Developing a Sustainable, Resilient, and Equitable Global Cold-Chain

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A sustainable, resilient, and equitable cold-chain will be crucial for addressing multiple challenges ranging from global food and health security to poverty reduction. While cold-chain capacity has been growing in recent decades, the business-as-usual development pathways will: (1) likely not deliver against these challenges under traditional private-sector-led business models, as the areas where cold-chain investments are the most needed often do not present an immediate commercial business case; (2) suffer from a top-down and reductionist approach with a sole focus on cold storage rather than connectivity; and (3) not address the disconnect between low- and high-income countries. Hence, we argue for a radical change in the business model where governments work

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together and actively invest in the development of cold-chain as a part of low-income countries' critical infrastructure through a public-private-community partnership model (PPCP). This would not only help low-income countries achieve their socioeconomic goals, but would also be critical for high-income countries, as it is likely that 500 million small-holder farmers in low-income countries will play a prominent role in feeding the global population of 9.7 billion by 2050. PPCP could unlock investments in acute areas that are often perceived as high-risk by the private sector alone, ensuring equitable access to sustainable and resilient cold-chains. However, such a step-change in the business model should be underpinned by a robust understanding of the real value of the cold-chain and return on investment.

INTRODUCTION

Cold-chains are critical infrastructure that are vital for a well-functioning society and economy. They are complex, multi-dimensional, temperature-controlled supply chains that maintain perishable produce and/or temperature-sensitive products at their optimum temperature and environment from source to destination, preventing qualitative and quantitative product losses and ensuring their safety. They underpin our access to safe and nutritious food and health, as well as our ability to eradicate rural poverty, spur economic growth, and deliver socioeconomic development. While the global cold-chain capacity has been growing in recent decades, the growth has not been equitable in terms of access.

One of the major reasons behind this lack of equitable access is that, for food at least, cold-chains are mainly owned and governed by the private sector, which focuses on and prioritizes its financial returns rather than its impact on the economy, environment, and society as a whole. Governments have no stakeholder relationship with these networks. As a result, cold-chain investments do not typically deliver toward societal issues including food, nutrition, and health security, and thus they do not generate sustainable and equitable benefits for all. In fact, they sometimes even exacerbate inequalities rather than address them.

Another major aspect of cold-chains that is often overlooked is their global nature. Cold-chain development and equitable access in low-income countries are not simply about solving major socioeconomic challenges in these countries, but also about ensuring global food and health security. Given that the majority of the world's uncultivated arable land is located in low-income countries, they are likely to play a key role in feeding the global population. Currently, most of these countries remain net importers

of food, as they suffer from low yields and high amounts of food loss, both in terms of volume and value. This mainly stems from a lack of cold-chain access. Direct investments from high-income countries to solve these issues will not only benefit low-income countries, but also significantly contribute to the food and health security and cold-chain system resilience in high-income countries now and in the future.

Furthermore, cold-chain infrastructure, and the lack of it, have implications for global climate change and the environment. Food cold-chains alone were responsible for 4 percent of total global greenhouse gas (GHG) emissions in 2017, including the emissions from cold-chain equipment and food loss due to a lack of refrigeration.[1]

Hence, it is imperative to deliver cold-chains sustainably with minimum environmental impact. Again, this requires collaboration between low- and high-income countries that has the potential to facilitate sustainable cold-chain development through technology and knowledge transfer.

Overcoming these challenges will require a step-change in the cold-chain business model whereby governments become a partner in cold-chain development as a part of national critical infrastructure. It is paramount that the government pay particular attention to unlocking investments in acute areas that are often perceived as high risk by the private sector, but benefit social, economic, and environmental interests and ensure inclusive and equitable access to cold-chains. Governments of both high- and low- income countries need to work towards a shared goal of sustainably improving resilience of both the local and global food systems through a public-private community partnership model (PPCP) approach to achieve food and health security for all. Under PPCP, governments could facilitate a shift in conceptions of success away from direct cash returns for private sector owners and operators, and toward inclusive, equitable, and sustainable development underpinned by the active involvement of the community. Governments of low-income countries could complement their resources with direct investments from high-income countries, but also through access to sustainable technologies and skills. Such a step-change in the business model, however, needs to be catalyzed and underpinned by a robust understanding of the real value and "return on investment" of sustainable, resilient, and equitable cold-chains to facilitate governments' investments.

