TECHNOLOGICAL INTERVENTIONS IN INDIAN FOOD SYSTEMS AND THE FUTURE OF FOOD SECURITY

EMBASSY OF DENMARK
New Delhi

INNOVATION CENTRE DENMARK

Tata-Cornell Institute

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This report was prepared as a part of a project titled, "Indian Food Systems Challenges and Technological Interventions: An Investment Platform," funded by the Royal Embassy of Denmark, New Delhi, India. The project was supported by Dr. Jakob Williams Ørberg, Danish Councellor for Innovation, Research and Higher Education, jakorb@um.dk

Required citation: TCI (Tata-Cornell Institute). 2022. Technological Interventions in Indian Food Systems and the Future of Food Security. Ithaca, NY: TCI.

ISBN: 979-8-218-00713-3

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Copy editing: Patricia Mason

Design and layout: DragonFish Studio - www.DragonFish.design

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Cover photo: A farmer uses a laptop at a produce market in Madhya Pradesh, India. (Photo by Neeraz Chaturvedi on Shutterstock)

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ABBREVIATIONS

AAA maize . . . . Affordable, Accessible, Asian Maize
Agritech . . . . . agricultural technology
AGMARKNET . Agricultural Marketing Information Network
AI. . . . . Artificial Intelligence
AO . . . . Avaaj Otalo
AoA . . . . Agreement on Agriculture (WTO)
APLM . . . . Model Agriculture Produce and Livestock Marketing Act, 2017,
APMCs . . . . Agricultural Produce Marketing Committees
APMR . . . . Agricultural Produce Markets Regulation
BMI . . . . Body Mass Index
BNI . . . . Biological Nitrification Inhibition
CA . . . . Conservation Agriculture
CACP. . . . . Commission for Agricultural Costs and Prices
CAGR. . . . . Compound Annual Growth Rate
CCRL . . . . CDSL Commodity Repository Limited
CDSL . . . . Central Depository Services (India) Limited
CFC . . . . Chlorofluorocarbon
CH4 . . . . Methane
CHCs . . . . Custom Hiring Centers (farm machinery)
CIMMYT. . . . . . International Maize and Wheat Improvement Center
CMERI . . . . Central Mechanical Engineering Research Institute
CO2 . . . . Carbon Dioxide
CPB . . . . Conventional Plant Breeding
CPR . . . . Common-Pool Resources
CRISPR . . . . Clustered Regulatory Interspaced Short Palindromic Repeats
CSISA . . . . Cereal Systems Initiative for South Asia
CWC . . . . Central Water Commission
DMLs . . . . Direct Marketing Licenses
ECA . . . . Essential Commodities Act, 2020
e-NAM . . . . e-National Agricultural Market
e-NWR . . . . Electronic Warehouse Receipts
FaaS. . . . . Farm as a Service models
FAO . . . . Food and Agriculture Organization of the United Nations
FAPAFS. . . . . . . Farmers (Empowerment and Protection) Agreement on Price Assurance and Farm Services Act, 2020
FDI . . . . Foreign Direct Investment
FLW. . . . . Food Loss And Waste
FPOs . . . . Farmer Producer Organizations
FPTC . . . . Farmers Produce Trade and Commerce (Promotion and Facilitation) Act, 2020
FSA . . . . Food Systems-Based Approach
FSS . . . . Farm-Saved Seed
GEE . . . . Google Earth Engine
GHG . . . . Greenhouse Gas
GIS. . . . . Geographic Information Systems
GMOs . . . . Genetically Modified Organisms
GST . . . . Goods And Services Tax
GWP . . . . Global Warming Potential
HFC . . . . Hydrofluorocarbon
HTP. . . . . High-Throughput Phenotyping
HYV. . . . . High-Yielding Variety
IAMAI . . . . Internet and Mobile Association of India
IARCs . . . . International Agricultural Research Centers
ICAP . . . . India Cooling Action Plan
ICAR . . . . Indian Council of Agricultural Research
ICDS . . . . Integrated Child Development Services
ICEX . . . . Indian Commodity Exchange Limited
ICRISAT . . . . . . International Crops Research Institute for the Semi-Arid Tropics
ICT . . . . Information Communication Technology
ILCI . . . . "Feed the Future" Innovation Lab for Crop Improvement
IoT . . . . Internet of Things
IPM . . . . Integrated Pest Management
IPNM . . . . Integrated Plant Nutrition Management
IRRI . . . . International Rice Research Institute
KCC . . . . Kisan Call Center
KHETI . . . . Knowledge Help Extension Technology Initiative
KVKs . . . . Krishi Vigyan Kendras
MAS . . . . Marker-Assisted Selection
MCX . . . . Multi-Commodity Exchange
MDMS. . . . . Mid Day Meal Scheme
MLAs. . . . . Machine Learning Algorithms
MSPs . . . . Minimum Support Prices
NAGS . . . . National Active Germplasm Sites
NARS. . . . . National Agricultural Research Systems
NABARD. . . . . . National Bank for Agriculture and Rural Development
NBPGR . . . . National Bureau of Plant Genetic Resources
NCCD . . . . National Centre for Cold Chain Development
NCDEX . . . . National Commodity & Derivatives Exchange
NERL. . . . . National e-Repository Limited
NFHS . . . . National Family Health Survey
NGS . . . . Next-Generation Sequencing
NIR . . . . Near-Infrared
N2O . . . . Nitrous Oxide
NMCE . . . . National Multi-Commodity Exchange of India Ltd.
NPBTs . . . . New Plant Breeding Technologies
NSC . . . . National Seeds Corporation
NSEL . . . . National Spot Exchange Limited
NSS . . . . National Sample Survey
NSSO. . . . . National Sample Survey Organization
NWR . . . . Negotiable Warehouse Receipt
PDIL . . . . Projects and Development India Ltd.
PDS . . . . Public Distribution System
PGR . . . . Plant Genetic Resources
PM . . . . Particulate Matter
PPP . . . . Public–Private Partnership
R&D . . . . Research And Development
ReMS. . . . . Rashtriya eMarkets Services Pvt. Ltd.
RRBs . . . . Regional Rural Banks
SAU . . . . State agricultural university
SDB . . . . Solar Bubble Dryers
SDGs . . . . Sustainable Development Goals
SEC . . . . Search, Experience, and Credence classification
SHGs . . . . Self-Help Groups
SI . . . . Sustainable Intensification
SMS . . . . Short Message Service
SSCs . . . . State Seeds Corporations
SRR . . . . Seed Replacement Ratio
TALEN . . . . Transcription Activator-Like Effector Nucleases
TCI . . . . Tata–Cornell Institute
TRU . . . . Transport Refrigeration Units
UCX . . . . Universal Commodity Exchange
UMP . . . . Unified Market Platform
USAID . . . . United States Agency for International Development
VAT . . . . Value-Added Tax
WTO . . . . World Trade Organization

1 • INTRODUCTION

As India's population rises, incomes grow, and with rapid urbanization, its citizens' food preferences are also changing. Consumer preferences have moved away from a quantity-based to quality-based focus on food. In the past two decades, the share of staple grains—rice and wheat—in diets has steadily declined, while consumption of nonstaple foods, such as fruits, vegetables, and livestock products, has increased. According to the consumption expenditure surveys of the National Sample Survey Organization (NSSO), monthly expenditure on cereals and cereal products decreased from 41.1% to 10.8% in rural India between 1971–72 and 2011–12. The rising demand for diversified agricultural products has brought about opportunities and challenges for the Indian agricultural sector. Small farms have opportunities to commercialize, diversify to produce higher value crops for the market, improve agricultural incomes, and improve access to a varied food basket at the household level.

The challenge of responding to changing demand has been of two kinds. First, smallholder production systems are disadvantaged in accessing commodity markets, credit, purchased inputs, technology, and extension services to increase and diversify production. Second, increasing productivity and diversification of food for a rising population increases the use of resources (land, water, and inputs), as well as environmental externalities in the form of emissions. As the agricultural sector influences and is influenced by climate change, increasing production is closely related to reducing production risks (Abraham and Pingali 2020).

India has made drastic strides in ensuring food security in the seven decades since independence. Through technological advancements, brought about through the Green Revolution, food grain production increased from 82.02 million MT in 1961 to 275.11 million MT in 2016 (Directorate of Economics and Statistics 2020, 71). The primary goal of the technological intervention was to boost agricultural productivity to be able to deliver the population's caloric needs, and thus, avoid famines. To this end, the Green Revolution was successful. Despite progress in poverty reduction and increased productivity, food security challenges remain, however. The current number of undernourished in India is 189 million (FAO 2020, 182). According to the National Family Health Survey (NFHS–4) released in 2016, 38.4% of children under the age of 5 are stunted, and 38.3% of children in the same age group are underweight. Concomitantly, obesity or overnutrition has been on the rise. Between 2005–06 and 2015–16, the prevalence of adult obesity almost doubled, from 9.3% to 18.9% in men and 12.6% to 20.6% in women.

The two contrasting figures of malnutrition depict a story of two India's. One India with fast urbanizing or agriculture-led states, such as Punjab, Haryana, Maharashtra, Karnataka, Kerala, and Tamil Nadu, has increased agricultural productivity and incomes to reduce poverty at a faster pace. These states have experienced a rise in the prevalence of obesity. Another India includes states like Bihar, Uttar Pradesh, Odisha, and West Bengal, which did not fare well in agricultural development and are playing catch-up, with hunger and micronutrient deficiencies prevalent (TCI 2020).

Agricultural technology is the central feature in this story that has put different states on different growth trajectories. While the whole country benefited from the increased production of staple grains from the Green Revolution, only a few states adopted Green Revolution high-yielding variety (HYV) technologies and reaped agricultural development benefits. In 2030, with a population of 1.51 billion people, India will be the most populous nation. Feeding an additional 150 million people and meeting the demand for a diversified food basket, while rectifying the country's prevailing food insecurity, is the reality of India's food security challenge. The central questions are: how do we increase production and minimize the corresponding environmental impact? How do we ensure equitable agricultural development in all regions, and what agricultural technologies are relevant to improving food supply and agricultural incomes sustainably? Shedding light on these questions is the main aim of this report on agricultural technologies.

Technology plays a critical role in achieving food security, but the approach will be different from the Green Revolution of the 1960s. Technology for agricultural development needs to go beyond just technologies to increase yield. While yield increases and yield stability are essential, new technologies in computation and analytics, as well as advances in genomics, are needed to breed climate-resilient, less resource-intensive, and highly nutritious crops in a shorter time. Information communication technologies (ICTs), using remote sensing, drone technologies, and high-tech services, fill knowledge gaps to aid in better use of resources and decision-making during intensification. ICTs for farms and markets enable service provisions for rectifying scale disadvantages, improving access to mechanization, and increasing bargaining power. Technology for efficient cooling and drying to reduce food waste and losses and increasing marketing options for small farms are examples of the need for technology beyond yield increase.

This introductory chapter presents the conceptual framework used in this report on technology for Indian agriculture. We begin by looking at the intensification of agricultural production during the Green Revolution. Identifying limitations of technology adoption, especially highlighting the extent of crop and regional inequalities and the environmental externalities, we identify the major drivers of technological innovation in the agricultural sector to meet India's current and future food security needs. We identify plant breeding, farm management, harvest, postharvest, and market access interventions as primary focus areas, mindful of India's spatially varied needs. The final section summarizes the four chapters of the report dedicated to modern crop breeding technologies, farm management practices, harvest, and postharvest interventions, and improved market access technologies.

MOVING FROM INTENSIFICATION TO SUSTAINABLE INTENSIFICATION

Concerns about humankind's ability to feed themselves in the wake of the growing population are not new. In the 18th century, when the human population numbered less than 1 billion, in his famous *Essays on the Principle of Population*, Thomas Malthus ([1798] 2009) observed that because the population grew exponentially while food production increased in a linear manner, food insecurity would be the doom of humanity. His work postulated that when population growth exceeds food supply, the emerging crisis points will manifest in famines, diseases, and other checks on the population. In the 1950s, the Malthusian fears were alive and well in India. With a population of over 350 million people and a birth rate of 6 births per woman (Dumont 2015), and the Bengal famine just a decade earlier, having killed an estimated 2.1 to 3 million people (Dyson and Maharatna 1991), concerns about India being able to feed itself were real. India produced 48.1 million tons of food grains in 1951 (about 144.1 kg per capita per year). Still, agricultural production was subjected to high fluctuations, warranting food rationing and the importation of food (Hatti 1977).

By the 1960s, India was dependent on the wheat exports under the PL-480 Food for Peace program by the United States and with a population close to half a billion, commentators were convinced that unless consumption reduced and the population controlled, the consequences would be apocalyptic. In the 1960s and 70s, two seminal works – one for and one against the Malthusian theory emerged. Paul Ehrlich's *The Population Bomb* (1978) and Ester Boserup's *The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure* (1965). Interestingly, both of these works were influenced by developments in India.

