions for each sustainability domain for each individual research/innovation project or funding stream analyzed, based on its title and any other description or keywords available. Examples are given in Table 2. We define both a broad (minimum requirements) and a narrow (more demanding)

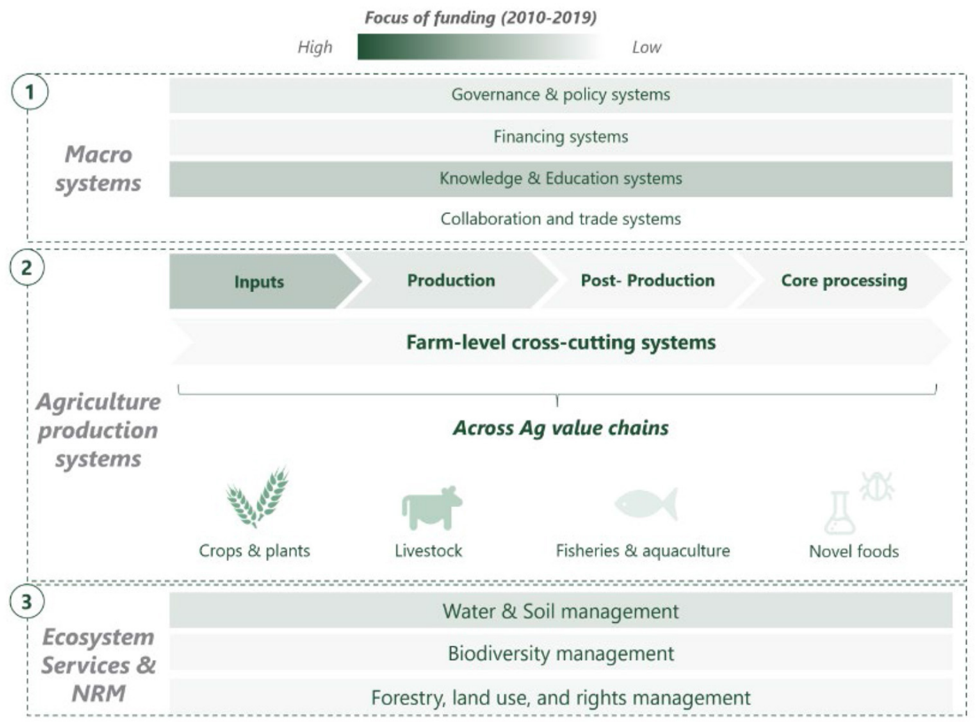

FIGURE 2
Framework of analysis for innovation funding. Source: Dalberg Asia (2021a).

TABLE 1 Funding for innovation in agriculture: what the study included.

	Funding type	Proportion considered	Example of inclusions
1	Research and development (R&D)	100%	Research and product development funding to develop a new seed variety
2	Extension/marketing	% Depending on funding description	Programs training farmers on using new agroforestry practices; Marketing spends for a new hybrid seed
3	Institutional/infrastructure		Management and maintenance of research institutions; Operations of programs to modernize slaughterhouses
4	Policy reform		Funding in implementation or adoption of agricultural policies, e.g., reform of fertilizer subsidies
5	Process/business model changes		PE/VC funding for startups developing digital marketplaces for purchase and sale of agricultural produce

Source: Dalberg Asia (2021a).

meaning of SAI (Figure 3), and report results according to the broad definition, except where otherwise noted:

- *Broad definition of SAI:* Funding that intends to produce both gains in productivity and improve environmental sustainability.
- *Narrow definition of SAI:* Funding that meets the above criteria, and also intends to improve human (nutrition, education) *or* social (equity) dimensions, as shown in Figure 3.

2.1.4. The Global South

This term used in this report follows the World Bank classification of low- and middle-income countries, which includes countries and territories in Asia (including China but excluding Japan, Singapore, and South Korea), Central America, South America, Mexico, Africa (including South Africa), and the Middle East (excluding Israel). Further, this study looks at funding targeted "for" the Global South. This means that it considers innovations intended to specifically impact Global South nations. However, for two funding sources—governments and PE/VC investors—this study looks at funding "in" the Global South nations, since based on expert interviews, this seems a suitable proxy for funding for the Global South. For example, most funding for agricultural research in Kenya is focused on Kenya or other Global South nations.

2.2. Limitations of the study

The estimates in this study have many sources of uncertainty. Data on agricultural innovation funding, especially SAI innovation,

TABLE 2 Examples of stated intentions considered under each sustainability domain.

Economic	Environment	Social	Human	Productivity
Increasing output per unit input	Improved soil quality	Social equity	Improved nutrition	Improving yields
Reducing variability of profit	Improved biodiversity	Gender equity	Health and food safety	
Reducing cost of production	Improved water quality	Reduced conflict	Food security	
	Mitigation of climate change		Improved capacity to learn	
	Reduction of ocean acidification			
	Fuel availability			
	Biogeochemical flows			

Source: Dalberg Asia (2021a). Domains based on Stewart et al. (2018) (www.sitoolkit.com).

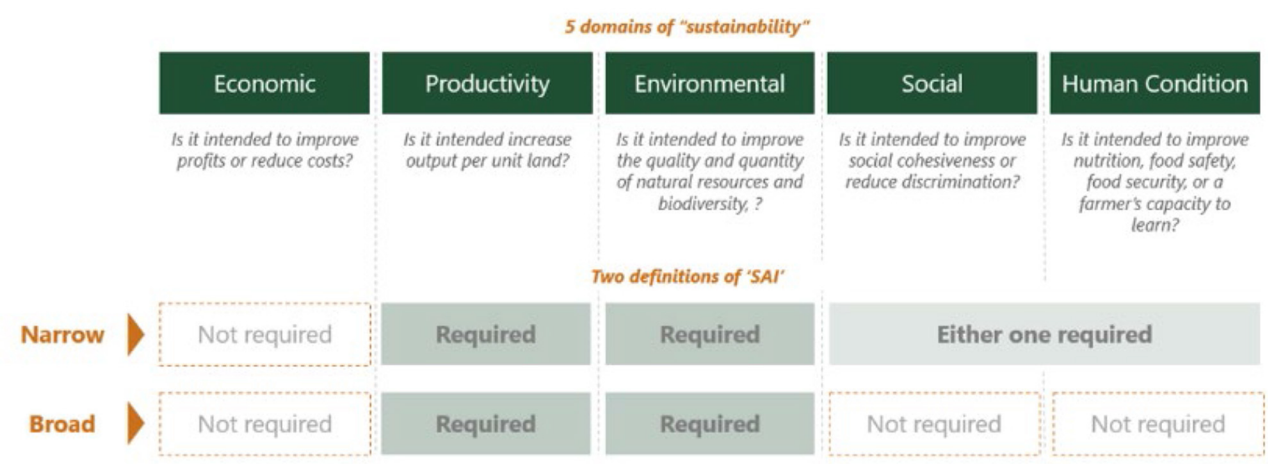

FIGURE 3
Broad and narrow definitions of sustainable agricultural intensification (SAI) based on stated intentions. Source: Dalberg Asia (2021a). Five domains of sustainability based on Stewart et al. (2018) (www.sitoolkit.com).

is not easily accessible, and few countries or organizations report this data in sufficient detail. Since many of the specific analyses in this report are, to the best of our knowledge, being carried out for the first time, they incorporate assumptions and extrapolations based on the best information we could obtain, including expert opinion. Specific assumptions, multipliers and sources are fully listed in the detailed methodology (Dalberg Asia, 2021b).