THE NEED FOR A SUSTAINABLE, RESILIENT, AND EQUITABLE GLOBAL COLD-CHAIN

Socio-economic Dimension

Foodborne diseases cause around 600 million people to fall ill and

over 400 million people to die annually. This is due in part to the lack of a food cold-chain to ensure the safety and quality of food from farm to plate.[2] According to the Food and Agriculture Organization (FAO), more than 820 million people in the world are hungry today while 2 billion people suffer from food insecurity. Even in North America and Europe, 8 percent of the population does not have regular access to safe, nutritious, and sufficient food.[3] Each day, 25,000 people die from hunger while the lack of effective refrigeration directly results in the loss of 526 million tons of food production annually (or 12 percent of the total food produced), which could feed an estimated 1 billion people.[4] At the same time, more than 1.5 million people globally lose their lives due to vaccine-preventable diseases each year again due in part to the lack of a health cold-chain that would deliver life-saving vaccines and other temperature-sensitive medicines without compromising their safety and effectiveness.[5] Estimates suggest that 25 percent of vaccines reach their destination with degraded efficacy primarily because of operational cold-chain failures. Logistical issues alone are responsible for 30 percent of all scrapped pharmaceutical products, and 20 percent of temperature-sensitive products are damaged because of broken cold-chains.[6]

These issues create significant costs for both economies and livelihoods. The total food produced for human consumption but lost and wasted along the supply chain costs the global economy an estimated USD 936 billion a year[7] excluding social and health impacts. Another estimate by the FAO suggests that food loss reduces income by at least 15 percent for 470 million smallholder farmers across the world.[8] Moreover, the global cost of vaccine wastage due to product exposure to temperatures outside of their recommended range is estimated to be USD 34.1 billion annually. This estimate does not include the substantial physical burden and financial cost of illnesses that could be avoided with the timely delivery of effective and potent vaccines.[9] Estimates also suggest that every U.S. dollar spent on child immunization provides USD 44 worth of economic benefits in low- and middle-income countries.[10]

Equitable cold-chain access is another dimension that needs urgent attention. 500 million small-holder farmers who farm fewer than five acres account for a large proportion of the world's poor and hungry and live on less than USD 2 a day.[11] At the same time, these farmers account for a large share of food producers in low-income countries. For example, in Sub-Saharan Africa, small-holder farmers contribute 80 percent of the food produced within their country.[12] However, about 37 percent of *all* food is lost between production and consumption in the region, and almost 50

percent of fruits and vegetables is lost mainly due to improper cold-chain management.[13] Small-scale farmers in low-income countries do not have access to cold storage facilities, let alone an end-to-end cold-chain with robust connectivity. For example, only 5 percent of firms in the food and agriculture sector in Rwanda have refrigerated trucks, while 9 percent have a cold room to store fresh produce.[14] For small and marginal farmers, where the majority of post-harvest food losses occur, functional cold-chains are completely absent (less than 1 percent of cold-chain capacity).[15]

Recently, disruptions to food and vaccine provisions (e.g., the COVID-19 pandemic, political conflicts, natural disasters, and the knock-on effects from increased energy, transport, and other costs) have highlighted the critical role of cold-chains globally. The impacts of disruptions have fallen disproportionately on poor, disadvantaged, and often marginalized individuals and communities in both low- and middle-income and high-income countries. This has resulted in significant and potentially long-lasting adverse effects on public health and social balances.