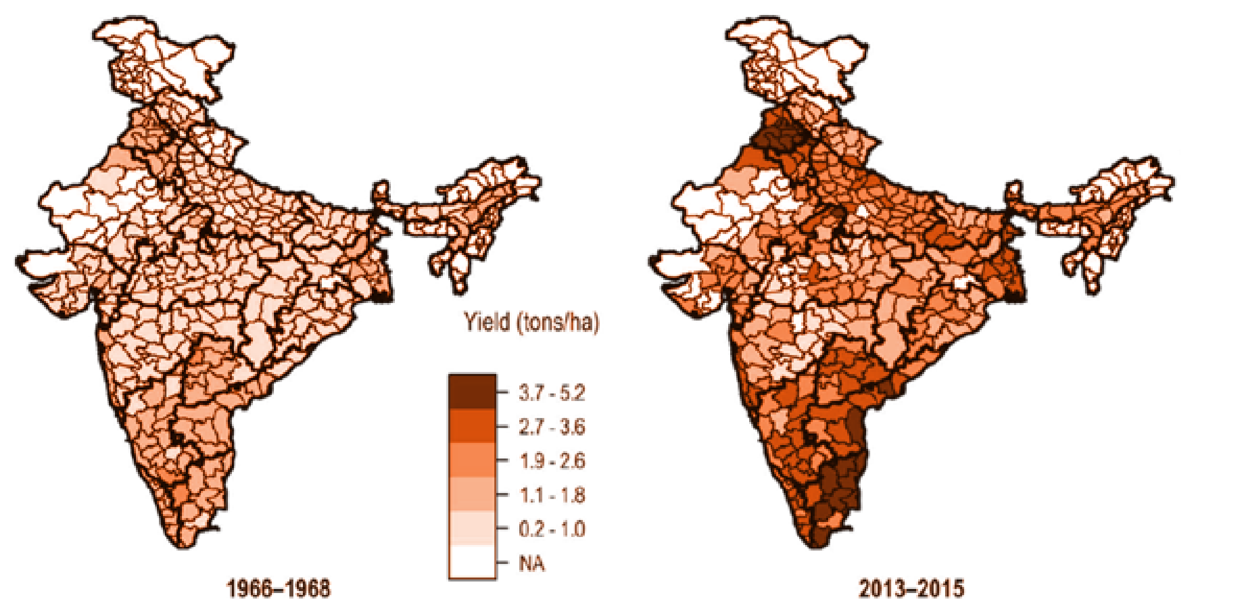
As the title suggests, Ehrlich's pessimistic book opened with a taxi ride in Delhi, a city with 2.6 million inhabitants in 1966. Overwhelmed by crowds, he wrote that "the battle to feed all of humanity is over" (Ehrlich 1968, xi), and hundreds of millions of people would eventually starve to death due to food shortages and depleted resources. With India, in particular, Ehrlich (1978, xx) wrote: "I don't see how India could possibly feed two hundred million more people by 1980." Ester Boserup, the Danish economist, challenged the notion of an upper limit to food production. Her influential work, *The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure* (1965), was greatly influenced by her work in India between 1957 and 1960.

Her mostly nontechnical work argued that a growing population induced innovation to better utilize existing resources through new technologies—a process called agricultural intensification. For example, when demand for food rises in different farming systems, long fallows will be replaced by shorter fallows, chemical fertilizers will be used to restore fertility, and farmers will move from annual cropping to multiple cropping systems to increase productivity. The intensive agriculture systems are supported by technological innovation and will lead to improved labor productivity and more efficient production, thus increasing agricultural output. Boserup's ideas have since been engaged and explored in the context of farming systems, especially in Africa (Pingali, Bigot, and Binswanger 1987; Binswanger and Pingali 1988).

THE GREEN REVOLUTION AND AGRICULTURAL INTENSIFICATION IN INDIAN WHEAT AND RICE SYSTEMS

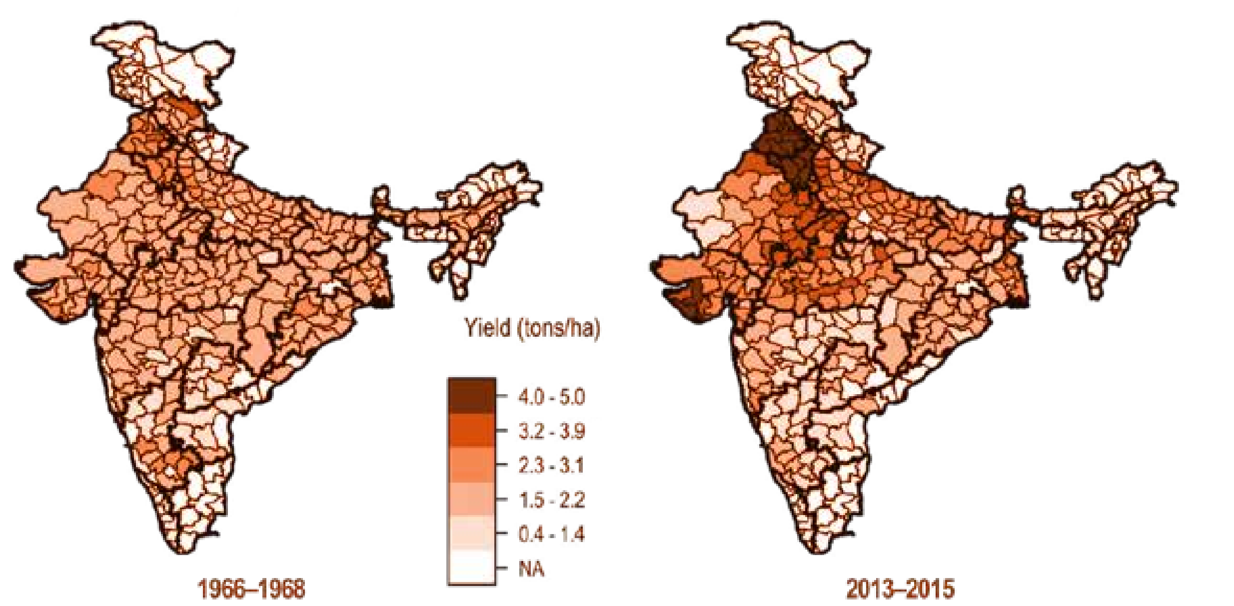
Through the use of HYV seeds and other inputs and better irrigation infrastructure under the Green Revolution, some parts of India moved from a single cropping rainfed system to a multi-cropping irrigated system. The development was a sound testimony to Boserup's agricultural intensification thesis (Boserup 1965). While Green Revolution technologies increased yield and tripled wheat and rice productivity, saving much of the developing world from intense food shortages and famines, they had their limits. The Indian Green Revolution's significant limitations were that intensification led to unanticipated environmental externalities, and the benefits of intensification were location-specific and crop-specific, leading to regional inequalities in development (Pingali et al. 2019). Although India achieved productivity increases with only 30% of arable land expansion (Pingali 2012), intensive cultivation and poor farm and resource management led to diminished biodiversity, increased greenhouse gas (GHG) emissions, and overuse of inputs. The emergence of monocropping in rice–rice systems of south India and wheat–rice systems in the Indo-Gangetic plains put a strain on land use. Electricity and fertilizer subsidies have resulted in fertilizer overapplication, leading to chemical runoffs, soil degradation, and water table depletion (Pingali 2012; Abraham and Pingali 2020; Mahapatra 2020).

Figure 1.1: District-level rice yields, 3-year averages 1966–68 and 2013–15



Source: Food, Agriculture and Nutrition Report, Tata–Cornell Institute (2020)

Figure 1.2: District-level wheat yields, 3-year averages 1966–68 and 2013–15



Source: Food, Agriculture and Nutrition Report, Tata–Cornell Institute (2020)

The benefits were location-specific because only the regions with access to irrigation and areas receiving high rainfall effectively adopted HYV. The benefits were crop-specific because HYVs were developed solely for wheat and rice, disincentivizing other traditional crop cultivation, such as millets and pulses. **Figures 1.1** and **1.2** show, respectively, that wheat and rice yields grew in the irrigated regions of Punjab, Haryana, and parts of the Indo-Gangetic plains. The southern states benefited from growth in rice yields, giving rise to monocropping systems.

DISPARITIES IN ECONOMIC DEVELOPMENT AND NUTRITIONAL OUTCOMES AND THE ENVIRONMENTAL IMPACT

The two significant and interrelated consequences of the Green Revolution technologies' location and crop-specificity are: first, nutrition-rich coarse grains and pulses were crowded out of more productive lands. Access to irrigation and the higher yield potential of HYVs incentivized wheat–rice systems in the Indo-Gangetic plains and rice–rice systems in the southern states, reducing pulses and coarse cereal availability (Abraham and Pingali 2020). Second, the rate of technology adoption under the Green Revolution and diversification of agriculture led different states along different growth trajectories. States, such as Uttar Pradesh, Jharkhand, Madhya Pradesh, Chhattisgarh, Bihar, Odisha, and West Bengal, did not reap the benefits of the Green Revolution to its fullest, due to low technology suitability, poor infrastructure, and lack of infrastructure support (Prahladachar 1983; Bajpai and Sachs 1996). The northwestern states of Punjab and Haryana and the southern delta regions of Andhra Pradesh And Tamil Nadu, with a comparative advantage in irrigation and rainfall, were able to emerge as Green Revolution leaders through the rapid adoption of HYV technology.

Other states, such as Kerala, Maharashtra, and Karnataka, which did not have a comparative advantage in staple grain production, capitalized on the growing demand for other higher value crops (Rao, Shand, and Kalirajan 1999; Pingali et al. 2019)—Kerala, in crops such as fruit, spices, and rubber from local and global markets, and adoption by Maharashtra and parts of Karnataka of the new crops and varieties of cotton and oilseeds. As a result, these states witnessed a transformation in their agricultural sectors. In contrast, states, such as Bihar, Uttar Pradesh, Madhya Pradesh, and Odisha, which continued to rely on low-yield, rainfed staple grain production, lost out.

Pingali et al. (2019) classified states into three categories—*agriculture-led growth states, urbanizing states,* and *lagging states*, based on GDP per capita in these states, the share of agriculture in GDP, and urbanization rates. Agriculture-led states have high GDP per capita, with agriculture remaining an essential contributor to GDP growth, and low urbanization rates. States with high GDP per capita and high urbanizing rates are urbanizing states. Finally, those states with low GDP per capita and low rates of urbanization are classified as lagging states. **Table 1.1** shows the classification of states according to their developmental characteristics.

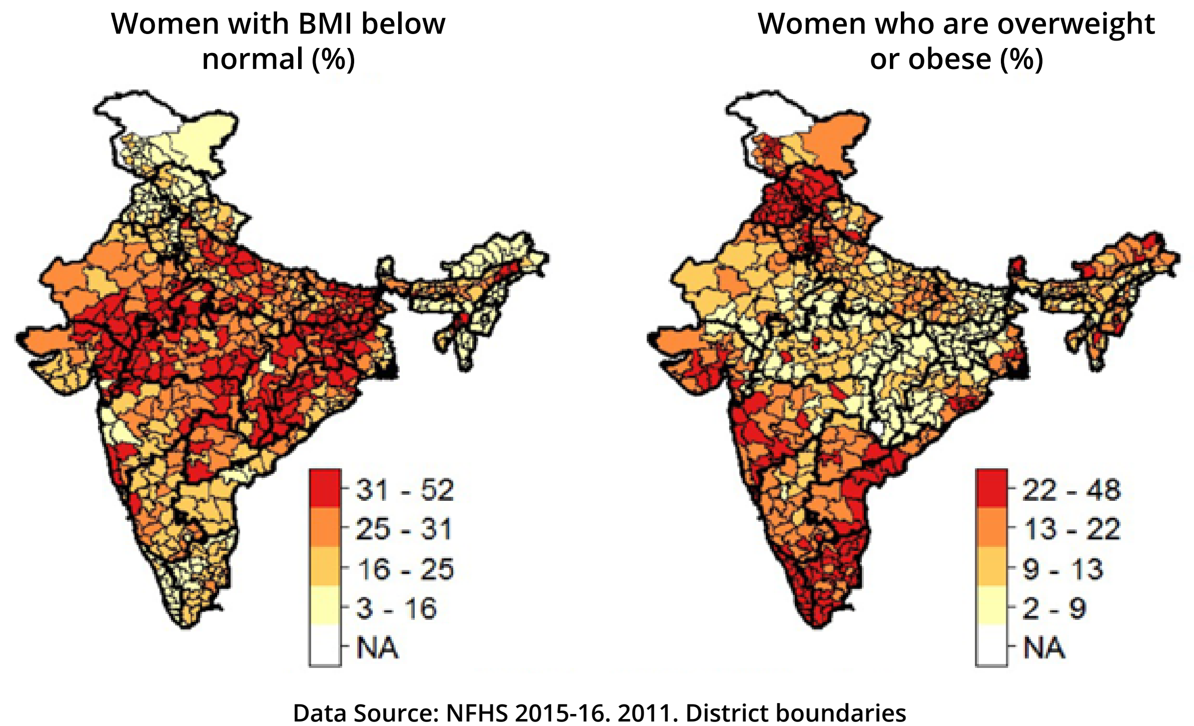
Food security challenges in India, as a consequence of differential regional development of agriculture, have also been varied. India's lagging states have undernutrition and micronutrient deficiency rates comparable to lesser developed countries and sub-Saharan Africa regions. Urbanizing and agriculture-led states have fared far better in tackling undernutrition and micronutrient deficiencies, with indicators similar to Southeast Asian and Latin American countries (Pingali

Table 1.1: Classification of states into high and low potential areas			
Typology	Agriculture-led growth states	Urbanizing states	Lagging states
Criteria	Low urbanization rates and high GDP per capita. Share of agriculture in state GDP is relatively high	High urbanization rates and high GDP per capita. Declining share of agriculture in state GDP	Low urbanization rates and low GDP per capita, and low productive agricultural sector
States	Punjab, Haryana, Andhra Pradesh, Himachal Pradesh	Kerala, Goa, Maharashtra, Tamil Nadu, Gujarat, Karnataka, Telangana, Uttarakhand	Bihar, Madhya Pradesh, Uttar Pradesh, Odisha, Jharkhand, Chhattisgarh, West Bengal, Rajasthan, Jammu and Kashmir, northeast states

Source: Pingali et al, 2019

et al. 2019; Pingali and Abraham 2019). The more developed states, however, face the challenge of rapidly rising rates of obesity. **Figure 1.3** shows the distribution of overweight or obese women and those with body mass index (BMI) below normal. In the maps, the story of the two India's becomes clear. The lagging states that did not benefit from agricultural development are saddled with undernutrition, and the more developed states must reckon with rapidly rising overnutrition.