The study extrapolated global funding from the sum of the largest funders, especially for public and private sector funding. Detailed data were not obtained for any but the largest private investors and countries. This led to two major limitations: the global analysis could not be disaggregated (e.g., by continent), and the analysis was potentially biased by those included: in particular, detailed country data on SAI investment was limited to India, and some food companies were excluded (FAO, 2022). Pray and Fuglie (2015) expertly discuss the challenges with estimating private sector funding for agricultural R&D. The development partners category excludes funding not captured by the Organization for Economic Co-operation and Development (OECD). Stat database, for example public research funding provided by the Global North but not counted as Official Development Assistance (ODA); funding not marked as research or innovation; and some philanthropic and multilateral funders that do not report details of their projects within the OECD Creditor Reporting System—but this is a less important limitation.

As in some similar studies of funding flows (Biovision and IPES Food, 2020), our analysis of SAI funding is based on stated sustainability *intention*, not the finally-achieved outcomes (and impacts), for which data were very rarely available due to long lags between investment and outcomes at scale (Frontier Economics, 2014; Rijsberman, 2016; FAO, 2022), as well as the challenge of attributing outcomes to specific innovations (Maredia et al., 2014). This is an important limitation of the study that may lead to over- or under-estimating SAI outcomes in individual cases—but without better data, it is not easy to tell whether there is a consistent overall bias. Stated "good intentions" may over-estimate SAI outcomes in many cases, not only because of potential greenwashing (Gatti et al., 2019) but because of the inherently risky and long-term nature of research and innovation. Equally, stated intentions may underestimate SAI outcomes when increased productivity alone has positive effects on sustainability outcomes such as poverty, nutrition or climate change mitigation (Searchinger et al., 2019; Fuglie et al., 2022).

Furthermore, as the study relies on project or program funding descriptions to identify SAI intentions, there are likely to be underestimates due to inadequate descriptions. Underestimation is potentially more likely in the case of Global South governments, which are under less pressure to describe their innovation programs as sustainable than are development partners and large-scale private sector companies. On the other hand, in some cases, particularly for private corporations, SAI tagging was applied to large areas of funding when more granular data were not available (e.g., using annual reports), and this may have overstated specific intentions for individual projects and funding streams.

This data did not allow us to distinguish between different degrees of sustainability, or between "incremental" and "transformational" innovation (Gliessman, 2015). For example, a piece of research on precision application of pesticides (to reduce the quantity applied) would be identified as "environmentally sustainable intentions," i.e., the same as an agroecological investment. This is a limitation of this study which can only be fixed in future by broad agreement on definitions and improving reporting standards.

Finally, our analysis measures *external funding* into innovation and not cash or labor investments made by farmers or other direct value chain actors in their own enterprises, although this is recognized to be globally important (MacMillan and Benton, 2014; Waters-Bayer et al., 2015).

3. Results

Here we examine the main patterns of funding in agricultural innovation for the Global South over the period 2010–2019, and the allocation of these funds across funding sources, implementing agencies, and sub-sectors and value chains within agriculture.

We estimated average total annual funding on agricultural research and innovation for the Global South between 2010 and 2019 to be about $60 billion per year (range $50–70 billion). This total represents just 4.5% of agricultural output value in the Global South (as sourced from FAO.Stat datasets on agricultural value-added, constant US$). This innovation funding intensity compares poorly to the energy sector, another critical sector for economic growth and tackling climate change, which has sub-sectors spending 6% of revenue on R&D alone (and significantly higher if other innovation cost heads, such as marketing the innovation, are considered) (Osborne, 2019). If an equivalent ratio (6%) were applied to the agriculture sector, this would imply a non-trivial increase of about $20 billion a year in innovation funding for the Global South.

Over the decade examined (2010–2019), overall funding in agricultural innovation increased. The first half of the decade saw substantial growth averaging ∼7% per annum, driven primarily by increases in government as well as private sector funding. However, large private sector investment in innovation decelerated to 2% per year in the second half of the decade, as discussed below.

R&D as traditionally understood—i.e., conducting scientific research or developing new technical products and services—accounted for just 33% of total innovation funding. Marketing of technical innovations (a fraction of overall marketing funding by organizations), along with public and private sector extension services and training programs to help farmers and producers adopt these innovations, accounted for 37%. Innovations that intend to create or strengthen institutions or infrastructure accounted for another 26%—for instance, programs such as the Rashtriya Krishi Vikas Yojana (https://rkvy.nic.in) and National Horticulture Missions (https://hortnet.gov.in) in India. Innovation funding for new policies and subsidies for adoption of innovations only accounted for only a small fraction of the overall funding spend (<5%), although it was possible that some policy funding was counted under other types of innovation. Increased funding for policy innovation, as well as bundling policy and institutional reform with technical innovation (Barrett et al., 2020), could drive sustainability transformation at scale. For example, in Brazil, EMBRAPA (The Brazilian Agricultural Research Corporation) has worked closely with the government to develop agricultural policies that enable productivity and sustainability within the sector (see Dalberg Asia, 2021c), and CGIAR also works extensively with policy-makers (Njuki and Nicol, 2021).

3.1. Main funding sources, value chains, and recipients

The main patterns of funding are shown in Figure 4. Using $60 billion as the denominator, Global South governments account for about 60–70% of total innovation funding; the private sector about 15–30%; development partners (multilateral development banks, bilateral aid agencies and philanthropic foundations) about 8%; and startups funded by PE/VC 2–3% of the total.

Funding for innovation in food commodity value chains increased (both real terms and percentage) by about 50% over the decade examined (Figure 5). Crops received 50–60% of value chain-related funding, with livestock <20% and fisheries and aquaculture about 5%. Crops account for 80–90% of the cumulative innovation funding made by the private sector and startups, largely due to innovation programs at large seed, pesticide and fertilizer companies such as Bayer Crop Science, ChemChina, Syngenta and John Deere (farm equipment for crops) that invest significantly in both R&D and marketing of innovations.

Overall, the innovation funding in crops from the private sector is higher than their proportionate contribution to overall output value (Figure 6). However, innovation funding for both fisheries and livestock are expected to increase significantly in the future due to the high commercial value of these categories. A higher focus on sustainability will be important given the high environmental footprints, especially for livestock (Herrero et al., 2015) and aquaculture. We found a significant increase in funding (both real terms and percentage) for fisheries and livestock in PE/VC funding to agricultural innovation over the decade (from a low base): livestock and fisheries received only about 1% of funding in 2010, but this had increased to close to 10% by 2019.

While funding for alternative proteins still forms a small fraction of overall funding in agricultural innovation, this is growing very rapidly in the Global South, as it is globally (Dion et al., 2020; FAIRR, 2021), and if successful models and products emerge, some innovation funding from livestock and fisheries might get redirected to this space.