Environmental Dimension

Conventional cold-chains are typically energy-intensive, relying on fossil fuel energy sources and refrigerants with a high global warming potential. The emissions come from the energy to operate refrigeration equipment and refrigerated vehicles (indirect emissions), and from the leakage of refrigerant gasses into the atmosphere (direct emissions). Cooling technologies, such as refrigeration, air conditioning, and fans, already account for more than 7 percent of all GHG emissions.[16] These emissions could double by 2030, and triple by 2100.[17] Hydrofluorocarbons (HFCs) are in fact the fastest-growing source of GHG emissions in the world because of the increasing global demand for space cooling and refrigeration.[18] For example, existing cold-chain technologies alone account for one-third of HFC emissions.[19] Looking further into the distribution stage, a transport refrigeration unit consumes up to 20 percent of a refrigerated vehicle's diesel and emits high levels of airborne pollutants—six times as much nitrogen dioxide (NOx) and twenty-nine times as much particulate matter (PM) as a modern Euro VI truck propulsion engine.[20] According to the World Health Organization (WHO), 7 million people die prematurely each year because of air pollution; these hidden polluters cannot be ignored.[21]

However, there are also food loss emissions because of a lack of cold-chains, which were estimated to be 1 gigaton of carbon dioxide-equivalent in 2017. As such, the existing food cold-chain and associated equipment

emissions, plus food loss caused by a lack of cold-chains, are responsible for around 4 percent of total GHG emissions.[22] Moreover, food loss incurs costs from the wasted agricultural inputs that went into producing it, including fertilizers, land, water, and energy. For example, according to the Food and Agriculture Organization of the United Nations (FAO), food loss and waste account for 250 kilometers of the world's freshwater annually,[23] and 1.4 billion hectares or 30 percent of the world's agricultural land area.[24]

We need to address food loss by rapid deployment of cold-chain. Globally, less than 50 percent of all food would benefit from refrigeration.[25] This number is particularly low in low-income countries, as only 20 percent of the perishable food that is produced is refrigerated (compared with 60 percent in high-income countries).[26] The GHG emissions from cold-chain equipment are expected to rise significantly as cold-chains expand in low- and middle-income countries. For example, without intervention, food cold-chain emissions are set to double in India by 2027.[27] Furthermore, additional capacity will be sought to improve health cold-chains, which have gained a greater significance because of the COVID-19 pandemic. If this expansion follows the business-as-usual deployment pathways, it will continue to add significant GHG emissions, which could easily compromise climate and developmental goals, targets, and commitments.

REALIZING THE BENEFITS

As cold-chains continue to gain attention as one of the key pillars of socio-economic development, it becomes increasingly important to understand how to deliver cold-chains (1) sustainably with minimum environmental impact; (2) equitably, providing access for all, including poor, disadvantaged, and marginalized farmers and their communities, as well as women and youth; and (3) while ensuring that they are future-proofed and resilient against changes to the system and future risks and disruptions. Achieving this will require a paradigm shift towards a different way of thinking that goes beyond simply taking business-as-usual action.

First, over the years, a private sector-led cold-chain business model, especially in low-income countries, resulted in cold-chains suffering from sub-optimal investments and a piecemeal approach, perpetuating issues around equitable access. This approach fails to deliver against society's most acute cold-chain needs mainly because the areas that are most in need, such as small-scale and marginalized farmers, producers, and their communities, often do not present a compelling business case for the private sector. This is due to uncertainties around the success and/or length of time before

businesses can expect a financial return. Hence, the private sector is often reluctant to invest in such areas without some level of guarantee from the government or multilateral organizations that minimize the risk of investments. For example, because of private-sector-dominated development, around 72 percent of Rwanda's cold storage capacity is used for flowers, while only 1 percent is used for fruits and vegetables.[28]

Second, where there have been interventions targeting underserved communities, they are often donor-driven, and the approaches are top-down and reductionist. They typically focus solely on cold storage, disregarding the actual cold-chain, a complex, multi-dimensional system that includes both static and mobile elements that must work seamlessly together, technical training needs, and appropriate business models. As a result, most interventions fail to achieve or sustain the desired impact, leading to inefficient allocation of resources and potentially higher financial and environmental costs in the long run. The World Bank, for example, has funded ten cold-storage rooms in Rwanda in the past few years, but estimated that at least 96 percent of the target farmer communities do not use them.[29] Furthermore, many donors are not fully aware of the environmental impact of the interventions that they are supporting, often deploying low-efficiency and high-global-warming-potential refrigerant technologies.