Figure 1.3: The distribution of women with body mass index below and above normal



Source: Food, Agriculture and Nutrition Report, Tata–Cornell Institute (2020)

As India becomes the most populous country in the world, with 1.65 billion citizens forecast by 2050, two significant developmental challenges require urgent attention. The first challenge is to ensure the food security for its future population while addressing the current problem of food insecurity. The task here would be to increase food grain production by about 42% (or by 377 million MT) over 2015 levels while also diversifying and expanding production to include nutrient-rich, higher value crops, such as fruits and vegetables, coarse grains, and pulses (Pingali et al. 2019). Intensification and the shift toward higher value agriculture are knowledge- and resource-intensive and, thus, will impact the environment and be affected by climate change. Therefore, the second challenge is to increase agricultural production sustainably by limiting environmental externalities in land and water degradation and the emission of greenhouse gases.

The term *sustainable intensification* (SI) describes increasing agricultural productivity while reducing environmental harm through improved input use efficiency (Pretty and Bharucha 2018). Concomitantly, managing production risks from climate change, such as droughts, floods, and temperature increases, and reducing crop loss through efficient farm and value chain management will be vital. Agriculture affects and is affected by climate change. Agricultural production practices alone will not be sufficient to address risks and eventualities. Technology-supported sustainable food systems are the key to addressing India's current and future food security challenges. Technological innovation in plant breeding and farm management levels, as during the Green Revolution and beyond at the harvest, postharvest, and marketing stages will play a significant role beyond merely aiding intensification at the production level, to the achievement of SI of the food systems.

TECHNOLOGICAL INNOVATION IN FOOD SYSTEMS BEYOND THE GREEN REVOLUTION

A food system is an interconnected web of activities linking agricultural production, marketing, processing, and consumption to strengthen nutrition access and utilization for individuals and households (Pingali et al. 2019). In a food system, various stakeholders (scientists, farmers, workers, traders, processors, retailers, service providers, and consumers) carry out different activities (scientific research, farming, buying, selling, and consumption) to ensure that food gets from the farm to plate. Crop technologies, farm management, storage, distribution, marketing, food safety, and standards work together to ensure food availability, environmental sustainability, and better health and nutrition outcomes. A holistic food systems-based approach (FSA) considers both the production and consumption and their interlinkages in meeting food security goals of improving access, availability, and health and nutrition outcomes (Pingali et al. 2019).

Limiting intensification and environmental sustainability to just seed and farm management technologies and systems gives only a partial view of food security challenges and potential solutions. The supply-side of food systems look at seed and farm management systems, the continuum to harvest and postharvest practices, and market linkages and participation. The emphasis on technologies beyond the farm and looking at the food systems on the supply side as a whole is critical at two levels. One, decisions made at seed development stages and farm management levels will influence harvest and postharvest interventions. For example, the decision to diversify to higher value crops will determine technology and infrastructure at the harvest and postharvest and marketing levels, significantly impacting mechanization, energy use for storage, preservation, and cold chain development. Second, commercialization or market participation opportunities incentivize changes in production practices. When farms decide to increase market participation, new seed technology and farm management technology adoption increases at the farm level. Therefore, harvest, postharvest, and marketing stages are vital to intensification and environmental sustainability and are a part of the continuum for SI of food systems.

THE NEW DRIVERS OF TECHNOLOGICAL INNOVATION IN FOOD SYSTEMS

The food system's supply side is composed of plant breeding and seed systems, farming practices and management, harvest and postharvest practices, and market access. The process of intensification involves changes in practices in each of these interconnected elements. Technology and access to technology are vital for SI in food systems. However, if approaches are to have a broader scope and impact than the approaches of the Green Revolution, technological innovations will need to consider the influence of four main drivers. Table 1.2 highlights environmental challenges, shift from producer to consumer orientation, scale disadvantages of smallholder production, and changing private and public sector roles in agriculture as the four main drivers of technological innovation.

Table 1.2: Drivers of technological innovation in the agricultural sector

Drivers	Areas of technological innovation
Environmental challenges	– Reduce the impact of intensification and diversification on the environment – Manage climate change and environmental risks
Shift to higher consumer orientation	– Meet the requirements of higher value and nutritious food production – Food safety and standards, health requirements in food
Scale disadvantages of smallholder production	– Enable smallholder technology adoption – Increase smallholder commercialization through effective smallholder-to-market linkages and reduced transaction costs
Changing private and public sector roles	– Policy environment to incentivize innovation in farm and market-level technologies – Public–private partnerships for public goods creation and increased private sector response in the agricultural sector

Environmental Challenges

The environmental challenges for intensification come from the fact that the agricultural sector influences and is influenced by climate change. Intensification is input- and knowledge-intensive, putting pressure on land and water resources and raising emissions as energy requirements at the production and value chain stages increase. Agriculture is a large emitter of GHG, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). Agriculture contributes 18% of India's total emissions, and rice and livestock production contribute 36.9% and 38.9% to GHGs, respectively, by way of anaerobic and enteric fermentation (Vetter et al. 2017). Climate change impacts food systems through reduced agricultural yields and livestock productivity; increased production uncertainty; deterioration of natural resources, soils, and water quality; and reduced nutrients in crops. Innovations in plant breeding technologies and farm management practices are required to develop mitigation and adaptation strategies in the wake of climate change. At the harvest, postharvest, and marketing stages, preservation strategies in cold storage and cold chains to reduce food loss and ensure health, hygiene, and safety are also a challenge that requires technological innovation. Climate change adaptation and mitigation needs are drivers of technological innovation in food systems.

Shift from producer to consumer orientation

Demographic change in the form of population growth, income growth, and rapid urbanization in India are fueling dietary transitions and consumer preferences away from traditional staples, such as wheat and rice, toward nonstaple foods, such as fruits, vegetables, and livestock products and from *quantity* to *quality*. The diversification of diets to higher value agricultural products has provided new growth opportunities for rural India, especially with the rise of supermarkets, hypermarkets, and e-retail in food. In 2019, modern food retail sales in India grew by 12%, and although online grocery sales in 2019 were only 5% of total organized grocery retail, they grew by 27% (Sawant 2019). Sales are expected to grow to US$18 billion from the current US$1 billion by 2024 in online grocery retail (FE Bureau 2020). Harnessing the new growth opportunities means leveraging technological innovations to (1) access quality inputs, information, and extension services, as well as manage resources and risks associated with higher value crops; (2) adopt harvest and postharvest practices to reduce food loss and waste; and (3) minimize transaction costs and information asymmetries to access markets. While producer-oriented Green Revolution technologies focused on yield and calorific needs, new technological innovations are driven by the need to diversify to higher value, quality-sensitive agriculture products.

Scale disadvantages of smallholder production

Higher value agricultural products are highly differentiated, requiring higher labor, monitoring, technology, and credit inputs than staple grains. Diversification to higher value crops increases production costs, management inputs, and risks at the production level and requires specialized storage and transportation at the postharvest and marketing levels due to their high perishability. Economies of scale disadvantages constrain smallholders' ability to access credit, high quality inputs, information, and technology to diversify and produce for the changing demand, as well as access specialized value chains. The Green Revolution technologies were successful in smallholder economies such as India's because HYV technologies were scale-neutral and could be adopted by smallholders. With over 80% of agricultural landholdings small and marginal in size, mechanization, extension and quality information, cold storage facilities, and access to specialized supply chains for small farms is vital for commercialization and diversification. ICT-enabled farm service delivery, access to specialized value through aggregation, and reduced information asymmetry through rapid quality assessment innovations are critical to rectifying scale disadvantages and making technology accessible.

Changing private and public sector roles in agriculture

The question of who provides the technologies is an important one. Both private and public sector research and development (R&D) is critical for agricultural development, and one is not a substitute for the other. The Green Revolution was a testimony to how agricultural R&D, as a public good, developed institutional capacity in plant breeding and enabled the adoption of HYVs to achieve food sufficiency in many developing countries (Pingali 2012). Since 1991, private sector investment in agricultural R&D has grown exponentially. While India's public sector R&D, as a proportion of agricultural GDP, was close to 2% in 2013, the private sector's investment had risen to 13% from a modest 4% in the 1980s (Ferroni and Zhou 2017). The public sector role is critical for the R&D of self-pollinated crops—including staple grains and pulses—and livestock, weather and climate-related data systems, and the creation of public goods such as critical infrastructure for connectivity. Private sector investment in public goods is absent, as investment returns are negligible. However, the state's public goods creation and enabling policy environment can facilitate private sector response in building public–private partnerships (PPPs) and investments in R&D and infrastructure in food systems. In many economic sectors, PPP models, in which the private sector finances capital-intensive projects, shares risk and technology, and enables business development for economic growth, can boost innovation in various food system segments. Strategic and symbiotic PPPs in plant breeding, value chain infrastructure development, and agricultural markets will drive investments in agricultural technological innovations.

Innovation in the agricultural sector has region-specificity, as technological needs in the lagging regions differ from urbanizing and agriculture-led states. While the lagging states will need to play catch-up with the states that benefited from the Green Revolution's innovations, the newer production challenges of climate change and existing resource constraints make it critical to have public sector research. **Table 1.3** lays out the report's analytical framework, which looks at the four supply-side components of food systems, the innovation systems, and technology needed in lagging, agriculture-led, and urbanizing states, along with the corresponding Sustainable Development Goals (SDGs) that they will help to address.

This report has five topical chapters addressing the challenges and way forward for each Indian food system's supply-side components. In the second chapter, "Modern crop breeding technologies for India—improving genetic gain," we examine the challenges of India's crop-breeding technological approaches. We assess the agronomy challenges since the Green Revolution and the institutional capacity of the Indian National Agricultural Research Systems (NARS). The challenges are to increase genetic gains so as to improve diversification, increase yields and quality of nonstaples and other crops, enhance resistance to biotic and abiotic stresses, and limit environmental externalities, such as soil degradation and water table depletion. We discuss the need to build capacity within NARS to adopt modern plant technology that is driven by product profiles, advances in machine learning, informatics, and data science. Modern techniques in genomic services and analysis, phenomics, and breeding informatics will increase genetic gains and reduce breeding cycle time to respond to food security needs in a timely manner. We also touch upon new plant breeding technologies (NPBTs), such as second-generation genetically modified organisms (GMOs) and their potential for increased genetic gains and reduction of breeding cycle time. This deliberate shift in focus will bring attention to low potential areas or regions that did not benefit from the initial Green Revolution due to resource constraints, such as access to irrigation, which is central to modern crop-breeding technologies.

Table 1.3: Supply-side components of food systems and technological drivers

Drivers	Technological innovations in lagging states	Technological innovations in urbanizing and agriculture-led states	Technological drivers
Plant breeding systems	Improve genetic gains in yields of cereals, coarse cereals, and pulses; reduce biotic and abiotic risks; improve nutrition quality in crops through biofortification	Improve genetic gains in yields of fruits and vegetables; reduce biotic risks; limit environmental externalities of intensive production	– Environmental challenges – Consumer orientation – Public and private sector roles
Farm management	Technologies for smallholder access to information and extension services through information communication technologies (ICTs); mechanization services for labor-saving and reduced emissions; technology for effective input use, especially water.	Technologies for smallholder access to information and extension services through ICT services for reduced emissions; technology for effective input use to reduce environmental externalities	– Environmental challenges – Consumer orientation – Scale disadvantages of smallholders – Public and private sector roles
Harvest and postharvest	Preservation and storage technologies to reduce loss; energy-efficient drying and cold storage	Preservation and storage technologies to reduce loss; energy-efficient drying and cold storage	– Environmental challenges – Consumer orientation – Scale disadvantages of smallholders
Market access	Reduce transaction costs and improve smallholder participation in electronic markets through effective quality determination and price discovery mechanisms	Reduce transaction costs and improve smallholder participation in electronic markets, commodity futures markets, and warehouse receipt systems through effective quality determination and price discovery mechanisms	– Consumer orientation – Scale disadvantages of smallholders – Public and private sector roles

The chapter, "Farm management practices, information communication technologies, and sustainable intensification" discusses the significant production-level challenges of smallholder food systems in India since the Green Revolution. We highlight the need for closing the information gap through data availability to ensure successful implementation and uptake of SI, by which productivity increase can be achieved with reduced environmental and resource depletion. We specify the role of ICTs and ICT-enabled farm services in (1) improving access to and disseminating data using satellite imagery, drone systems, and other precision agriculture technologies for farm-level decision-making; (2) enabling access to mechanization, farm management practices, and gender-focused farm service delivery services through Farm as a Service (FaaS) models, thus ensuring scale- or gender-neutrality of technology adoption; and (3) increasing farmer social capital and networks to facilitate aggregation and collective action, leading to better conservation practices for sustainable agriculture. The rapid development of ICT infrastructure, combined with increased mobile phone usage, has expanded the scope for addressing information availability and asymmetry problems and technology access issues. Increasing commercialization of the agricultural sector has incentivized the emergence of start-ups in FaaS, precision agriculture, and provision of input services. The current investment in farm service provision enterprises is still low, despite the high potential for investment and growth, which the chapter emphasizes.