The main recipients (users) of agricultural innovation funding are government agencies (∼50%) and private companies (∼30%); universities and research institutes (∼16%), with

FIGURE 4
Flow of funds by source and recipient of innovation funding 2010–2019 (annualized, constant 2019 prices). Source: Dalberg Asia (2021a).

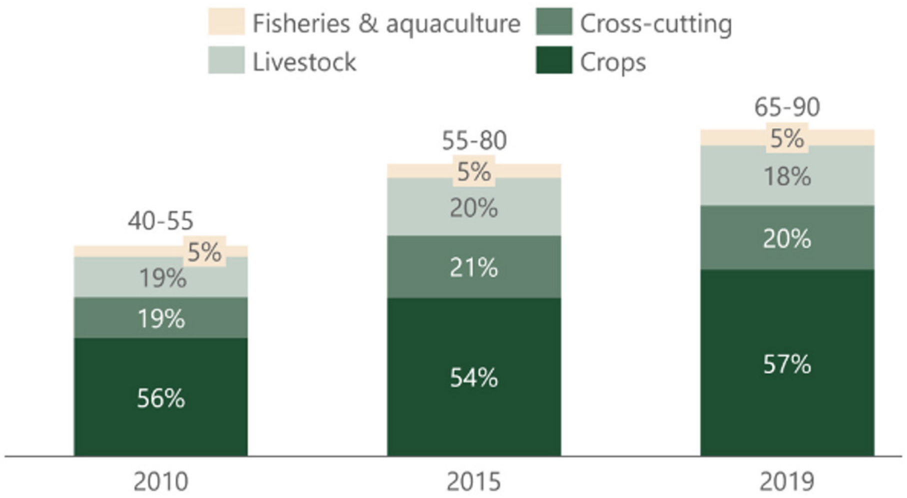

FIGURE 5
Estimated total agricultural innovation funding for the Global South by main value chain in 2010, 2015, and 2019 (US$ billion, constant 2019 prices; see text for definition of cross-cutting). Source: Dalberg Asia (2021a).

non-governmental organizations (NGOs) and civil society organizations (CSOs) accounting for <5%. There are clear patterns in funder–recipient pairs for agricultural innovation funding. Governments mostly fund public programs. Similarly, private companies' channel most of their innovation funding back into their own or other private sector firms, with a tiny fraction being directed toward universities and public research institutes—for example, in Brazil, Bayer and Syngenta have both collaborated with the federal research agency, EMBRAPA (Dalberg Asia, 2021c).

3.1.1. Global South governments

Governments are the largest funders of agricultural innovation in the Global South, accounting for about $40 billion (range $35–45 billion), or about two thirds of the total (Figure 4). This is equivalent to 10–13% of *all* agricultural-related funding by governments in the Global South (using the expenditure on agriculture, forestry and fishing as reported in the FAOSTAT database). Public funding in agriculture innovation is dominated by China, India, and Brazil, with these three governments accounting for nearly 40% of overall agricultural innovation in the Global South (Table 3).

Of the total public funding about 37% goes toward marketing programs and 27% of public funding on agricultural innovation goes toward technology and R&D activities. Science and technology funding in agriculture largely goes to single government apex research institutions that coordinate agricultural research in their respective countries or utilize funding for their own research, with the remaining funds flowing to state level and affiliated agricultural research institutes and universities. Examples of apex research institutions include the Chinese Academy of Agricultural Sciences (CAAS), the Indian Council of Agricultural Research (ICAR), EMBRAPA in Brazil, and the Kenya Agricultural and Livestock Research Organization (KALRO).

Governments, in their enabler role, fund more on innovations to help new products and services get adopted and scale than on R&D to create those new products. An average of 37% of public funding goes toward agricultural extension and training programs, while about 34% goes toward institutional funding, new infrastructure, and agrarian reform. An example from the second category is the dairy entrepreneurship development program in India, which among its other objectives, intends to modernize dairy farms for production of clean milk and bring structural changes in the unorganized sector so that initial processing of milk can be taken up at the village level.

There were, however, striking differences between countries (Figure 7). China alone accounts for approximately half of all Global South government innovation funding in agriculture, followed by Latin American governments (driven by Brazil with 20–30% of regional funding) and South Asian governments (driven by India at 50% of the regional funding). As also noted by Chai et al. (2019), China has overtaken the USA in agricultural R&D on a purchasing power parity basis—and this has been reflected in high agricultural Total Factor Productivity gains in China, of over 3% per year (OECD, 2019).

Government funding increased over the decade examined, consistently driven by China (5% annual growth) and India (9% annual growth). Brazilian government funding on the other hand stayed fairly constant over the period, despite growing agricultural exports and output, even declining slightly after 2014. Some public funding in Brazil has been substituted by innovation funding by large companies such as Bayer and Syngenta, who have funded agricultural research within Brazil in recent years including through prominent collaborations with EMBRAPA (Dalberg Asia, 2021c).

Nearly half (47%) of all innovation funding by governments goes toward crops, but in India this was higher, at nearly 70%. Approximately 27% of funding focuses on cross-cutting themes such as forest preservation, water conservation and general agricultural reforms, especially prominent within countries such as Brazil. Livestock and fisheries receive only 20% of the overall funding on innovation by governments. Compared with the relative output value of crops, governments spend relatively more on crops than livestock and fisheries (Figure 6), perhaps because a majority of the agricultural workforce is employed within the crops value chain.

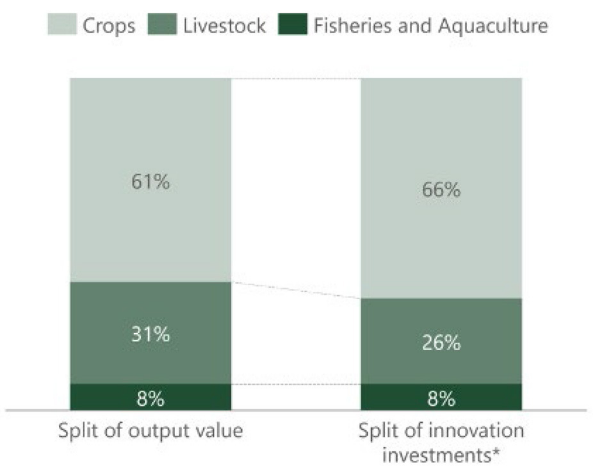

FIGURE 6
Estimated annual funding by private companies for agricultural innovations focused on the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a).

3.1.2. Private corporations

Private corporations funded ∼$13 billion (in the range of $9–18 billion) annually over the last decade on agricultural innovation for the Global South, accumulating to $150 billion (ranging from $90–180 billion), representing 15–25% of the overall agricultural innovation funding for the Global South. The funding is roughly evenly split between R&D funding and non-R&D funding in marketing and adoption support. Key players include agriculture-related divisions of global giants such as Bayer Crop Science, Syngenta and Archer Daniels Midland. While smaller agribusinesses also contribute to innovation in the agriculture and food sector, they have a very small financial contribution compared to the largest global agricultural corporations (see also OECD, 2019).