There needs to be a needs-driven, systems-level approach to cold-chain provision to meet current and constantly evolving future cold-chain needs effectively with minimal climate and environmental impact. Such an approach demands understanding that the cold-chain challenge that low-income countries face is not merely about deploying more equipment. It is about establishing a robust, seamless, temperature-controlled, end-to-end connectivity from farm to fork, supported by the following: (1) fit-for-market and purpose technologies to cater cold-chain needs effectively and to avoid short-lived solutions; (2) energy and transport infrastructure to ensure seamless operation and connectivity from source to destination; (3) policies and regulations to facilitate uptake of appropriate solutions at scale; (4) finance and business models to enable equitable distribution of risks and costs to overcome issues around affordability and viability as well as the value created from investments in cold-chain equipment and infrastructure; and (5) skills and capacity at all levels from farmers, to ensure uptake and improve post-harvest practices, to technicians and engineers to ensure adequate installation and maintenance of technologies. Achieving this without using conventional fossil fuel-based, inefficient, and climate-polluting technologies is imperative to avoid significantly higher GHG emissions.

The same should be ensured for health cold-chains from production to point of use in order to deliver safe and effective vaccines, blood, and other life-saving medicines at the right place and time, and under the right conditions. At the same time, the "next-generation" vaccine cold-chain needs to be developed, including sub-zero temperature requirements, to support scientific breakthroughs in mRNA vaccines so that they can reach their full potential and make the most global impact in a sustainable and reliable manner.

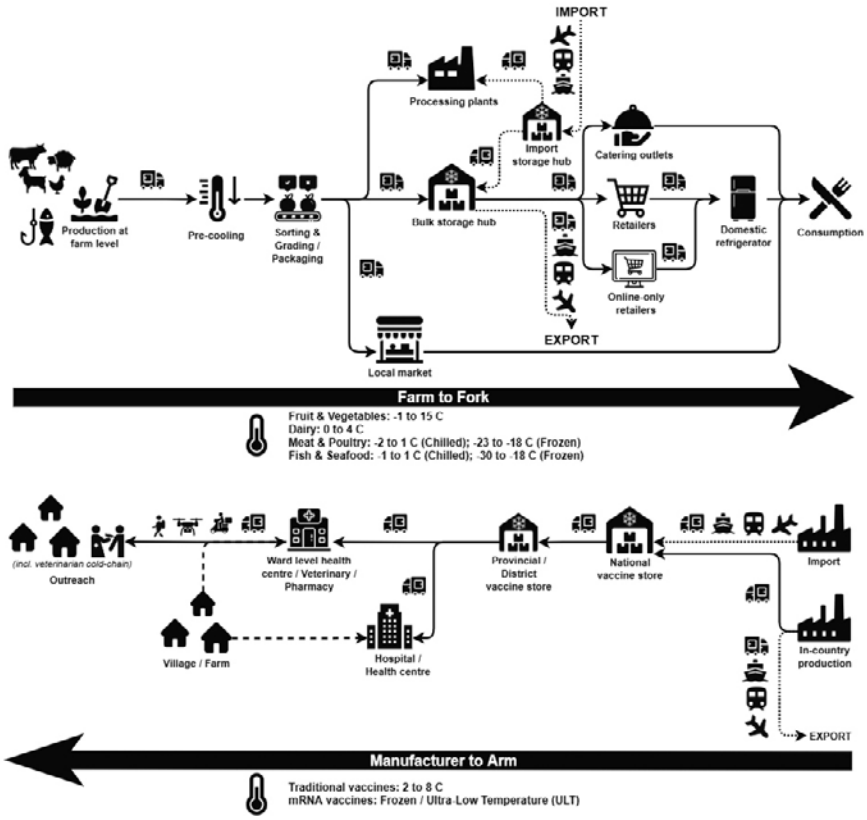

Figure 1. Typical cold-chain flow from farm to fork and vaccine manufacturer to arm