The chapter "Preventing food loss and waste—technology in harvest and postharvest systems" defines food loss and waste (FLW) and looks at the stages and extent of FLW at harvest and postharvest stages. Taking stock of India's storage facilities and storage challenges for both perishables and nonperishables, the chapter emphasizes the need for more energy-efficient cold storage facilities for marketing perishable commodities. We examine the role of new technologies in improving storage and transportation facilities to reduce food loss, ensure safety, reduce emissions, and enable sustainable production and consumption. Efficient harvest and postharvest management are critical for preventing FLW and ensuring food safety at the farm and household levels. Technological focus to aid harvest and postharvest loss in perishable commodities will help diversify and improve commercialization. The chapter looks at the harvest and postharvest characteristics influencing technological adoption in perishable and nonperishable commodities. Assessing variations in economic risk, and monitoring intensity, cost of storage, and transportation that differentiates technology requirements in perishable and nonperishables, we determine the need for technology and investment in specialized storage, logistics, and allied services in perishable value chains and nonfarm employment growth opportunities that they possess.

The fifth chapter, "New market platforms and technology to improve smallholder participation," accesses the scope of emerging technologies in increasing the uptake of alternative market platforms, such as electronic markets, commodity futures markets, and warehouse receipt systems. We identify the institutional environment (laws, rules, and regulations) and systems, infrastructure, and technology to reduce information asymmetry and allow for uptake and increased participation, two conditions necessary for increased involvement in alternative platforms. We look at markets in the context of the farm bills of 2020 that removed market restrictions, allowing for the emergence of a unified market platform and the technological interventions required to reduce information asymmetries and connectivity disadvantages and improve bargaining power critical to increased participation. While the Farm Bills were repealed in November 2021, we find the changes it proposed to be relevant to the context of new market platforms and emerging marketing technologies. Agricultural market reforms and ICT progress, made possible by mobile phone penetration and cheap data availability, create conditions rife for interventions to improve information access and market participation. Improved market access at the country level is critical for commercialization, income, and economic growth. Alternative market platforms, supported by technology to reduce transaction costs from connectivity issues, information asymmetry, and low bargaining power, can increase smallholder commercialization and respond better to increasing demand for higher-value agricultural products.

The final chapter synthesizes the central argument we make in this report. We differentiate between the sustainable food systems intensification and the Green Revolution based on four technological drivers of environmental challenges: shift from producer to consumer orientation, scale disadvantages of smallholder production, and the changing role of the private and public sectors roles in agriculture. A demand-responsive food system will adapt to shifting demand for healthier foods with changes at the farm, market, food processing, and food business levels. Technology will continue to play a role on the supply side, and an improved institutional environment through freer markets is vital for a synchronized system.

2 • MODERN CROP BREEDING TECHNOLOGIES FOR INDIA—IMPROVING GENETIC GAIN

Crop breeding technologies have been central to achieving food security globally, especially in the last 100 years (Evenson and Gollin 2003). During the Green Revolution, yield increase achieved by introducing high yielding varieties (HYVs) in major staple grains, such as wheat, rice, and maize, coupled with mechanization and increased input intensity, helped food systems cope with rising population pressures in Asia and Latin America (Pingali 2012). Higher yields led to the increased availability of food, reduced food prices, and improved incomes of farming households, reducing global hunger and poverty in developing countries considerably (Eicher and Staatz 1998; Fan et al. 2005; Qaim 2017). Crop breeding technologies continue to be highly relevant to achieving food security, and their importance has increased in the 21st century. Crop breeding between 1960 and 1980 contributed to 20% yield growth and to 50% between 1980 and 2000 (Evenson and Gollin 2003; Qaim 2016, 2020).

In crop breeding, a plant's genetic potential is manipulated to achieve genotypes with enhancements in desired phenotypes. The increase in trait performance or genetic potential achieved through artificial selection over time is referred to as genetic gain (Xu et al. 2017). Green Revolution technologies focused predominantly on yields through conventional plant breeding. Conventional plant breeding is a time-intensive activity controlled by the biology of crop science, institutional landscape, and infrastructure. Depending on the crop, a new variety can take anywhere from 7 to 10 years to develop (Lenaerts, Collard, and Demont 2019). The challenges of today's food systems for increasing yield and dealing with climate-related risks require genetic gains in drought, heat, salinity and flood tolerance; disease and pest resistance; nutritional quality of food; and yield. Accelerating plant breeding pace through reduced cycle time—defined as the number of selection cycles per year from one generation to the next generation's seed—is critical for responding to food security challenges.

Modern plant breeding technologies aim to achieve a more rapid rate of genetic gains by manipulating selection intensity, selection accuracy, heritability, and cycle time. Among these factors, reducing cycle time is the most powerful way to achieve increased rates of genetic gains (Cobb et al. 2019). New plant breeding technologies (NPBTs), such as genetically modified organisms (GMOs), gene-edited crops, and enhancements, have shown the potential to address yield and resilience challenges. However, modern techniques in conventional breeding, such as genomic selection and high-throughput phenotyping (HTP), emanating from computer science, biology, statistics, and robotics, show the most potential in public sector breeding programs to increase genetic gains and reduce breeding cycle time (Godwin et al. 2019). Here, we refer to modern techniques in conventional breeding as modern plant breeding technologies.

For India, crop breeding technologies remain essential to ensuring yield stability for cereals in high potential areas and increasing yields in coarse grains and pulses that are grown primarily on low potential areas. In low potential areas, increased resilience to biotic and abiotic stress and improved nutritional quality of foods to address the persistent problem of micronutrient malnutrition remains vital. This chapter will first examine the challenges of India's plant breeding technological approach. We assess the agronomy challenges since the Green Revolution and the institutional capacity of the National Agricultural Research System (NARS). The second part discusses the need to build capacity within NARS to adopt modern plant technology, driven by product profiles, advances in machine learning, informatics, and data science. Modern techniques in genomic services and analysis, phenomics, and breeding informatics will increase genetic gains and reduce breeding cycle time to respond quickly to food security needs. We also touch upon NPBTs such as second-generation GMOs and their potential for increased genetic gains and reduction of breeding cycle time.

CROP BREEDING TECHNOLOGIES IN INDIA—MAJOR CHALLENGES FOR MEETING FOOD SYSTEM NEEDS

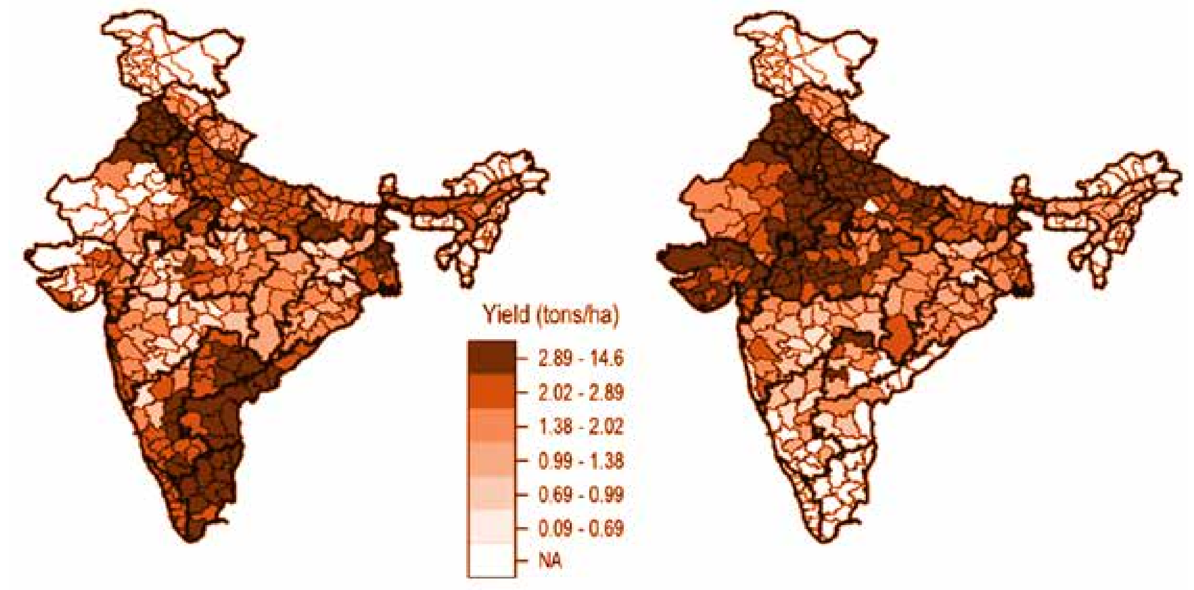
As a country, India has achieved food security in a caloric sense and has a food grain stock of 73.85 MT, which is 3.5 times the strategic reserve requirement of 21.04 MT. Today, the challenges are diversification of production to address micronutrient malnutrition, managing agroclimatic risk to decrease crop loss, developing rainfed agricultural systems, and improving food quality. Addressing these challenges requires shifting from Green Revolution-inspired institutions and policy toward a crop-neutral agricultural approach. This section looks at the limitations of the Green Revolution technologies and how they have shaped the current challenges and the research and development (R&D) capacity of NARS in adopting NPBTs.

GREEN REVOLUTION TECHNOLOGIES AND THEIR LIMITATIONS

In the 1960s, donor-supported public research programs led to the development of HYVs of seeds through conventional breeding, resulting in a drastic increase in staple grains yields, especially of wheat, rice, and maize. Except for sub-Saharan Africa, the introduction of HYVs, coupled with investments in irrigation, fertilizer, pesticides, and mechanization, led to as much as a tripling of the yields, pulling regions out of food scarcity and reducing aggregate poverty (Pingali 2012; Pingali et al. 2019; Qaim 2020). With the help of germplasm and expertise provided by the International Agricultural Research Centers (IARCs) at the outset, the Indian wheat and rice breeding programs released 111 crosses of wheat and 287 crosses of rice between 1977 and 1990 (Traxler and Pingali 1999). An essential aspect of Green Revolution technologies was that they were scale-neutral so that even small producers could adopt them (Pingali et al. 2019). As a result of widespread adoption, countries like India could triple yields with only a 30% increase in land under cultivation (Pingali 2012).

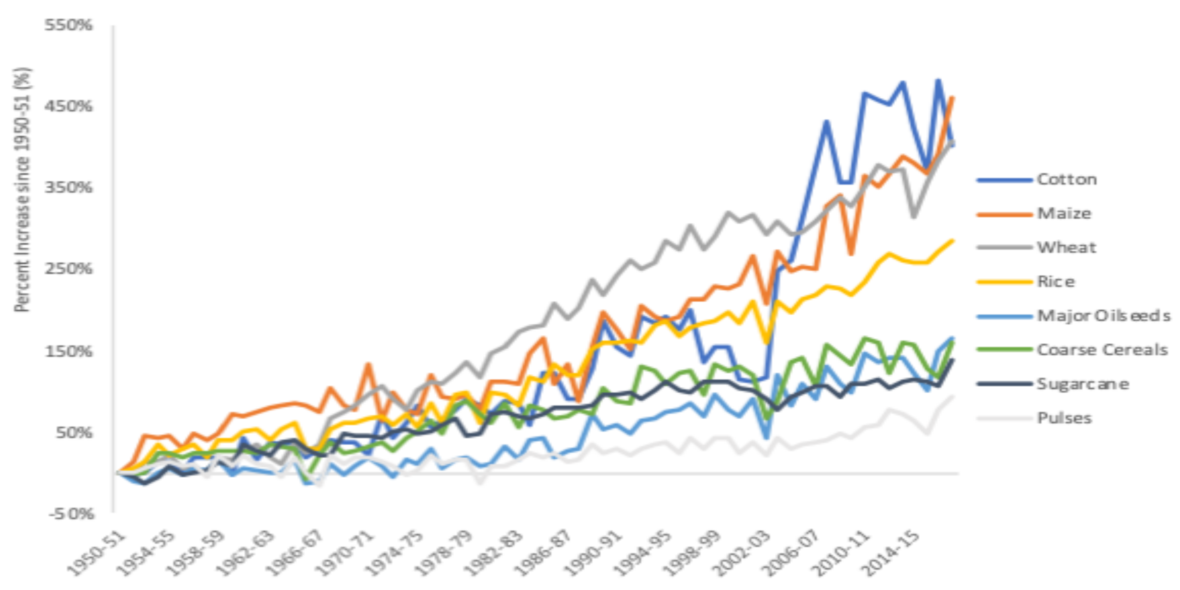
The limitations of the Indian Green Revolution were that its benefits were location-specific and crop-specific, which led to unanticipated environmental externalities that have since emerged as a challenge to the food system (Pingali et al. 2019). The benefits were location-specific because only the regions with access to irrigation and areas receiving heavy rainfall effectively adopted HYVs. Figure 2.1 shows the wheat and rice yields in 2015–17 at the district levels in India. Yields for rice and wheat are significantly higher in the irrigated regions of Western Uttar Pradesh, Punjab, and Haryana, for rice in the eastern peninsular region. In comparison, the wheat and rice yields in the lagging regions have been low.

Figure 2.1: District-level average yields of rice and wheat (2015–17)



Source: Food, Agriculture and Nutrition Report, Tata–Cornell Institute (2020)

Figure 2.2: Yield trends in selected crops in India (from 1950–51 to 2016–17)



Source: Food, Agriculture and Nutrition Report, Tata–Cornell Institute (2020)

The benefits were crop-specific because HYVs were developed only for wheat and rice, disincentivizing other traditional crop cultivation. Figure 2.2 shows the growth in yields of selected crops from 1950–2017. Although we see a strong upward trend for wheat and rice and a late spurt for cotton (after the introduction of Bt Cotton), the yields of nutrition-rich coarse grains and pulses have lagged. These crops were crowded out to make way for intensive wheat–rice systems in Haryana, Punjab, and western Uttar Pradesh and rice–rice systems in the southern states. Intensive cultivation, inputs, and market subsidies resulted in the overuse of inputs such as land, water, and chemical fertilizer, leading to chemical runoffs, soil degradation, and water table depletion (Pingali 2012; Abraham and Pingali 2020;

Innovations to address the shortcomings of the Green Revolution approach, while cognizant of the new and emerging challenges of climate change risks and the environment, will determine the direction of crop breeding technology innovation. Fundamentally, the narratives around plant breeding and policy need to be crop agnostic and trait diverse. By crop agnostic, we mean that the focus of breeding technology needs to move beyond staple grains to coarse grains, pulses, and fruits and vegetables, enabling diversification. By trait diverse, we mean that the technological focus, while recognizing yield stability as important, should be on improving biotic and abiotic resilience and food quality. These approaches will focus on lagging states which did not benefit from the Green Revolution developments. To achieve these goals, R&D development in both the public and private sectors is imperative, and new tools are at hand.