Farm mechanization (∼25% of total) and pesticides (∼23% of total) represent the largest sub-sectors in terms of innovation funding by the private sector (Figure 8). Funding in these sub-sectors is dominated by large companies including John Deere, Cargill, Bayer Crop Sciences and Syngenta, and focuses predominantly on crops. Other sizable categories include funding from meat and poultry processing companies (∼10%), animal health companies (∼6%), fertilizer companies (∼3%) and commodity-specific processing companies (∼3%), while fisheries and aquaculture are estimated to receive <2% of the total innovation funding. Precision agriculture-related innovation funding forms ∼1% of the total funding by private companies; however, it is the fastest growing category, growing at ∼25% a year in the past decade (as also noted by Fuglie, 2016) for PE/VC spending on precision agriculture).

TABLE 3 Funding in agricultural innovation by Global South governments.

Governments	Total funding in agricultural innovation	% of total govt. funding in agricultural innovation	% of total funding in agricultural innovation
China	$20 bn ($15–25 bn)	48%	33%
India	$3 bn ($2.5–3.5 bn)	7%	5%
Brazil	$2 bn ($1.5–2.5 bn)	5%	3%
Rest of Global South	$17 bn ($15–20 bn)	40%	28%

Source: Dalberg Asia (2021a).

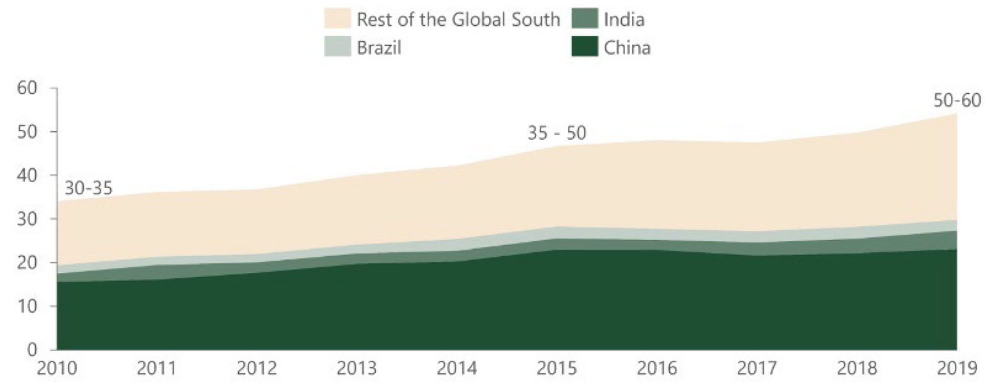

FIGURE 7
Estimated annual government agricultural innovation funding in the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a).

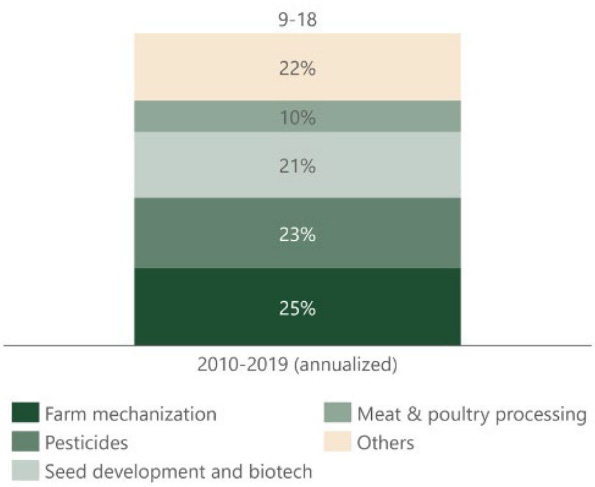

FIGURE 8
Estimated annual funding by private companies for agricultural innovations focused on the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a).

Overall, agribusinesses saw a deceleration of overall innovation growth (to 2% annually) and a slight fall in their R&D intensity ratios (defined as expenditures over sales) over the final years of the decade examined (for instance, Syngenta's R&D intensity fell from 10.1% in 2017 to 6.7% in 2019). The deceleration was most noticeable in large agricultural input companies in sectors such as farm mechanization, seeds development and biotech. According to private sector experts we interviewed, this is likely because agricultural input companies face high costs of innovation due to an increasingly restrictive regulatory environment and increasingly complex next-generation innovations, which together with consumer preferences have pushed these companies to focus on incremental innovations instead of breakthrough ones, calling for a need to de-risk private capital to stimulate transformative innovations (see also Kurth et al., 2020).

3.1.3. Private equity and venture capital investors

PE/VC investors funded $1.3–2 billion per year in agricultural innovation between 2010 and 2019 (Figure 4), accounting for 2–3% of the overall innovation funding in agriculture for the Global South. Although PE/VC funding represents a small share of the overall agricultural innovation funding, a large percentage of this funding is for disruptive innovation that can have an outsized impact if the technologies work and the business models prove viable (Cirera and Maloney, 2017). For example, startups that increase information availability on markets, climate and agronomic recommendations will help smallholder farmers but also put pressure on intermediaries within the value chain, which causes dynamic effects on the way business is conducted in the sector. Another example is startups that create new markets and increased value for byproducts and waste from agriculture.

The thematic analysis (Figure 9) drew from databases that capture granular flow in the PE/VC investors, and then modeled funding for the Global South to count funding into startups, not just in the Global South but also into companies based in the Global North where spillovers are likely (for detailed methods see Dalberg Asia, 2021b). Examples of such spillovers include a German startup, Plantix, which has developed an AI engine to detect pests in crops and has a significant user base in India (GINSEP, 2021). Innovative technology-enabled agri-marketplaces and farmer engagement platforms (offering a combination of information, market linkages and sometimes financial support) received ~60% of all PE/VC agriculture funding, followed distantly by seed development and biotech startups at ~15%. Examples of companies that received funding include Ninjacart (India), Fruitday (China) and Meicai (China), which are all focused on creating tech-based business models that use advanced analytics to drive supply chain efficiencies in agricultural value chains. Examples of seed development companies that received funding included Advanta (India) and Nuziveedu Seeds (India). From a commodity lens in terms of technologies, marketplaces, farmers engagement and biotech, crops attract the highest share of PE/VC funding, although funding that cut across commodity chains also received a notable proportion of funding, driven largely by funding for innovative agricultural financing companies that target both

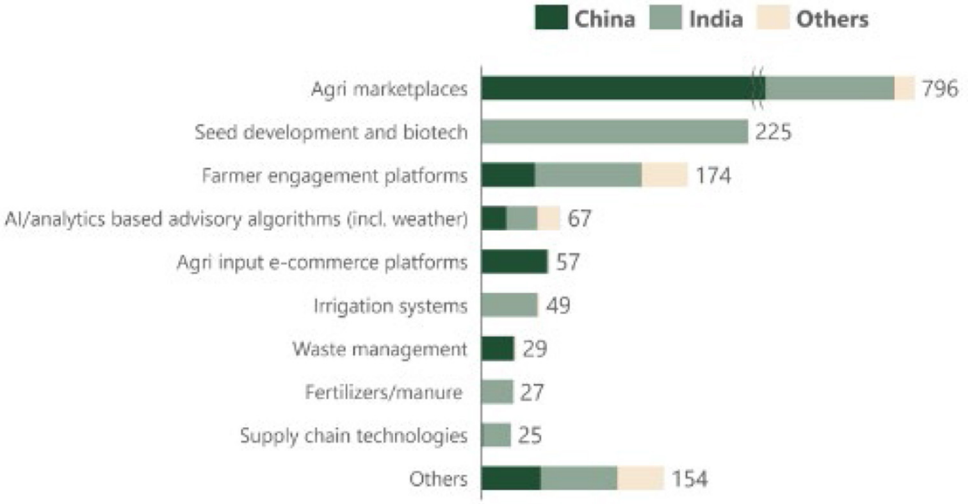

FIGURE 9
Estimated annual innovation funding by private equity and venture capital investors in agriculture-related start-up companies based in the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a) and Tracxn.

individual farmers and agricultural businesses (see Dalberg Asia, 2021d).