There is also the need to recognize that cold-chains are global. Food production will need to increase significantly to feed the expected human population of 9.7 billion by 2050.[30] This would require closing the 56 percent gap in the global food supply between what was produced in 2010 and what will be needed in 2050.[31] Reducing food loss and waste by 25 percent by 2050 could close the food gap by 12 percent.[32] With 60 percent of the world's uncultivated arable land lying in Africa, for example, the

continent will likely play a key role in feeding the surging global population. Unlocking this potential is only possible with the development of robust cold-chains that reduce food loss, ensure the quality and safety of food produced, and connect African farmers to international markets.

Just as important, the effect of climate change on disease vectors, such as mosquitos, coupled with increased population movement, is expected to significantly increase both the likelihood and impact of future outbreaks of infectious diseases. With such diseases likely to originate from low-income countries, there is a need to take a global approach to health cold-chains to ensure there is the capacity to avoid the transformation of an outbreak into an epidemic or even a pandemic.

NEED FOR A STEP CHANGE IN THE BUSINESS MODEL

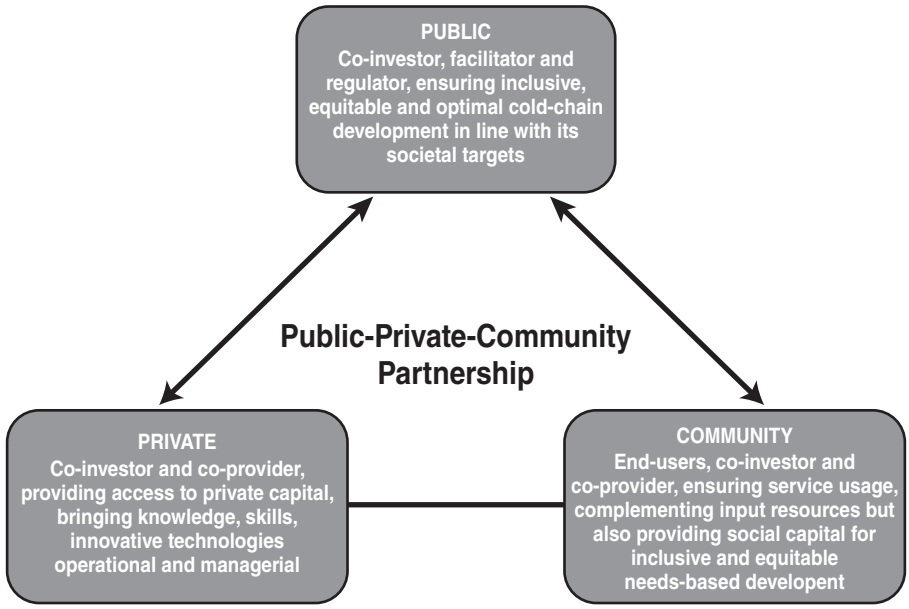

Figure 2. Public-private-community partnership model

Developing a sustainable, resilient, and equitable global cold-chain that seamlessly integrates both ends of the chain – source and end-user countries – will unlock multiple benefits critical to sustainable development and economic growth in low-income countries. It will also help ensure resilience and sustainability of the global food system. Achieving this requires taking a global approach in which all governments take a stakeholder role in the development of the cold-chain to form an integral part of a low-income country's infrastructure. Under this approach,

not just the local government, but also the governments of high-income countries must directly invest with the private sector in those areas with the most need, but that do not present an immediate business case for the private sector alone. A PPCP approach simultaneously could:

Enable local governments of low-income countries to complement resources with direct investments from high-income countries as well as access to sustainable technologies, knowledge, and skills with the private sector's involvement, thereby improving the efficiency, the resilience, and environmental sustainability of operations. Governments' collaborative involvement as stakeholders in cold-chain development, which requires seamless integration of different sectors, from producers, processors, and retailers to consumers, could also improve food safety and quality across borders.