CHALLENGES FOR AGRICULTURAL RESEARCH AND DEVELOPMENT FOR PLANT BREEDING IN INDIA

NARS is one of the world's largest and most complex research systems (Mruthyunjaya and Ranjitha 1998). NARS is responsible for coordinating agriculture research, education, and extension services, including animal sciences, horticulture, and fisheries. The Indian Council of Agricultural Research (ICAR) is the NARS apex research body, under which are four deemed universities, 65 ICAR Institutions, 14 National Research Centers, 6 National Bureaux, and 12 Project Directorates. At the state level, 56 state agricultural universities (SAUs) are at the forefront of agricultural research, training, and extension provision.

NARS was instrumental in bringing the Green Revolution to fruition in India. The ICAR and the SAUs adapted the HYVs from CGIAR to suit Indian conditions and distributed them through the National Seeds Corporation (NSC) and the State Seeds Corporations (SSCs). The National Chemical Laboratory in Pune helped with developing efficient methods for pesticide production. The Projects and Development India Ltd. (PDIL) designed and built fertilizer factories, and the Central Mechanical Engineering Research Institute (CMERI) helped develop tractors cost-effectively (Mruthyunjaya and Ranjitha 1998; Pal and Tripp 2002; Pray and Nagarajan 2014). Together, these different bodies provided inputs and technical knowledge for the dissemination and adoption of technologies. The Indian NARS were highly successful in wheat and rice breeding programs.

In the past few decades, with changing R&D requirements of the agricultural sector, NARS has suffered some challenges. According to the Economic Survey (2015–16), published by the Government of India, the three significant challenges of NARS are (1) inadequate public investment in agricultural research; (2) the slow development of scientific temper and research competence; and (3) low productivity of scientists. India's spending on agricultural research is below that of China, Bangladesh, Brazil, and Indonesia, in terms of R&D as a proportion of agricultural GDP. Although expenditure grew from 28,763 million rupees in 2000 to 49,836 million in 2014, agricultural research spending as a share of agricultural GDP (agricultural research intensity) fell from 0.34% to 0.30% during the same period (Stads et al. 2016). Concerning spending allocation, 73% of financial resources go into salaries, 18% into operating and program costs, and only 10% into capital investment and infrastructure (Stads et al. 2016). As a result, building research capacity and upgrading have suffered.

SAUs that carry out region-specific research and extension funded by the state find it hard to meet their operational requirements (Ramasamy 2013). Agricultural universities are affected by resource crunch, shortage of competent faculty, poor collaboration, low lab-to-field connection, and innovation (Tamboli and Nene 2013). The total number of agricultural researchers (in full-time equivalents) declined from 13,106 in 2000 to 11,786 in 2009, and rose marginally to 12,747 in 2014. These challenges have eroded research capacities and scientifically temper universities, making them less effective in bringing about the transformative change required for Indian agriculture (Stads et al. 2016).

The seed sector in India was dominated by the NSC, a public sector undertaking until the New Policy on Seed Development of 1988. The 1988 law allowed for the importation of horticulture seeds and oilseeds, pulses, and coarse grains for two years by foreign companies collaborating with Indian seed firms. In the post-reform period and consequent reforms, including the National Seeds policy (2002), private companies emerged as dominant players. Currently, over 500 seed companies supply close to 58.52% of seeds in India. Rallis India, Advanta Seeds, Kaveri, Mahyco, Nuziveedu Seeds, Rasi Seeds, J. K. Agri Genetics, VNR Seeds, and international companies, such as Bayer, Syngenta India, and PHI Seeds, along with the NSC are major players in the seed sector.

The expansion of the seed sector is, however, skewed. Private sector R&D has increased drastically, focusing on breeding programs to release improved cultivars on high-value crops, such as maize, sunflower, fruits, and vegetables, and cash crops like cotton and soybeans (Tiwari 2020). Investments in R&D in the public sector have not been increasing steadily, despite changes in needs and challenges. The public seed sector's ambit remains meeting the requirement of high-volume, low-value crops, such as rice or wheat.

In high potential areas where there is diversification to higher-value crops, the share of private companies selling hybrid seeds has been as high as 90%, with higher seed replacement ratios (SRRs). The SRR is as low as 20% in low potential areas, especially for pulses and oilseeds. The challenge is far worse for smallholder farmers, with only 24% of submarginal and 29% of marginal farmers reported to replace seeds every year, compared to 40% by large farmers (Singh and Agrawal 2018). According to the Department of Agriculture, Cooperation and Farmers Welfare report of 2016, the informal seed sector is composed mainly of farm-saved seed (FSS), which account for 65–70% of the total seed requirement in India, while the public and private sectors together contribute the other 30–35% (Directorate of Economics and Statistics 2016, 19).

The private sector is selective in seed research, primarily focusing on high-value and low-risk crops. In contrast, the public sector concentrates on staples, coarse grains, and pulses, with lower commercial value but integral to nutrition, especially for the poor. These crops are also grown in low potential regions that did not benefit from the Green Revolution. Improving genetic gains and reducing breeding cycle time in these crops to address region-specific risks and nutritional needs remain in the periphery of public research domains. Considering the current institutional challenges of public sector R&D in India, significant changes are required. Product and process innovations are necessary to enable improved country-level breeding capacities with technological upgrading at its center.

THE TRAJECTORY FOR PLANT BREEDING TECHNOLOGIES IN INDIA

New crop varieties with the potential for increasing productivity and welfare gains in improved incomes and nutrition, while limiting environmental impacts and weathering climatic shocks, are critical to meeting India's food security challenges in the 21st century (Pingali 2012). Innovations in both conventional breeding and NPBTs, such as GMOs and gene editing, will help meet these challenges. Innovations in conventional plant breeding are needed to enable genetic gains, emphasizing reduced breeding cycle time through modern techniques to respond to food systems' needs. This section will look at technologies and processes emerging in conventional plant breeding and the need for institutional capacities and collaboration in breeding programs to enable their adoption, thereby aiding developing economies like India to respond better to their food systems challenges. We will specifically discuss the need to improve NARS' institutional capacities to achieve genetic gains and reduced cycle time through conventional breeding and the role of NPBTs in addressing food security challenges.

IMPROVING THE INSTITUTIONAL CAPACITY OF CONVENTIONAL PLANT BREEDING SYSTEMS

A breeding system's institutional capacity is its ability to innovate and carry out crop improvement activities leading to genetic gains and introduce new, economically relevant, and resilient crops and varieties that enable food and nutrition security in the system's respective regions. It encompasses an organization's resource endowment, human capital, management, and technical expertise in developing crops with traits relevant to producers, the agro-industry, and consumers, which are essential to addressing a particular country's food security concerns.

Advances in genomics, phenomics, and breeding informatics play vital roles in discovering agronomic traits (Wallace, Rodgers-Melnick, and Buckler 2018) and enable reduced cycle time. The new tools to make breeding systems efficient have been adopted in the CGIAR systems, but NARS is still playing catch-up (CGIAR 2018). Adopting these technologies alone is not sufficient for building institutional capacity; the capacity to match improved varieties to farmer seed demand must also be strengthened. A goal-driven breeding system to determine food system needs, user demand, and context-specific agronomic conditions is essential for high adoption rates of breeding programs. Here, we discuss the importance of priority setting in breeding programs and new technologies in genomics, phenomics, and breeding informatics in developing institutional capacity in the Indian NARS.

Product profiles and demand-focused breeding

The public sector breeding programs are critical for a resilient food system in India. The private sector R&D has increased in India since the 1990s but has played a selective role in seed research, primarily focusing on high-value and low-risk crops. Research on staples, coarse grains, and pulses—crops essential for food security and public health—remains under the state and the public sector's ambit. Breeders, as scientists, have always played the central role in breeding programs as sole decision-makers. However, in recent years, their roles have been transformed from sole decision-makers to leading multidisciplinary teams of scientists, social scientists, and policy analysts (Godwin et al. 2019). As breeding is a time-consuming and resource-intensive process, effective priority setting to determine the traits to breed for becomes exceptionally important.

In private sector breeding programs, product profiles guide the development process. A product profile is a roadmap that lays out the traits and characteristics for which a particular breeding program is breeding. These profiles are often developed through discussions, market studies, and consensus from various stakeholders, such as scientists, farmers, gender groups, policy markets, and final consumers. They aid the effective utilization of resources to breed varieties relevant and in line with demand. In India's low potential areas, specific crop traits to limit biotic and abiotic stress, enhance nutrition quality, and ensure yield stability, especially in nonstaple crops, are imperative. As these challenges are location-specific, the capacity of SAUs to carry out priority setting becomes essential.

Improving social science expertise through an increase in the number of women scientists (currently only 18% of scientists in NARS are women), along with the integration of priority setting using their expertise is a step to strengthening regional research capacity and effective resource utilization in breeding programs. Breeding for stakeholder demand will also enable higher adoption rates and better food system outcomes in regional or national programs. Priority setting and gender analysis can also lead to the development of the food system-appropriate crop varieties that generate economic growth, employment for women and youth, meet nutritional requirements, and reduce environmental externalities.

Technical and technological capacity for genetic gain

Genomics

The breeding pipeline involves genomics, phenomics, and breeding informatics processes to shorten breeding cycle time and enhance genetic gains. Genomics is the study of an organism's genome and its expressions in nature. Various techniques are used to sequence, assemble, and analyze the genome's structure and functions, allowing us to determine how different genes or sets of genes express themselves as desirable or undesirable traits. Plant genetic resources (PGR), the primary genetic material for crop improvement, are rich and varied in India due to the agro-climatic diversity. ICAR and the National Bureau of Plant Genetic Resources (NBPGR) have linkages with over 40 National Active Germplasm Sites (NAGS) to collect and preserve diversity. The National Genebank of NBPGR currently has over 400,000 accessions of germplasm belonging to nearly 1,187 species (Tiwari 2020). NPBTs represent the potential to exploit these vast genetic resources in rapid and efficient methods and expand the number of desired traits that can be simultaneously incorporated into commercial varieties.

The emergence of new sequencing technologies, such as next-generation sequencing (NGS), has allowed for mass sequencing of genomes and transcriptomes, leading to discovery of new genes and regulatory sequences, bringing an understanding of the molecular basis of complex traits (Tiwari 2020). Advances in genomics and bioinformatics have given rise to molecular breeding methods such as marker-assisted selection (MAS), in which genes or sets of genes underlying a particular trait are identified and bred for their expression.

Unlike in traditional breeding, genetic markers for traits are known in MAS, so that they can be tested at the seedling stage rather than assessing the mature plant phenotype, thereby shortening breeding time, increasing accuracy, and reducing costs (Lenaerts, Collard, and Demont 2019). MAS is prevalent in the private sector breeding programs and has helped improve genetic gains (Eathington et al. 2007; Crosbie et al. 2008). Traditionally, building internal genomic services capacity within breeding programs was capital intensive, and the utilization rates within institutions were low, making them unviable. However, in recent years, affordable, externally provided genomic services are available, and breeding programs can avail them cheaply rather than investing in equipment and personnel. Molecular breeding, however, requires the development of expertise at the institutional level. Breeders need to be competent in conventional and molecular breeding techniques (Natesh and Bhan 2009) and know which genomic services to use according to breeding needs.

Phenomics

Phenomics is the assessment of complex traits of a plant such as growth, yield, tolerance, resistance, physiology, architecture, and other expressions of a genotype when in interaction with the environment (Li, Zhang, and Huang 2014). Phenotyping or identifying gene expressions in field contexts is often labor intensive, detail oriented, time consuming, destructive of plants, and requires meticulous data management (Furbank and Tester 2011; Chen et al. 2014). High throughput genotyping, discussed previously, allows for discovering and analyzing genetic markers in plant populations (Edwards, Batley, and Snowdon 2013); however, HTP is only catching up. HTP involves noninvasive, nondestructive, digital technologies such as imaging to gather information and quantify phenotypic traits in a population of plants (Costa et al. 2019).

Accurate phenotyping provides understanding of a plant growth's genetic architecture and aids in efficient decision-making in breeding programs and evaluation of results of MAS, conventional breeding, and NBPT (Blum 2014; Desta and Ortiz 2014; Hickey et al. 2019). HTP is also necessary for increasing genetic gain and lowering breeding cycle time through efficient allocation of resources. Traditional bottlenecks in the Indian NARS for adapting HTP have been high costs and coordination; poor data connectivity; poor data management, modeling, and data integration; and poor alignment of phenotyping and real-life scenarios (Tiwari 2020). Recent developments, however, in improved data connectivity and the emergence of apps such as Phenoapp and data management systems such as BreedBase can remedy these problems. The major challenge is to train personnel and scientists to use the apps and data management systems to integrate HTP into the breeding pipeline.

Breeding informatics

Modern genomics and phenomics generate massive quantities of data, so the capacity to collect and analyze quality data is central to maximizing breeding efficiency and genetic gains. Data management facilitates informed bioinformatics, and genomic selection techniques enable phenomics data collection and management to enhance breeding programs' effectiveness. Good data also enables mathematics-accelerated breeding or simulation modeling to help breeders design efficient breeding programs with proposed scenarios (Tiwari 2020). Regional cloud computing hubs and web-based applications to support data management should emerge as necessary data infrastructure in breeding programs. Breeding information systems will also help integrate the various components of the breeding pipeline from priority setting to genomics and breeding informatics.