China and India are the largest users of PE/VC funding in agriculture (both domestic and international), together accounting for ∼90% of PE/VC agricultural investments, far ahead of Kenya (∼3%), and Nigeria, Brazil, Argentina and Mexico (each about 1% of total).

3.1.4. Philanthropic, multilateral, and bilateral agencies

Based on data from OECD databases, average funding by development partners for agricultural innovation is estimated to be at ∼$6 billion per year between 2010–2019 on average (about 8% of the total).

Funding by development partners is dominated by bilateral agencies (about 70%, although reducing in amount and share over the decade), followed by multilateral grants with about 25%. The USA is the leading bilateral funder, followed by European countries and Japan. While multilateral agencies such as the World Bank's International Development Association (IDA) and the International Fund for Agricultural Development (IFAD) are very important funders of research and innovation, especially in low-income countries, most of their funding takes the form of loans to national governments, which are counted here as national funding. Philanthropic foundations, dominated by the influential BMGF, on average accounted for about 10% of funding by development partners, or about 1% of all agricultural innovation funding for the Global South; however, this notably increased (both real terms and percentage) from <4% of the total in 2010 to 13% in 2019 (Figure 10).

Overall, nearly half (46%) of bilateral and multilateral grants for agricultural innovation was targeted toward sub-Saharan Africa. South Asia and Latin America received about 12% each, followed by other regions. Within South Asia, Afghanistan received ∼50% of all funding for the region, followed by India, Pakistan, Bangladesh and Nepal, which received ∼10–12% each. Nearly two thirds (∼65%) of philanthropic funding goes to sub-Saharan Africa—fairly evenly spread across countries—with other major recipients being in Latin America and Southern Asia (driven by India).

Finally, China and India themselves invest more than $600 million per year (together) in agricultural innovation funding as development partners, also mostly for sub-Saharan Africa. For example, China funds technology demonstration centers in Africa to promote the usage of and train stakeholders on new agricultural technologies to increase production and economic efficiency (Jiang et al., 2016), which may partly reflect the importance of Chinese agricultural imports from Africa.

By value chain the pattern of investments is slightly different by development partners than other groups, with relatively less emphasis on crops (∼40%, compared to >50% by governments and >90% by the private sector). About 15–20% of innovation funding by development partners ($300–400 million/year) went to livestock over the decade examined, and a similar amount to fisheries and aquaculture. However, between 2014 and 2018, bilateral and multilateral funders tripled their funding to fisheries and aquaculture, while philanthropies increased theirs tenfold. Finally, funding that cross-cuts all value chains constituted ∼12% of total funding by development partners.

One pattern worth further investigation is an apparent shift of innovation funding by development partners away from R&D during the decade, toward funding for uptake and scaling of innovations. Nearly 20% of innovation-related funds were spent on R&D for agriculture around 2010, which almost halved to under 10% by 2018. Examples of investment in scaling include funding by IDA in Tanzania's Accelerated Food Security Project, which included improving farmers' access to agricultural knowledge, technologies, marketing systems and infrastructure (World Bank,

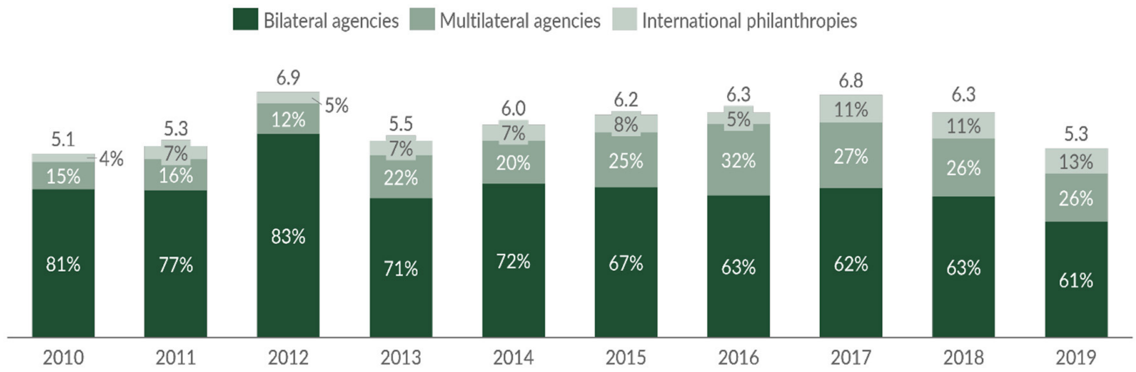

FIGURE 10
Funding by development partners in agricultural innovation focused on the Global South 2010–2019 (US$ billion, constant 2019 prices). Source: Dalberg Asia (2021a) and OECD.Stat.

2014); and funding by the UK through an International Climate Fund with the intention to promote sustainable low-carbon land use and forest management in small and medium-scale farms by encouraging technological progress in Brazil (DEFRA, 2013). While uptake and scaling of current innovations is undoubtedly a very critical issue to address, particularly for small-scale farmers that are the majority producers in the Global South, investment in R&D is equally important for future transformation of food systems (Fuglie et al., 2019; Herrero et al., 2020), and it is important to maintain a good balance.

3.2. Innovation funding use by different systems

We segmented funding into three main systems (as shown in Figure 2). Layer 1, macro systems, includes governance and policy institutions, financing systems, knowledge and education systems within agriculture, as well as international and domestic trade. Layer 2, production systems, includes core agricultural value chains and production activity therein. Layer 3, ecosystem services and natural resource management systems, includes systems to manage, conserve or develop ecosystem services and underlying factors necessary for, or impacted by, agricultural production such as soil, water, biodiversity, forests and land.

The results in this section are a synthesis of all funder categories: governments (data here is mostly extrapolated from the Indian government due to data gaps—a major limitation), the private sector, PE/VC and development partners.

3.2.1. Macro systems (policy, financing, knowledge, trade systems)

During the period 2010–2019, an average of $20–25 billion was funded annually for innovations in macro systems, forming 30% of the overall agricultural innovation funding. For example, out of the USD 1.53B funding by the Indian government (mostly to ICAR), a large fraction (USD 0.96B) of innovation funding in this layer is focused on agricultural knowledge and education systems; staff costs and project related expenses at higher education institutes, universities and public research institutes. Other components of Layer 1—governance systems/policy support (USD 0.33B), financing (USD 0.23B) and collaboration and trade systems (USD < 0.01B)—received limited fractions of innovation funding. Such is also the case for CAAS in China, EMBRAPA in Brazil and KALRO in Kenya. Further, based on expert inputs, only a negligible portion of research projects in agricultural research institutes and education institutes gets commercialized. Therefore, more strategic integration of the private sector is needed that can not only improve commercialization but also improve private sector funding.