Reduce investment risks for the private sector given government's policy-making powers, as well as communities' direct involvement as the end-users, securing the demand for services (e.g., through contractual agreements). It could also enable the private sector to reach a wider community and provide them with a structure that would contribute towards achieving Corporate Social Responsibility aspirations.

Enable target communities to access sustainable cold-chain technologies and market connectivity as well as relevant skills and knowledge. Direct involvement of the community in the development of clean cold-chain and provision of services would improve acceptance and take-up of new cold-chain technologies and practices and ensure cold-chain services better respond to the community's needs. Under PPCP, communities' traditional consumer-only role could be transitioned into a co-provision role. For example, communities could be co-owners or investors of their local cold-chain facilities and provide resources for energy production or complement the energy demand of facilities (e.g., biomass or surplus energy from decentralized renewable energy technologies). Furthermore, within the PPCP model, non-governmental organizations can play an intermediary role between the actors in partnership, mediating between community interests and those of the government and the private sector.

However, understanding the "real value" and return on investment of a sustainable, resilient, and equitable global cold-chain by identifying, quantifying, and, where possible, monetizing the multiple benefits it could deliver, is critical to facilitating the government's proactive involvement as a stakeholder in the development of the cold-chain. These benefits translate into reductions in other costs (e.g., reduced cost of food loss to the economy; reduced healthcare expenditure associated with malnutrition

as well as air pollution; and reduced undernutrition, which can exacerbate death rates among children, reducing the workforce and impacting national productivity) or lower economic losses (e.g., savings for governments that subsidize energy production and consumption due to reduced cooling energy demand through clean technologies). If these impacts were to be quantified as part of a cost-benefit analysis, it would greatly improve the return on investment. Hence, more detailed analysis is needed locally, nationally, and globally across multiple dimensions, such as health, productivity, education, and income, with established links to strategic goals, targets, and commitments, considering equity issues to understand the real cost of lack of cold-chains to economies and societies.

IN SUMMARY

In order to feed 9.7 billion people in a warming and resource-constrained world in 2050 and address the most acute socio-economic developmental challenges in low-income countries, a radically new approach to the global food system development is needed. The world should shift focus from simply more production to addressing food loss and ensuring proper management of the food that is harvested as an equal priority. Of equal importance, it needs to be recognized that empowering 500 million small-holder farmers in low-income countries by making agriculture in these countries more productive and profitable, including increasing access to high-value markets and exports, is critical not only to alleviate food insecurity and poverty in low-income countries, but also to unlock their potential to feed the global population.

A change in approach is also needed in the health dimension. The COVID-19 pandemic has been a wake-up call for the world, and revealed the weakest links in health systems and cold-chains. Future pandemics are likely to happen more frequently, and if the world's preparedness and response capacity is not improved, they may have an even greater social and economic impact. While border controls and other national strategies help to contain the spread of infectious diseases to some degree, the COVID-19 pandemic has shown that there needs to be a global approach to health cold-chains to ensure that low-income countries have the capacity to contain outbreaks quickly before they become epidemics or pandemics. In this regard, the capacity gap between high- and low-income countries is evident: as of October 2022, 68 percent of the world's population has received at least one dose of a COVID-19 vaccine. Yet only 23 percent of people in low-income countries have received at least one dose.[33] One of

the main reasons behind this gap is the lack of adequate health cold-chain in these countries.

We argue that the business case for integrated cold-chain development for governments is already clear even only from the food loss perspective, without considering the co-benefits, such as economic gains from prevention of food value loss, improved food safety, reduced health-care costs, new jobs, and investment opportunities. All these benefits could be achieved through a PPCP approach wherein governments become investors, play the facilitator and regulator role, and give direction to cold-chain development. Governments could work together and align their efforts with the private sector in line with national and global objectives and ensure an inclusive and equitable cold-chain access, taking into account communities' service needs in the decision-making processes.