Collaborations for improved technical capacity

Collaboration and cooperation with complementary institutions are essential components for the smooth functioning of breeding systems (Traxler and Pingali 1999). The Green Revolution's success resulted from strong collaboration with IARCs of CGIAR, especially with the International Maize and Wheat Improvement Center (CIMMYT) and the International Rice Research Institute (IRRI). Today, collaboration within NARS institutions in India continue collaboration with CGIAR institutions, especially the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), as well as association with university systems in India and abroad. Private sector collaboration through public–private partnerships (PPPs) remains vital for technology transfer and the building of robust breeding systems capable of addressing current and emerging food systems challenges. The nature of the NARS–CGIAR collaboration in deploying NPBTs to develop tailored varieties for today's food system needs is very different from that which was used to access CGIAR germplasm in the past.

IARC–National Agricultural Research Systems collaborations

Since the late 1960s, IARCs have played a critical role in collaborating with NARS in developing countries, beginning with the Green Revolution. IARCs channeled research from developed countries' university systems and contextualized it for developing countries through pre-breeding and cultivar development research (Traxler and Pingali 1999). Germplasm from the IARCs, as mentioned earlier, provided the foundations for the early crossing programs of ICAR that led to hybrid development. To diversify crop research to coarse grains and pulses, IARCs such as ICRISAT will continue to be necessary partners. ICAR has been collaborating with ICRISAT to develop climate-smart crops in legumes and dryland cereals since 2017. Since then, 42 varieties of improved chickpeas have been released, and ICAR–ICRISAT varieties currently make up 53% of chickpea breeder seeds in India (ICRISTAT 2021). As neighboring South Asian countries, Myanmar, and sub-Saharan African countries have similar crop requirements for coarse grains and pulses, breeding system improvements can have high cross-border food systems significance through sharing and spillovers.

Collaboration and building capacity of state agricultural universities

Collaboration within the Indian NARS to ensure capacity building at the regional levels is an important mechanism to ensuring crop breeding meets regional agronomic priorities and requirements. The ICAR institutions have better infrastructure, funding, and scientific expertise compared to SAUs. State universities are responsible for training the agricultural sector's scientific workforce and often suffer from poor infrastructure and budget constraints. With only 10% of the total budget allocated to infrastructure (Stads et al. 2016), upscaling facilities, adopting new breeding technologies, and educating a competent scientific workforce are challenging. Removal of budget constraints, improved collaboration, and trickle-down scientific competence from ICAR institutions will significantly help bring a regional focus to crop improvement and better training of the scientific workforce.

University systems–National Agricultural Research System collaborations

University research systems of developed countries influenced the building of institutional capacity of IARCs, which led to the development of Green Revolution technologies. Norman Borlaug's first introgressions, using the Japanese Norin 10 dwarfing gene from material acquired from Washington State University (Dalrymple 1986; Traxler and Pingali 1999), is a significant example. Cornell University-led "Feed the Future" Innovation Lab for Crop Improvement (ILCI), funded by the United States Agency for International Development (USAID), is an updated version of university systems engaged in building capacity that targets the transfer of NPBTs to NARS breeding programs for staple crops in the Caribbean, West, East, and Southern Africa. The ongoing project attempts to advance plant breeding tools, technologies, and methods to increase yields, enhance nutrition, and build greater resistance to biotic and abiotic stressors toward goals of reducing malnutrition and hunger and providing equitable benefits to women and youth. A collaboration of ICAR institutions and SAUs with university research labs abroad will enable improved scientific competence, technology transfer, and cooperation in public breeding programs.

Public–Private Partnerships in Plant breeding

The new world of NPBT-led crop improvement presents immense opportunity and significant challenges in constructing effective PPPs. In principle, PPPs are effective ways to encourage public system innovations, reduce research costs, improve research competence, and address urgent socioeconomic problems with shared resources. The private sector breeding programs and research capacities are far ahead of public research systems, both in developed and developing countries. However, in terms of genetic materials collected and germplasm, the public sector and IARCs have substantial resources, of which the access can benefit private companies. In the past, these raw resources were not much use to the private sector. It was costly and slow to generate genetic information through growing accessions and collecting phenotypic information. However, with new genomic services available (provided by the private sector), these gene banks are valuable because of the new means for unlocking the genetic information. The public sector can benefit from technology spillovers and improved access to technology.

The Nordic Public–Private Partnership for Pre-breeding was formed as a PPP, in which 11 breeding companies and public research institutions collaborated to address concerns about accessing material for pre-breeding programs to develop pre-breeding genetic material. The affordable, accessible, Asian maize (AAA maize) program is a PPP program between CIMMYT and Syngenta Foundation to develop drought-tolerant, low-cost, hybrid maize in low rainfall areas. These are two examples of successful PPP collaborations.

Improved institutional capacity of NARS to carry out breeding programs, which are effective at increasing genetic gains, is critical to enabling PPPs in the first place. High-breeding capacity gaps between private and public breeding programs may impede or dissuade cooperative endeavors. Collaboration with IARCs and university systems can often be the first step, especially in SAUs. Private breeding programs have made significant advances with new plant breeding technologies (NPBTs).

NEW PLANT BREEDING TECHNOLOGIES AND FOOD SYSTEMS

NPBTs are emerging methods that go beyond traditional breeding to increase genetic variability. The two dominant NPBTs are GMOs and gene-editing. With GMOs or transgenic crops, recombinant DNA techniques manipulate individual gene codes to introduce desirable traits. The fundamental difference between conventionally bred and transgenic plants is that conventional breeding results in a new variety, while transgenic development produces a new trait (Qaim 2020). The cited advantage is that varietal diversity can be preserved while only changing traits (Krishna, Qaim, and Zilberman 2016). In gene editing, DNA of an organism is inserted, modified, replaced, or deleted to create mutations, or integrate foreign genes, using methods and systems, such as zinc finger, Transcription Activator-Like Effector Nucleases (TALEN), and the widely popular Clustered Regulatory Interspaced Short Palindromic Repeats (CRISPR) system (Vats et al. 2019; Qaim 2020; Schindele, Dorn, and Puchta 2020). An advantage of gene editing techniques over earlier genetic engineering methods is that insertions or deletions can be precisely targeted to specific locations in the host genome, instead of by random insertions.

NPBT can be more precise, productive, and faster than conventional plant breeding (CPB) and has found use in biofuels, food, cash and fodder crops, livestock, fisheries, and forestry. Unlike CPB, the first generation of GM crops focused on biotic stress. They were engineered to have tolerance or resistance to insects, pesticides, and herbicides. Examples of these were Bt maize, Bt cotton, pat-maize, and GT soybeans, among others. In India, Bt cotton was the only first-generation GMO introduced by private multinationals and is highly successful in the Indian agriculture sector, as the cotton production has already tripled (Directorate of Cotton Development 2017, 30). A stronghold on the hybrid seed market is a motivating factor for the private sector for investing in the development of hybrid wheat and rice to profit from the potential value of hybrid seed sales.

Second-generation GMOs are developed for abiotic stress (drought, flood, and salinity) tolerance and nutrient content (protein, amino acids, fatty acids, starch, vitamins, minerals, and enzymes), enabling the creation of resilient and more nutritive crops (Flachowsky and Aulrich 2001; Buiatti, Christou, and Pastore 2013; Rao, Pray, and Herring 2018). In the coming years, gene-editing technology will offer the opportunity to significantly increase the rates of genetic gain and domesticate wild or neglected plants over a short period. Referred to as de novo domestication (Fernie and Yan 2019), it can contribute to enhancing agrobiodiversity and potentially improve nutritional qualities (Singh et al. 2019).

So far, no second-generation GMOs have been allowed in the Indian agricultural sector. How gene editing is regulated and presented to the public would greatly matter in this regard. First-generation GMOs have genes inserted from outside the organism. CRISPR does not use foreign genetic matter, so it may not need to be regulated in the same way or called a GMO. Scientists believe this technology would play a significant role in breeding when GMO restrictions are eased. GMOs are among the most tested and regulated products globally, and even with permission to release them in a country, the testing is expected to be stringent. Although they may deliver increased genetic variability and breeding cycle time, the time from development to approval might negate the advantages of efficiency. For now, these technologies are more in the sphere of private sector breeding programs, and their foray into public sector breeding programs remains uncertain.

THE WAY FORWARD

The successful rice and wheat breeding program of NARS was instrumental in India's Green Revolution success. The need for a second green revolution stems from the fact that the first Green Revolution was crop-specific, location-specific, and did not account for environmental externalities. The new challenges of increasing diversification through improved yields of nonstaples, coarse grains, and pulses; increasing resistance to biotic and abiotic stresses; improving the nutritional quality of foods; reducing growing time and limiting environmental externalities, such as soil degradation and water table depletion are drivers for modern plant breeding technologies. This deliberate shift in focus will bring attention to low potential areas or regions that did not benefit from the initial Green Revolution, due to resource constraints such as access to irrigation. A shift to modern plant breeding technologies is necessary for improving genetic gains (targeting yield, nutrition, biotic and abiotic resistance) and reducing cycle time. Reduced cycle time is an essential variable in determining genetic gain and crucial for timely response to food systems challenges.

- Modern plant breeding technology upgradation in the Indian NARS will be fundamental to achieving genetic gain in staple grains, nutrient-rich coarse grains, and pulses. Product profile-guided breeding, the use of state-of-the-art genomic services for MAS, using technology to collect and manage phenotypical data, integrating effective data management systems, along with increased scientific competence of scientists, will aid in the effective use of resources, reduced costs, and timely release of crop varieties and increase adoption rates.
- Collaboration and cooperation are central for technology upgradation and institutional capacity building in breeding programs within the Indian NARS. IARCs and NARS collaborations have been strong since the 1960s and will continue to play a role. Cooperation with university systems and the private sector can help develop capacity building within the IARC systems and NARS—these collaboration and cooperation need to be built.
- Strengthening SAUs that train the scientific workforce and conduct location-specific research is essential to addressing the R&D requirements of lagging states and disparate agroclimatic zones. Collaboration with foreign universities and research centers can help effect knowledge and expertise transfer.
- The private sector breeding programs and research capacities are more advanced than public research systems. However, in terms of genetic materials collected and germplasm, the IARCs have vast resources. PPPs are effective ways to encourage public systems innovations, reduce research costs, and improve research competence.
- While new plant breeding technologies, such as GMOs and gene editing, effectively increase genetic variation and reduce breeding cycle time, they are capital intensive. They will remain squarely within the ambit of the private sector.
- Stringent, time-consuming regulatory processes also lead to longer approval times that may mitigate the advantages of shorter breeding cycle time for increasing the rate of genetic gain. Streamlined regulatory processes to allow and approve second-generation GMOs will be imperative for timely response to food systems challenges.

3 • FARM MANAGEMENT PRACTICES, INFORMATION COMMUNICATION TECHNOLOGIES, AND SUSTAINABLE INTENSIFICATION

Although modern plant breeding technologies can help achieve higher genetic gain and lower breeding cycle time in seed development, farm management practices influence how new varieties are adopted and reach their optimum potential. Farm management practices consist of land preparation, crop rotation, water management, nutrient management, and pest management. The process of intensification is input-intensive in terms of energy, labor, machinery, and natural resources use and can impact the environment. Sustainable intensification (SI) is a set of practices that aims at increasing agricultural productivity while limiting environmental harm through improved input use efficiency (Pretty and Bharucha 2018).

Along with the intensity of inputs, SI is also knowledge intensive. In smallholder production systems, knowledge dissemination related to practices; weather, geographical, and ecological conditions; access to machinery; and farm-level services can be daunting. The roles of technology and social innovation to develop capacity and improve production practices in smallholder agricultural systems are critical. Information communication technologies (ICTs) can play a crucial role in adoption, technology dissemination, and SI. ICT is an umbrella term for devices, applications, and tools allowing the collection, exchange, and transmission of data (World Bank 2011). Devices ranging from mobile phones, radio, cloud computing hubs, and satellite imagery can all constitute ICTs. ICTs essentially allow for closing the information gap, making information (and misinformation) and essential farm-level services readily available.

Increased mobile phone penetration and inexpensive Internet data in India presents new opportunities for data collection, information dissemination, farm service delivery, and extension services. Improved connectivity expands access to extension services, increases the demand for farm technologies, and creates business opportunities to efficiently deliver these technologies to smallholder farmers. Farm as a Service (FaaS) business models of agricultural technology (agritech) services for mechanization, crop advisories, and input access, tailored to small farms, as well as precision agriculture and farm input services are fast emerging start-ups in India. Although the investment in agritech between 2014 and 2020 for farm input services, precision farming, and FaaS has been about US$111, the market potential for this segment of agritech is estimated at close to US$3.4 billion and is estimated to multiply (EY 2020; Inc42 2020).

The use of technology in SI and farm management serves three primary functions: (1) maximizing productivity through resource use efficiency; (2) decreasing environmental externalities of production; and (3) improving the quality of life of producers by reducing health hazards of input use and reducing drudgery. In serving its agronomic, productive, and social functions and ensuring that farming is carried out with reduced environmental impact, effective farm management practices are central to achieving sustainable intensification.

This chapter discusses the significant production-level challenges of smallholder food systems in India since the Green Revolution. We highlight the need to close the information gap through data availability to successfully implement and uptake of SI. Second, we specify the role of ICTs and ICT-enabled farm services in (1) improving access to and disseminating data using satellite imagery, drone systems, and other precision agriculture technologies for farm-level decision-making; (2) enabling smallholder access to mechanization, farm management practices, and gender-focused farm service delivery services through FaaS models with scale or gender-neutral adoption of technology; and (3) increasing farmer social capital and networks to facilitate aggregation and collective action, leading to better conservation practices for sustainable agriculture.