3.2.2. Agricultural production systems (across value chains)

About $25–35 billion (~50% of the total) was funded annually for innovations in agricultural production systems, including production of inputs, processes, post-production, processing. Innovation funding into these areas comes from both governments (research funding, agricultural missions) and the private sector (research funding, production factories producing products and services, multi-disciplinary centers of innovation). Innovation projects in this area vary greatly; a few examples include the National Mission on Micro-Irrigation (Government of India, 2010) and Mission on Agriculture Mechanization (Government of India, 2017) and the Kenya Cereal Enhancement Programme (KALRO, n.d.). Funding in this category is also for demonstration projects at farms, to develop and distribute post-harvest technology, as well as research projects related to animal health.

Of the total innovation funds, the majority was for pre-harvest processing such as inputs (30%) and production (12%), while post-production (3%), processing (4%) and cross cutting (3%) received only little (Figure 11). Funding for farmer-saved and local seed systems was only about $2–6 million per year, or <0.5% of funding in innovation for seed systems for the Global South (Dalberg Asia, 2021e).

The private sector contributes ~50% of the innovation funding in Layer 2, funding ~$10–18 billion per year. Funding from large private corporations mostly goes to developing and marketing new

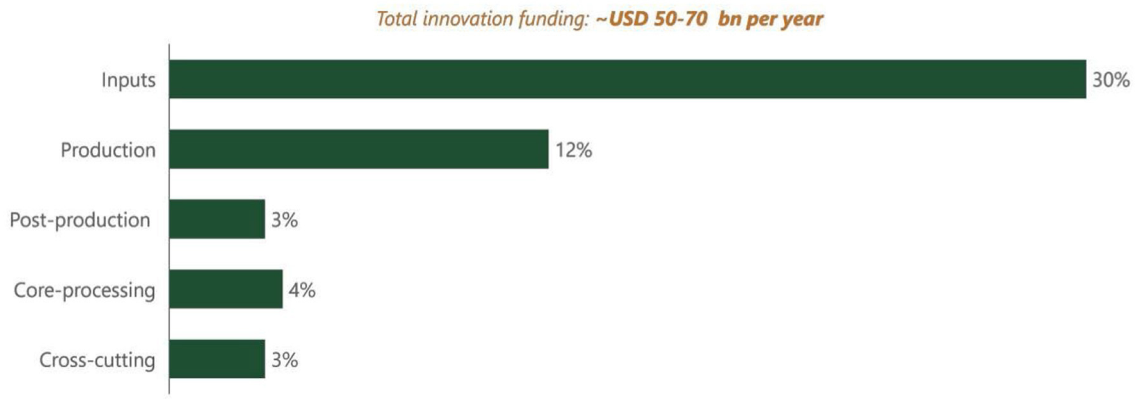

FIGURE 11
Percentage of total agricultural innovation funding by sub-layers in production systems 2010–2019 (annualized, constant 2019 prices). Source: Dalberg Asia (2021a).

production inputs. PE/VC funded startups tend to focus more on innovations in the post-production stage, covering supply chain technology as well as farmer engagement platforms, but are still small players.

3.2.3. Agriculture ecosystem services and natural resource management

Approximately $10 billion in innovation funding is utilized every year for the protection, conservation and development of ecosystem services as well as natural resource management; this represents ∼13–20% of all agricultural innovation funding. Funding toward these activities grew 5% annually over the decade examined, but still constituted the smallest portion across the three systems described above. Most of this innovation funding comes from government agencies or development partners, since this area is dominated by public goods that are not profitable for the private sector. This includes innovation in management of forests, biodiversity, soil and water conservation projects including watershed development, and training in new approaches in these areas. For example, IDA invests in countries in the Global South to improve water use efficiency through the adoption of water saving technologies and to increase surface and groundwater availability through the rehabilitation of small to medium irrigation schemes, terrace rehabilitation, bank protection works and other water and soil conservation activities (World Bank, 2016). Increasingly, however, there are startups that are focused on soil health management, water and biodiversity conservation through the use of data and analytics. For example, Shuxi Technology, a startup in China, provides data-driven precision agriculture solutions including recommendations to monitor soil health (Tracxn, n.d.a). An India-based startup, Sumo Agro, manufactures soil nutrients with the intention of supporting regenerative agriculture (Tracxn, n.d.b). The challenge for getting more private sector investment in innovation will be monetizing ecosystem benefits, which is proving challenging, although agricultural carbon payments are a growth area (IIF, 2021).

3.3. Funding innovation for sustainable agricultural intensification

We estimated that <$5 billion annually was targeted toward SAI innovation in the Global South, which is <7% of total funding over the period 2010–2019. Using our broad definition (where environment is the only "sustainability" element included), annual funding was around $3.4–4.7 billion, while using the narrow definition (which additionally requires a focus on social or human outcomes), the total was around $2–2.6 billion or <4.5% of total funding (Figure 12).

There is certainly much room for improvement in these estimates. Supplementary Figure 1 shows that all innovation intentions scored quite low; for example, intentions to improve productivity and economics were only mentioned for 28% of all funding, while other dimensions (environmental, social or human conditions) were much lower. Underestimates can result from poor descriptions of funding streams, in which specific intentions are not clearly indicated—although this is likely to be a more frequent problem with productivity (as some innovation proposal writers may assume productivity is an obvious objective and see no need to spell it out) than for environmental and social intentions. Scaling and extension activities may also lack clear descriptions of their intentions—particularly their environmental ones—which means that even in the case that they have clear socially-focused intentions, they would not get classified as SAI funding using our methods. Finally, as previously mentioned, an important limitation on the government estimates was that India was the only major country in the study sample that had sufficiently detailed data, so overall government estimates are based on the extrapolation of Indian numbers.

With the above caveats, it still seems reasonable to conclude that funding for innovation for SAI for the Global South is very low. Even tripling our figures would result in an estimate of a fifth or less of all funding with stated SAI intentions. Breaking down the numbers and data (with caution):

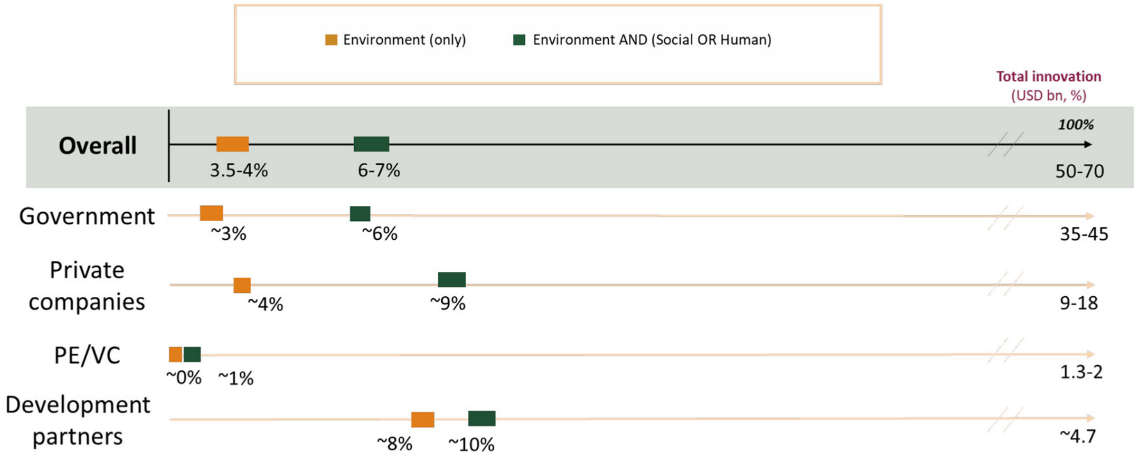

FIGURE 12
Funding for sustainable agricultural intensification as a share of innovation for narrow and broad definitions 2010–2019 (annualized, constant 2019 prices). Source: Dalberg Asia (2021a).