Developing a sustainable, resilient, and equitable global cold-chain requires coordination and cooperation among countries to address the disconnect between high-income and low-income countries in terms of cold-chain development and connectivity, as well as policy and regulations across technologies, food, and health, and to prevent beggar-thy-neighbor strategies. Governments, working with industry and other stakeholders, need to take a responsive and future-oriented approach to develop the most cost-effective and equitable pathways with minimum environmental impact, focusing on long-term potential and value rather than short-term performance. This requires global collaboration to: (1) understand how the size and nature of cold-chain needs in low- and high-income countries will evolve with changes in demographic conditions, climate, food production and consumption patterns, social norms, technologies, and innovations; (2) understand and minimize risks, and plan for future disruptions to the system, which are likely to happen more frequently; and (3) define how both ends of the chain should cooperate and coordinate actions to achieve equitable win-win outcomes.

If we come together, we can solve the wicked problem of how to deliver temperature-sensitive market connectivity to achieve global food and health security and resilience in a warming world, while at the same time economically empowering 500 million small-holder farmers, each reliant on less than five acres of land, with minimum environmental impact within a zero-emission strategy. ***f***

ENDNOTES

1 *The Carbon Footprint of the Cold Chain, 7th Informatory Note on Refrigeration and Food*, International Institute of Refrigeration, April 2021, https://iifir.org/en/fridoc/

the-carbon-footprint-of-the-cold-chain-7-lt-sup-gt-th-lt-sup-gt-informatory-143457.

2 Ashkan Afshin et al., "Health Effects of Dietary Risks in 195 Countries, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study 2017," *The Lancet* 393, no. 10184 (May 2019): 1958–72, https://doi.org/10.1016/S0140-6736(19)30041-8.

3 Food and Agriculture Organization of the United Nations et al., *The State of Food Security and Nutrition in the World: Transforming food systems for affordable healthy diets,* 2020, https://doi.org/10.4060/ca9692en.

4 John Holmes, "Losing 25,000 to Hunger Every Day," *UN Chronicle* 45 (3) (December 2009): 14–20. https://doi.org/10.18356/a54cde0d-en.

5 "Global Immunization: Worldwide Disease Incidence," *The Children's Hospital of Philadelphia*, February 7, 2020, https://www.chop.edu/centers-programs/vaccine-education-center/global-immunization/diseases-and-vaccines-world-view.

6 Nick Barrowclough, "The Cost of a Broken Cold Chain in the Pharmaceutical Industry," *Pharma-Mon*, August 20, 2020, https://pharma-mon.com/drug-storage-monitoring/the-cost-of-a-broken-cold-chain-in-the-pharmaceutical-industry/.

7 FAO, *Food Wastage Footprint: Full-Cost Accounting*, 2014, https://agris.fao.org/agris-search/search.do?recordID=XF2015001538.

8 *Waste and Spoilage in the Food Chain*, The Rockefeller Foundation, May 2013, https://www.rockefellerfoundation.org/report/waste-and-spoilage-in-the-food-chain/.

9 Anna Nagurney, "Keeping Coronavirus Vaccines at Subzero Temperatures during Distribution Will Be Hard, but Likely Key to Ending Pandemic," *The Conversation*, September 18, 2020, https://theconversation.com/keeping-coronavirus-vaccines-at-subzero-temperatures-during-distribution-will-be-hard-but-likely-key-to-ending-pandemic-146071.

10 Sachiko Ozawa et al., "Return On Investment From Childhood Immunization In Low- And Middle-Income Countries, 2011–20," *Health Affairs* 35 no. 2 (2016): 199–207, https://doi.org/10.1377/hlthaff.2015.1086.

11 "A Year in the Lives of Smallholder Farmers," *World Bank*, February 25, 2016, https://www.worldbank.org/en/news/feature/2016/02/25/a-year-in-the-lives-of-smallholder-farming-families.