AGRICULTURAL INTENSIFICATION, REGIONAL VARIATIONS, AND CHALLENGES FOR SUSTAINABILITY

Agricultural intensification during the Green Revolution took place with strong support from the state. The provision of high-yielding variety (HYV) seeds for wheat and rice was coupled with support by providing input subsidies (electricity, fertilizer), farm extension services, and mechanization subsidies. As intensification was conditioned on HYV and water availability, farmers cultivating other nonstaple crops, such as legumes and coarse grains in rainfed areas, were mostly left out from the ensuing innovations in farm management practices (Pingali 2012). The lopsided production incentives and the intensive monocropping resulted in significant environmental impacts, from soil degradation to water table depletion (Pingali 2012; Abraham and Pingali 2019). Here, we discuss the regional variation of agricultural intensification during the Green Revolution and corresponding environmental externalities, the aims and challenges of implementing SI in the context of information gaps, current extension service delivery mechanisms, and sociocultural challenges limiting access.

EXTERNALITIES OF INTENSIFICATION IN INDIA

Electricity, fuel (diesel), and fertilizer subsidies were incentives that the government provided the agricultural sector to increase the adoption of HYVs during the Green Revolution. Over time, continued subsidization of inputs has led to their overuse, especially in urbanizing and agriculture-led states, which saw productivity increases stemming from the Green Revolution of increased cash crops cultivation. Subsidized fuel and electricity for pumping water made the agriculture sector energy-intensive, and fertilizer subsidies made agriculture greenhouse gas (GHG)-intensive, especially concerning N2O emissions (Vetter et al. 2017). These problems are compounded by the fact that small farms that need these technologies are extremely starved for resources and have limited access to most inputs, information, and research and development (R&D), resulting in misuse and wastage (Kebede 1992; Fafchamps 2003; Carter and Barrett 2006).

The fertilizer consumption in India rose from 0.78 million MT in 1965–66 to 18.07 million MT in 1999-2000, and 27.3 million MT in 2018-19. Regionally, agriculture-led states have the highest per hectare consumption of NPK (nitrogen, phosphorus, potassium) fertilizers than urbanizing and lagging states (**Table 3.1**). NPK fertilizers need to be applied at a 4:2:1 ratio for optimal plant nutrition. Subsidies for nitrogenous fertilizers, in the form of urea, have been used, as they are more optimal than phosphorus-based and potassium-based fertilizers. Disproportionate subsidies have led to the overapplication of nitrogenous fertilizers, resulting in lower efficiency and soil health (Prasad 2009). In Punjab and Haryana, the application ratios in 2018–19 were 35:8:1 and 21:5:1, respectively. In Bihar, the ratio was 8:2:1, and states like Odisha and Andhra have more favorable ratios of 5:2:1 and 4.6:2:1, respectively.

Table 3.1: Average fertilizer (N, P, and K) consumption (kg/ha)

Category	2016–17				2017–18				2018–19			
	N	P	K	Total	N	P	K	Total	N	P	K	Total
Agriculture-led growth states	119.98	39.18	12.59	171.75	120.07	35.57	13.03	168.67	122.61	37.15	11.64	171.40
Urbanizing states	91.07	36.05	19.39	146.50	84.12	32.07	18.09	134.29	81.37	34.18	20.69	136.24
Lagging states	53.69	20.94	9.17	83.80	54.62	22.32	10.45	87.39	58.09	22.87	10.27	91.23

Source: Agriculture Statistics at a Glance (2020), Government of India

Electricity and diesel subsidies for irrigation have led to over-irrigation, severely depleting groundwater levels (Fishman, Devineni, and Raman 2015; Bhanja et al. 2017; Jacoby 2017) . According to the World Water Institute, 54% of India's total area faces high water stress, concentrated mostly in northwestern regions, where Green Revolution technologies were most successfully adopted (**Figure 3.1**). Almost all Punjab and Haryana districts and several western Uttar Pradesh districts are in the overexploited groundwater development stages (TCI 2020). In much of India's eastern part, where farm-level access to irrigation is low, water stress remains low to medium.

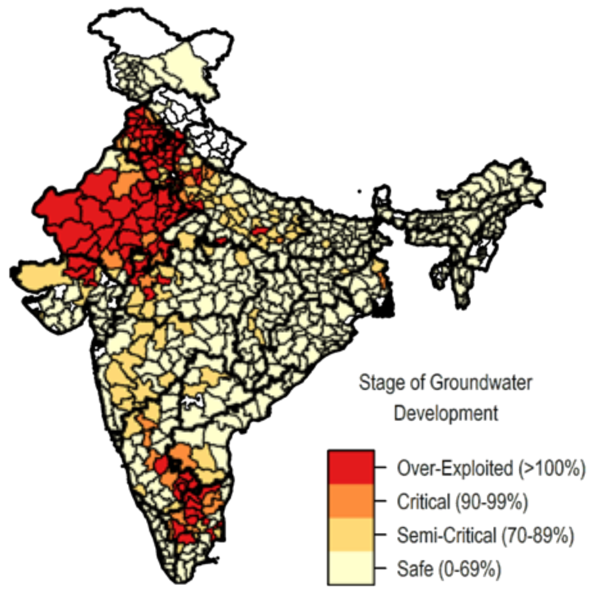
About 64% of India's land degradation is caused by water erosion (Mythili and Goedecke 2016). The remaining can be attributed to human-induced and natural soil degradation, resulting from deforestation, pollution, poor agricultural practices, overgrazing, and wind and water erosion. Agricultural practices of excessive tillage, heavy use of inorganic fertilizers and pesticides, poor irrigation and water management techniques, low carbon inputs, and reduced crop cycle planning are significant contributors to degradation (Bhattacharyya et al. 2015).

Table 3.2 shows that the northern and southern regions that have the largest degraded land areas resulting from water erosion and waterlogging, most likely from irrigation. Soil salinity/alkalinity is high in central India. Management practices specific to state-level challenges and their cropping systems will be necessary to reduce environmental stress and keep agricultural production sustainable.

IMPLEMENTATION OF SUSTAINABLE INTENSIFICATION APPROACHES AND MECHANIZATION

The agricultural sector is a large emitter of carbon dioxide (CO2) based and non-CO2 based GHGs, such as methane and nitrous oxide (N20). GHGs are known contributors to climate change by way of contributing to temperature change. The agricultural sector contributes 18% of India's total emissions, and rice and livestock production

Figure 3.1: Stages of groundwater development by district, 2013



Source: Food, Agriculture and Nutrition Report, Tata–Cornell Institute (2020)

contributes 36.9% and 38.9% of GHGs, respectively, and are the largest contributors (Vetter et al. 2017). Agriculture affects and is simultaneously affected by climate change, manifesting as changing weather patterns. Extreme weather events place undue risk on production activities. As demand for higher value agriculture also increases, the corresponding increase in resource utilization has the scope to increase emissions from the agricultural sector (Pingali et al. 2019). While climate change and

Table 3.2: Classification of land degradation in India by regions (in '000 ha)

Region	Water erosion	Wind erosion	Water-logging	Salinity/ alkalinity	Several degradations types combined	Total degraded area	Area	Degraded area (%)
North	23,449	9,040	4,396	3,342	335	40,562	101,061	40
Central	17,883	–	359	6,842	1,126	26,210	44,345	59
East	9,249	–	3392	2,322	194	15,157	41,833	36
West	16,446	443	599	1,869	1,993	21,350	50,743	42
South	22,330	–	5,031	1,902	1,302	30,565	63,576	48
Others	4,323			5,543	2,431	12,819	27,044	73
INDIA (%)	64	6	10	15	5	100		45

Source: Erosion (Mythili and Goedecke 2016)

environmental degradation were not part of the Green Revolution narrative, today, the need for interventions under SI practices is urgent.

Table 3.3 highlights the various SI methods, practices, and agricultural production, as well as the environmental challenges they target. The list is by no means extensive but is in line with the Indian agricultural sector's urgent needs. Soils hold the second largest carbon pool after the oceans and are also a significant component in nitrogen cycles, and thus a large GHG influencer (Chappell, Baldock, and Sanderman 2016). Conservation agriculture (CA) and integrated plant nutrition management (IPNM) are integral to maintaining or increasing yields while reducing carbon and nitrogen emissions through minimal soil disturbances and judicious input use. When coupled with biological nitrification inhibition (BNI) trait-manifesting seeds, these practices can reduce nitrogen loss and boost productivity (Subbarao et al. 2017).

Table 3.3: Sustainable intensification practices in agriculture

Sustainable intensification methods	Practices	Targeted problem
Integrated pest management	Using ecosystem methods and management strategies to minimize pesticide use and toxicity-targeted spraying, biological traps	Reduced pesticide use, reduced exposure to toxins
Conservation agriculture	Minimum soil disturbance through mechanization, permanent soil cover, crop rotation, soil erosion prevention, healthy soils	Reduced emissions, soil erosion, and fertility control
Integrated plant nutrition management	Organic and chemical inputs managed to prevent overuse and achieve optimum yield	Reduce emissions, reduce chemical runoffs, improve plant growth, improve plant nutrient intake for productivity increase, reduce overuse of fertilizers
Agroforestry	Integration of trees into cropping systems	Carbon cycling, improved water retention, prevention of wind and water erosion
Irrigation water management	Participatory irrigation, micro-irrigation, watershed management	Water conservation, increase in irrigation options, reduce erosion and salinity build-up
Intensive small- and patch-scale systems	Community farms, kitchen gardens, raised beds, vertical farms	Improve the diversity of produce where land resources are limited.

Integrated pest management (IPM) mixes management methods of identification and monitoring with prevention and control methods using ecosystem methods, such as traps, pest barriers, targeted spraying, and other strategies to reduce pesticide use, toxicity, and contamination. GMO technologies, such as Bt, have also helped in pesticide use reduction, improvement of yields, and lowering of production costs (Qaim et al. 2006; Subramanian and Qaim 2010). Agroforestry, or the integrating of trees into cultivation systems, can improve carbon sequestering while reducing land degradation through erosion. At the same time, irrigation management intervention can help with water conservation and prevent overuse. Both agroforestry and irrigation management can occur on individual farms, and collectively, through community-based programs (Palanisami 2006; Kajisa, Palanisami, and Sakurai 2007; Kaczan, Arslan, and Lipper 2013). Greening programs of community agroforestry initiatives, water user groups, and watershed management systems are examples of effective strategies for common-pool resources (CPR) management systems. Intensive small- and patch-scale systems range from urban farming initiatives to kitchen gardens (Pretty and Bharucha 2018). In India, there is good evidence to support the fact that kitchen gardens or small-scale intensive cultivation of selected nutrition-rich fruits and vegetables can improve food access at the household level and address seasonal deficits to quality diets (Gupta, Sunder, and Pingali 2020). The intervention proves critical for year-round access to nutritious food for more impoverished households with limited access to markets.

Implementation of SI is knowledge-intensive. Its adoption can be hindered by knowledge gaps resulting from insufficient data, insufficient mechanisms for location-specific extension services, and smallholder- and gender-specific capacity limitations. For effective SI implementation, good data, farmers' ability to adopt them, and knowledge dissemination channels are central. In addition to access to extension and information services, the high costs that farmers must incur to access modern agriculture technologies impede adoption. Often, accessing even necessary machinery, such as tractors, weeders, or harvesters, requires farmers to pay upfront costs that make them out of reach for most small and marginal farmers. The ownership of farm machinery also varies considerably with location, crop, and type of agricultural activity. While the national average for mechanization is 40–45%, the agriculture-led states of Punjab and Haryana (and western Uttar Pradesh) have higher farm mechanization rates of 70–80% overall and rates of 80–90% for rice and wheat (Directorate of Economics and Statistics 2020).

Mechanization varies across activities, and sales of tractors and power tillers outstrip all other equipment. Plowing and tilling are activities predominantly undertaken by men. Access to specialized machinery, such as threshers, rotavators, transplanters, reapers, zero till drills, laser levelers, and power weeders for sowing and transplanting, threshing, and pest management, activities—predominantly undertaken by women—is still low. While almost 40% of tillage and seedbed preparation and 60–70% of harvesting and threshing for wheat and rice are mechanized, the mechanization level for plant protection and irrigation is around 35% and below 15% for other crops (ICFA 2017). As a result, much agricultural work on small farms remains unmechanized and dependent on manual labor, with an undue burden on women. With productive male labor migrating to urban areas and increasing feminization of agriculture, access to farm machinery to reduce drudgery also becomes a gendered need.

DATA AVAILABILITY, SMALLHOLDER ACCESS TO TECHNOLOGY, AND EXTENSION SERVICES IN INDIAN AGRICULTURE

Successful implementation of SI in modernizing food systems requires three critical components—first, access to quality data and implementable information. To provide farmers with timely and relevant information about risks and agricultural conditions depend on good data availability. Based on information collected and analyses of the data, suggestions for acceptable practices can be disseminated for improving production. The second component is access to scale-neutral technology. Green Revolution technologies were highly successful in regions where they were suitable because they were scale neutral. Small farmers could access HYVs and adopt them, supported by subsidy systems and extension services tailored to assist implementation. Newer farm management practices require technology and mechanization (direct sowing machines, tractors, compactors for CA and IPNM, sprayers for IPM, for example) that may not necessarily be scale neutral—rectifying this becomes crucial.