- The proportion of innovation funding that has stated intentions of SAI for the government (<6%) appears slightly less than for the private sector (∼9%) and development partners (∼10%). This might be mainly a matter of presentation and requires further investigation. The private sector, with valuable brands at stake, is being asked to focus more on environmental, social and governance (ESG) outcomes, so might be better than government entities at articulating sustainability goals. Many large-scale private sector companies have their own standards and metrics for sustainability (e.g., OLAM, n.d.; Bayer, 2022), although they may not always apply these consistently across all their innovation work. Similarly, most development partners have a strong strategic focus on sustainability and a requirement to clearly state their objectives in project and program descriptions. Bilateral and multilateral funding to SAI (excluding China) was estimated to increase by ∼10% annually between 2010 and 2018, but was still only ∼8–10% of the total innovation spend at the end of the period examined.
- From an agricultural value chain perspective, SAI innovation (using the broad definition) funding percentages are low, ranging from 8% for fisheries and aquaculture to 5% for crops and only 2% for livestock (Supplementary Figure 2). This suggests that the majority of funding emphasizes productivity enhancements and not the other dimensions of sustainability. An increased focus on overall sustainability by prominent private sector players in livestock—companies such as Tyson Foods (USA) and BRF (Brazil)—could drive up SAI funding for this sector, as many of these large players currently have limited stated intentions around environmental sustainability.
- From an innovation area perspective, ∼8% of funding for technology-related innovation has clear SAI intentions, in contrast to ∼4% of institutional innovation funding and ∼3% of marketing and extension innovation funding (Supplementary Figure 3). As mentioned, the latter figures may be underestimated, as if funding streams do not mention environmental intentions, they do not get tagged under either the broad or narrow definition of SAI.

4. Discussion

Improving food and nutrition security while meeting sustainability targets is one of the main global development challenges facing this generation. A rapid and fundamental shift to more productive, sustainable and equitable ways of producing food (here called sustainable agricultural intensification or SAI) is needed, requiring significant innovation across different categories: technology, business practices, social institutions, finance, and policies (Tomich et al., 2019; Barrett et al., 2020; Blended Finance Taskforce, 2020; Fanzo et al., 2020; Herrero et al., 2020; Steensland, 2021).

This study estimates that overall innovation funding for the agrifood sector for the Global South (which in this study includes both R&D funding and the extension, marketing and other funding for innovation uptake) is around $60 billion ($50–70 billion) per year in 2019 US dollars, or around 4.5% of sector output. For such a critical sector, this seems relatively low: as a comparator, if funding were raised to match levels found in the renewable energy sector (Osborne, 2019), this would imply an additional $20 billion per year in funding. Rosegrant et al. (2022), in this collection, have estimated the size of the "investment gap" for research and innovation to meet some key Sustainable Development Goals (principally calorie-based hunger and greenhouse gas emissions) and project that this would need a minimum of $10.5 billion additional funding annually. Baldos et al. (2020) have also pointed out the significant global investment needed for agriculture to adapt to climate change.

We estimated that on average, across funder types, about 20% of innovation funding was allocated to R&D—with the largest share allocated to extension, marketing and behavior change (∼33%) and the rest to institutions, education and infrastructure. For development partners, there was a significant move away from R&D funding over the period examined (from nearly 20% of funding in 2010 to about 10% by 2019), with increased funding going to supporting scaling up existing innovations. Innovation uptake and user-led innovation are clearly areas needing support (MacMillan and Benton, 2014; Fuglie et al., 2019). However, it is also worth keeping an eye on the balance between these medium-term needs and the long-term, risky, but critical R&D funding needed to develop and pilot new institutions, practices, varieties, technologies and bundles thereof (Barrett et al., 2020) to address emerging issues.

An important finding is that only a small fraction of innovation funding within the agricultural sector has intentions of SAI, and that this fraction has not increased substantially in recent years. We estimate that over the decade examined (2010–2019), <$5–7 billion out of this (<7%) had visible environmental intentions, and <5% had both environmental and social/human intentions. Even allowing for challenges with these estimates, it appears that funding for SAI innovation is far too low to support transformation of food systems.

Finally, this study has revealed a widespread lack of availability, granularity and quality of the data on investment in innovation across all funder types, as well as a lack of common definitions, in particular for what funding is counted as promoting sustainability. This is a major cause for concern, as it is not possible to improve investment without adequate information.

What can be done to improve this situation? Five potential recommendations are suggested by this study.

First, all funder types need to increase their funding on research and innovation for agrifood systems, particularly for the Global South, which faces the most significant challenges of poverty, food insecurity and the effects of climate change.

Second, a global tracking system for research and innovation in agrifood systems is urgently needed, both to incentivize funders and innovators and to spot key gaps in investment. While there are several programs which currently track agrifood R&D and innovation, global coverage is patchy, financing is not always reliable, and systems are not harmonized. Based on the emerging findings of the working paper on which this report is based (Dalberg Asia, 2021a), CoSAI actively campaigned with others for the establishment of a global tracking system that would also include sustainability concerns (CoSAI, 2021; Compton et al., 2022). The United Nations Food and Agriculture Organization (FAO) has an important convening role. Its recently released report (FAO, 2022) introduces the vision, rationale, scope and methods for new Agrifood Systems Technologies and Innovation Outlook (ATIO), which will curate and publish information on innovation inputs and emerging and mature innovations as well as their potential to transform the agrifood system.

Third, a clear common framework and standards for measurement would be required to support a tracking system. This would need to cover general issues such as how to tag different types of innovation (e.g., in policy or finance), stages of research and innovation, and specific topics such as crops, as well as the degree of detail to collect (e.g., crops-cereals-maize-popcorn-popcorn variety x). FAO (2022) discusses this in detail, and also emphasizes the need for indicators and open access data for decision making and investment planning.