12 "How agritech can enable resilience in small farming communities," *Business Call to Action*, December 11, 2020, https://www.businesscalltoaction.org/guardian-news/how-agritech-can-enable-resilience-in-small-farming-communities.

13 Harriet Kariuki, "Innovation Is Key to Curbing Post-Harvest Losses in Africa," *Medium*, August 19, 2018. https://medium.com/@harriet436/innovation-is-key-to-curbing-post-harvest-losses-in-africa-755f2cde0b2f.

14 *Technology Audit for Fruits and Vegetables Value Chain Draft Report*, *National Industrial Research and Development Agency,* June 10, 2019, 21, https://www.nirda.gov.rw/uploads/tx_dce/Fruits_and_vegetable_tech_audit_report.pdf.

15 *Cold Chain Assessment: Status of Cold chain infrastructure in Rwanda*, NAEB, January 2019, 4, https://naeb.gov.rw/fileadmin/documents/Cold_chain_assessment_2019NAEB_final_version.pdf.

16 In total, around 80 percent of the GHG emissions from cooling technologies is associated with indirect emissions from energy use, whereas 20 percent is associated with direct emissions from refrigerant use. *See* UNEP TEAP, TEAP Decision Xxviii/3 Working Group Report on Energy Efficiency, 2017, https://ozone.unep.org/system/files/documents/TEAP-EEWG-Report-october2017.pdf.

17 "#Innovate4Climate 2019: How to Deliver Sustainable Cooling in a Warming World," World Bank, YouTube video, https://www.youtube.com/watch?v=G_1CRPmT6I4.

18 Cory Rand, Joel Jaeger, and Ipek Gencsu, *Phasing Down HFCs: Good for the Climate*

and the Economy, World Resources Institute, November 3, 2015, https://www.wri.org/insights/phasing-down-hfcs-good-climate-and-economy.

19 Manu Ravishankar, Sophie Bordat, and David Aitken, "Net zero cold chains for food: A discussion document on the case for philanthropic action," Carbon Trust, September, 2020, 9, https://www.carbontrust.com/our-work-and-impact/guides-reports-and-tools/net-zero-cold-chains-for-food.

20 *Liquid Air on the European Highway: The economic and environmental impact of zero-emission transport refrigeration*, Dearman, September, 2019, https://airqualitynews.com/wp-content/uploads/2015/09/Liquid-Air-on-the-European-Highway.pdf.

21 "Air pollution," *World Health Organization*, Accessed December 13, 2022, https://www.who.int/health-topics/air-pollution#tab=tab_1.

22 *The Carbon Footprint of the Cold Chain*.

23 Including the loss and waste that is not related to the lack of cold-chain.

24 Food and Agriculture Organization of the United Nations et al., *The State of Food Security and Nutrition in the World: Transforming food systems for affordable healthy diets.*

25 *The Role of Refrigeration in Worldwide Nutrition, 6th Informatory Note on Refrigeration and Food,* International Institute of Refrigeration, March, 2020, https://iifiir.org/en/documents/39820/download.

26 Ibid.

27 *Demand Analysis for Cooling by Sector in India in 2027*, India Bureau of Energy Efficiency, May, 2018, https://www.aeee.in/wp-content/uploads/2018/10/Demand-Analysis-for-Cooling-by-Sector-in-India-in-20271.pdf.

28 *Cold Chain Assessment: Status of Cold chain infrastructure in Rwanda*.

29 Ibid.

30 "Global Issues: Population," *United Nations*, Accessed December 13, 2022, https://www.un.org/en/global-issues/population#:~:text=The%20world's%20population%20is%20expected,billion%20in%20the%20mid%2D2080s.

31 *Creating A Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*, World Resources Institute, 2019, https://www.wri.org/research/creating-sustainable-food-future.

32 Ibid.

33 Edouard Ritchie, et al., "A global database of COVID-19 vaccinations," *Nature Human Behaviour* 5: 947–953 (2021), https://www.nature.com/articles/s41562-021-01122-8.