Fourth, as part of this, an agreed framework is needed to be able to distinguish more clearly what "counts" as funding for sustainability. While many investors and companies have started indicating their interest in supporting environmentally and socially sustainable agriculture, this has not translated into significant changes, in part because of ambiguous definitions and non-standard metrics. A common framework and measurement scale should be created by international institutions and used by funders. This should be based in the first instance on stated intentions [as in this study and other studies tracking innovation funding, such as Biovision and IPES Food (2020)], because the importance of clearly-stated desired outcomes is acknowledged in all planning for applied research and innovation (Andrew and Hildebrand, 2019). However, it is also important to have a means to track that stated intentions are in fact leading toward desired sustainability outcomes. There are successful examples of sustainability indicators used for some agricultural research, for example the Sustainability Intensification Assessment Framework by Musumba et al. (2017) and Stewart et al. (2018), used by projects funded by the US Agency for International Development (USAID). However, it is very challenging to come up with universally-applicable indicators for all types of agrifood innovation, due to the context-specificity, high drop-out rates and long time scales from innovation to impact at scale—and the complexity and high cost of attributing observed outcomes to specific innovations (Stevenson et al., 2018; Belcher and Hughes, 2021). Another article in this Research Topic (forthcoming, based on the working paper Zurek et al., 2022) tries to resolve this dilemma by proposing common principles for innovation that include verifying that the project/program is measuring progress toward agreed areas (food security, social equity, etc.) using suitable metrics for the context (Zurek et al., 2023). However, there are still many issues to resolve, including the perceived degree of sustainability (e.g., Biovision and IPES Food, 2020), and the balance between having many sustainability objectives and one or two highly focused ones that can be more rigorously measured and enforced (Tricks, 2022). The recent report from FAO (2022) also emphasizes the need for systematic tracking of data and filling the gaps.

Fifth, governance regimes and independent watchdog bodies need to include research and innovation in their oversight of agrifood investment. For example, the World Benchmarking Alliance and the Global Impact Investors Network both have influential agrifood monitoring systems (GIIN, 2020; World Bench Marking Alliance, 2022) but neither currently include indicators for research and innovation, although this is critical for future performance and sustainability.

The above five recommendations have implications for all funders. For example:

Governments of Global South countries can benefit from increasing their investment in research and innovation in agrifood systems (Alston et al., 2021; Stads et al., 2021). This can potentially be done by repurposing some existing funding, e.g., for some types of agrifood subsidies (FAO et al., 2021; OECD, 2021; Springmann and Freund, 2022). Governments could also aim to improve their tracking of funding for innovation, including common databases across ministries and departments, and move to adopt international standards for sustainability.

Private sector companies, in particular the enormous transnational corporations that dominate global technical R&D in global agrifood systems, have immense potential to promote or hinder sustainability (Folke et al., 2019; Schneider et al., 2020). Focusing all (or a larger part) of their research and innovation on sustainability could potentially have a huge effect.

Development partners have the funds, the networks and the influence to create a standard within the development sector for measuring SAI-related innovation funding. They could be the first movers, proving the benefits of measuring funding on a common sustainability standard and then advocating for its use across all types of funders including Global South governments, other international agencies, and private investors as well as their own funding.

This is a challenging agenda. *Civil society organizations and watchdogs* can play a role in pushing the major funders, but agrifood innovation has not traditionally been high on their list of demands. Strong social norms and governance regimes will be important in motivating change in innovation goals and objectives (Béné, 2022).

We acknowledge the importance of gender, division of labor, and producer sub-groups based on landholdings. However, we were not able to disaggregate data under those categories due to lack of granularity in the available data. It important that biophysical and social innovations are equitable and available to all categories and does not discriminate against any particular group including subsistence and commercial sectors. In addition, we could not separate data on farmers uptake of funding and innovations, but recognize that these are important challenges and reasons for low adoption and impact, especially in some regions of sub-Saharan Africa. There is certainly a need for balancing funds toward new innovations and adoption or scaling to reduce poverty and hunger, and improve food, nutrition and climate security.

This study was not designed to identify specific areas of under-funding—some of these have already been highlighted by other authors (e.g., Pingali, 2015; Haddad et al., 2016; Beintema and Stads, 2019; Tadele, 2019; Bollington et al., 2021). The decision on how much innovation funding should be allocated to a particular area is complex and often situation-specific. Nevertheless, a couple of areas stood out in this study as having potentially very low funding:

- Funding for innovation for post-harvest management and value chains in the Global South was estimated at less than a tenth of innovation in production and production inputs. This is potentially a major global area of under-investment, since post-production innovation plays a huge part in developing value chains (Reardon et al., 2019) and also in reducing food waste, which *inter alia* has important food security and climate change mitigation impacts (Chen et al., 2020; Cattaneo et al., 2021; Santeramo and Lamonaca, 2021).
- Another area of apparent underinvestment is farmer-produced and local seed systems. Innovation in local informal seed systems and farmer-saved seed gets <0.5% of all seed innovation funding, although these are the most important source of seeds for many farmers in the Global South (Coomes et al., 2015; McGuire and Sperling, 2016).

5. Conclusion

This study represents, to the best of our knowledge, the first attempt to measure funding going toward agricultural innovation in the Global South by governments, the private sector, development partners and PE/VC investors—going beyond technical R&D to measure complementary funding in scale-up and adoption as well as funding in innovation in policies, financial instruments and social institutions. In addition, this represents the first global attempt to measure the proportion of this funding to SAI that has stated intentions of promoting environmental, social or human sustainability.

Among the more striking patterns, we found that funding to innovation represents only 4.5% of Global South agricultural output, and that <7% of this agricultural innovation funding is explicitly focused on delivering environmental outcomes, while <5% has both environmental and social/human intentions. Specific areas which received very low innovation funding included post-production systems and local seed systems.

The results of this study were limited by the availability and quality of data on innovation. An important recommendation is the need to direct more funding toward creating a standardized approach to cataloging, classifying and measuring funding in innovation in agriculture being made by different categories of funders globally. Such a common standard of reporting agricultural innovation funding would go a long way in making future analysis easier and increased transparency about sustainability intentions would increase incentives for change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PVVP, NBh, JC, and RE conceived the approach to the research and led all aspects. NBh, VB, GJ, and KN conducted the analysis. All authors contributed to writing and editing and approved the final manuscript.

Funding

This research communicated as part of this paper was commissioned and funded by the Commission on Sustainable Agriculture Intensification (CoSAI). CoSAI was initiated and supported by the CGIAR Research Program on Water, Land, and Ecosystems (WLE), funded by the CGIAR Trust Fund and other donors (https://cgiar.org/funders). CoSAI Commissioners are independent, and facilitated by a Secretariat based at the

International Water Management Institute (IWMI) headquarters in Colombo, Sri Lanka. Partial funding support from Feed the Future Sustainable Intensification Innovation Lab funded by United States Agency for International Development (Cooperative Agreement # AID-OAA-L-14-00006). Contribution number 23-117-J from Kansas Agricultural Experiment Station.

Acknowledgments

This article is based on working paper (Dalberg Asia, 2021a) and associated methodology (Dalberg Asia, 2021b) from a study conducted by Dalberg Advisors (India) on behalf of the Commission on Sustainable Agriculture Intensification (CoSAI) and hosted on the CoSAI: https://www.iwmi.cgiar.org/archive/cosai/ and at https://hdl.handle.net/10568/114762. Acknowledgments for the full team, oversight group and others involved in the original study are included in the working paper.

Conflict of interest

NBh, VB, GJ, and KN were employed by Dalberg Advisors. PF was employed by Scriptoria.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer DS declared a past collaboration with the authors PVVP, NBh, RE, NBe, and JC to the handling editor.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1108949/full#supplementary-material

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