The third component is the capacity of smallholders to effectively improve production practices or implement the technology. Even when better seeds and other inputs are readily available, farmers' adoption rates may be low due to a lack of awareness or capacity to implement the technology. The introduction of new technologies comes with its own set of socioeconomic and cultural issues. For example, even though women's participation in agriculture has been increasing (Pattnaik et al. 2018), modern technologies can remain inaccessible for them. Various factors, such as lack of access to credit, mechanization perceived as men's domain, and lack of information or training about equipment, have been suggested as responsible for this gender gap (Rola�Rubzen et al. 2020). SI interventions require effective extension services and can also be community-based collective action initiatives. They need social capital to prevent collective action problems. Effective institutions for aggregation are essential to carry out activities like community-led agroforestry and watershed management through water user groups.

Historically in India, extension services have mostly been undertaken by public institutions—primarily, Ministries of Agriculture or Rural Development, the Agricultural Technology Management Agency, or *Krishi Vigyan Kendras* (KVKs)—and agriculture research universities with limited support from private agencies, such as agriculture input suppliers or buyers of produce (Glendenning, Babu, and Asenso-Okyere 2010). According to the data of 70th round of the National Sample Survey (NSS) (MoSPI 2013), about 40% of the cultivator households surveyed could access various sources' technical advice. The data shows vast regional differences. Farmers in the high potential states of Andhra Pradesh, Punjab, Haryana, and Himachal Pradesh have much better access to information from traditional and modern sources, including extension agents, radio, television, and the Internet, as well as agricultural universities (**Table 3.4**).

Table 3.4: Percentage of households reporting access to different sources of extension information

State category	Extension agent	Krishi Vigyan Kendras	Agricultural university/ college	Private commercial agents	Progressive farmers	Radio/ TV/ newspaper/ Internet	Veterinary dept.	NGOs
Agriculture-led growth states	10.63%	5.22%	5.87%	12.56%	19.12%	30.45%	22.69%	0.62%
Urbanizing states	7.88%	7.01%	2.42%	4.98%	21.15%	27.72%	13.37%	0.97%
Lagging states	6.62%	3.63%	2.23%	2.32%	13.02%	18.16%	9.46%	1.59%

Source: Analysis based on the National Sample Survey (NSS, 70th Round) data

A survey of 1,200 farmers in the Indo-Gangetic plains found that more than 90% of farmers relied primarily on their local networks and farmers from neighboring villages to obtain information on agriculture inputs (Mittal and Mehar 2013).

Furthermore, the survey found larger farmers with higher education levels are more likely to access information from modern sources such as mobile phones and the Internet. Information dissemination across states by extension agents, KVKs, and agricultural universities has been low. Information through linkages with progressive farmers, local networks and radio, TV, newspapers, and the Internet has been the highest in all states. The default potential of ICTs for information collection and dissemination through various mediums and networks can prove critical to reducing information gaps, make technology scale neutral, and improve social capital required for smallholder adoption.

INFORMATION COMMUNICATION TECHNOLOGIES IN FARM MANAGEMENT

Collection, exchange, and transmission of information using various mediums such as satellites, satellite imagery, drones, radios, television, computing hubs, among many others, form the backbone of ICTs. The efficient collection of reliable data is the first step of any information system. Once the data is gathered, making sense of this data, converting it into usable information, and disseminating it to targeted users is required for optimum impact. ICTs also serves a networking role of linking service providers to users, and peers to peers for information sharing and knowledge delivery. The use of ICTs in Indian agriculture has enormous potential in reducing information asymmetry and providing services to farmers that will enable them to raise productivity, mitigate production and market risks, and improve livelihoods.

India has one of the world's fastest-growing digital markets with 1.17 billion wireless subscriptions and 354 million cellphones in use (Kaka et al. 2019). According to the Internet and Mobile Association of India (IAMAI), the number of Internet users in India has increased from 205 million in 2013 to more than half a billion in 2019, with more than half of them (277 million) residing in rural areas (Mitter 2020). The number of Internet users and smartphone users is expected to grow to 750–800 million and 650–700 million by 2023, respectively (Kaka et al. 2019). The opportunities for the agricultural sector to utilize these technologies to improve production is enormous. In line with the three conditions essential for the effective implementation of SI interventions, here we look at how ICTs can (1) enable quality data collection and implementable information dissemination; (2) improve access to mechanization; and (3) build smallholder networks and social capital for aggregation and community-based SI.

INFORMATION COMMUNICATION TECHNOLOGIES FOR DATA COLLECTION, ASSIMILATION, AND INFORMATION DISSEMINATION

Aggregate-level and farm-level data are both essential for decision-making in the agricultural sector. Aggregate-level data on the weather for tracking drought and flood occurrence; on cropping patterns to monitor adoption rates, germplasm spread, and current farming practices; on irrigation to track water spread and availability; on soil and vegetation to assess land degradation and biodiversity, among others, are essential at the policy level to guide research, target extension services, and provide other support to different agricultural regions. Farm-level data to monitor moisture, soil nutrient content, and pest attacks are critical to implementing SI for pest and nutrient management and CA.

While aggregate-level data on rainfall, temperature, and humidity are relatively easier to acquire and are often collected by the meteorological department, cropping, irrigation, and status of soils and vegetation data have historically been more challenging to collect. Geospatial analysis based on high spatial resolution satellite imagery using Landsat satellite data and machine learning algorithms (MLAs) on the Google Earth Engine (GEE) cloud computing platform can help compile cropping, abiotic stress, land management, vegetation, irrigation, and soils data (Kumara Charyulu et al. 2016; Krishna, Aravalath, and Vikraman 2019).

Geographic Information Systems (GIS) data collected using satellite imagery also aids in collection of data not reported or missing in surveys to create national-level databases. ICRISAT and Tata–Cornell Institute's (TCI) District-level Database for Indian Agriculture and Allied Sectors, a one-stop shop for data related to India's food systems, uses remote sensing and GIS data to gather missing data on irrigated areas. Using 10m resolution data for Odisha and Gujarat and 250m resolution for Maharashtra, crucial data gaps have been filled.[1] Using these technologies can save costs incurred in surveying fields, collect data that are traditionally challenging to collect, and fill data gaps critical for research and policy-level decision-making.

Recent technological innovations in precision agriculture with low-cost sensors, drones, and automated data analytics at the farm-level can address crucial micro-level data gaps. It is now possible for small farmers to install moisture and nutrient meters, deploy drones for remote sensing, and obtain information about soil health, fertilizer suitability, crop growth, pest attacks, etc., almost in real time. Farmers can obtain real-time information regarding their crops, soil deterioration, dry regions, fungal infections, etc. Cloud computing and artificial intelligence (AI) can help analyze the data to suggest mitigating actions directly on mobile phones or dashboards, almost without human intervention. These advanced technologies can enable farmers to apply water, fertilizers, and pesticides more precisely and target specific areas, allowing them to be more profitable, efficient, safe, and environmentally friendly.

Digital extension services by public and private players through mobile phones are rapidly becoming common and are the primary source of information for farmers. The Ministry of Agriculture and Farmers' Welfare has a toll-free number to the *Kisan* Call Center (KCC), connecting farmers directly with scientists and experts who can advise them on agronomic issues (Ray and Chowdhury 2015; Kavitha and Anandaraja 2017). Several not-for-profit organizations and private enterprises have started services as well. Avaaj Otalo (AO), begun by the Development Support Centre in Gujarat, provides similar services as the KCC. The mKRISHI, developed by the Tata Consultancy Services, helps farmers access real-time customized information for farmers' decision-making. The Knowledge Help Extension Technology Initiative (KHETI) is another initiative that links small/marginal farmers and agricultural experts, allowing farmers to make videos (of pests and farm-level conditions) and receive customized feedback (Fu and Akter 2015). Some studies show that farmers availing themselves of these services are more aware; make informed choices of inputs, such as seeds and fertilizers, and are more likely to obtain higher yields and profits (Fu and Akter 2015; Vasilaky et al. 2015; Cole and Fernando 2020).

IMPROVING SMALLHOLDER ACCESS TO SCALE-SENSITIVE TECHNOLOGY

Access to information, technology, and mechanization will determine a smallholder's

[1] http://data.icrisat.org/dld/index.html

ability to implement SI practices. Farm mechanization is associated with reduced labor costs, increased productivity, and resource use efficiency (Tiwari et al. 2019). The increasing demand for diverse foods, coupled with reduced availability of farm labor due to urban migration in some pockets, has further pushed farmers toward greater mechanization in recent years. However, mechanization is scale-sensitive, and smallholder capital constraints impede implementation. In the wake of the feminization of agriculture, women are also disproportionately disadvantaged in accessing machinery. Recent innovations in ICT and the increased adoption of mobile phones have created new opportunities to build innovative business models that can provide farmers with customized equipment and machinery at specific farm value chains.

The agritech start-up space in India is growing rapidly. FaaS business models, precision agriculture, and farm input services have market potential of close to US$3.4 and are estimated to grow rapidly (EY 2020; Inc42 2020). FaaS models provide farm equipment and machinery on a pay-per-use basis, crop advisory services, and other input services, making farming solutions more affordable for most small farmers. Besides farm equipment and machinery, farmers can also avail themselves of other services, such as soil testing and crop protection, or buy inputs, such as seeds and fertilizers from business providers. Considering the vast potential to improve farmer incomes by making such services readily available, various state and central governments have launched their platforms, such as the Custom Hiring Centers (CHCs) Farm Machinery app to enable business providers to list their services on an easily searchable platform. The app has more than 133,000 pieces of agricultural machinery available for rent through 2,300 CHCs that have been established (Kumar 2020). **Table 3.5** lists some major FaaS model, service-providing companies and the products that they provide. A majority of these companies are located in urbanizing and agriculture-led states, while their penetration in lagging states is limited.

While precision agriculture can address some of the significant inefficiencies in farm management, these technologies' widescale deployment face a few hurdles. The cost of deploying sensors remains prohibitively high for small farmers. In lagging states where diversification and higher value agriculture incentives are low, incentives to invest by start-up may be insufficient. Hub-and-spoke models, in which sensors are deployed over a large area covering 150–200 farmers aggregated through producer organizations, helps precision agriculture technologies to be viable. Using the Watson Decision Platform and Internet of Things (IoT) by IBM and Microsoft's AzureBeats, respectively, start-ups have developed devices, sensors, and cloud-based systems providing Business-to-Business (B2B) and Business-to-Customer (B2C) services targeting smallholder agriculture (**Table 3.6**). AgSmartic, Fasal, Aibono, AgCode, Cropin, Agnext, KrishiHub, and Intello Labs have entered the precision agriculture services space. The start-ups have developed crop-specific and geography-specific solutions to cater to farmers' diverse needs, ranging from smart irrigation systems to early pest detection systems and hydroponic home kits (Singh, 2020). Precision agriculture service providers also serve businesses, such as big traders and retailers.

The southern states of Andhra Pradesh, Telangana, and Tamil Nadu have taken the lead in adopting various precision agricultural methods, primarily because of high penetration of the Internet and a more extensive smartphone user base. The availability of these services in lagging states is low, if not wholly absent. The precision agriculture market is expected to grow at over 10% compound annual growth rate (CAGR) to reach US$99 million by 2025 (TechSci Research 2020).

Table 3.5: FaaS delivery companies, services, and states of functioning

Company	Estd. year	Services and products	Presence
EM3 AgriServices	2013	Machinery rental to farmers, services like harvesting, soil and land preparation	Madhya Pradesh, Rajasthan, Uttar Pradesh
Gold Farm	2012	Provides farmers an app-based platform for booking farm equipment, including water pumps, tractors, and other irrigation machines	Karnataka, Tamil Nadu
Trringo	2016	Equipment rental	Karnataka, Maharashtra, Gujarat, Rajasthan, and Madhya Pradesh
Oxen Farm Solutions	2016	Provides services, including crop residue management, land preparation, planting, crop management, harvesting, and postharvest processing	Punjab, Madhya Pradesh, Uttar Pradesh, Chhattisgarh, and Odisha
KhethiNext	2015	Connects farmers with equipment providers, input suppliers, and experts	Andhra Pradesh, Telangana, and Haryana
Krishify	2019	Advice for farmers to determine the kind of services they require each season. Digital market for farm input	Haryana
BigHaat	2015	Crop advisory, access to markets, along with farm inputs, including seeds	Karnataka
Ujjay	2017	Crop advisory, product sales, mechanization services, access to markets	Telangana, Andhra Pradesh, Maharashtra
AgriBolo	2018	Connects farmers with experts, NGOs for training, aggregates services like farm mechanization, seed production, others	Rajasthan, Maharashtra, Punjab Haryana

Source: Inc42 (2020)

Despite the recent growth of farm service providers all across the country, some challenges remain to be addressed. Seasonal cropping patterns mean that almost all farmers in a region require farm equipment simultaneously, making asset management difficult for service providers. Moreover, even small delays in deploying equipment can result in substantial income losses for farmers and service providers (Daum et al. 2021). Lack of awareness and trust in mobile apps further hinders the farmer's ability to use these services on mobile phones, thus requiring support through local extension agents. Additionally, the traditional asset-heavy model has seen only moderate investor interest due to uncertain returns and long gestation periods. Therefore, technology-enabled service models that combine mobile apps with local agents, while at the same time providing flexibility in the deployment of equipment, are likely to be more successful in the future.

Gender focus in mechanization is also a pressing issue, considering the rise of women-led agricultural households. CHCs run by women providing services are more easily accessible by other women and have emerged in many states, including Bihar and Odisha, where male out-migration rates are among the highest. The Bihar Rural Livelihood Promotion Society or Jeevika, in partnership with Cereal Systems Initiative for South Asia (CSISA) and International Maize and Wheat Improvement Center (CIMMYT), have trained women's self-help groups and other stakeholders to take up SI practices, such as zero tillage and direct-seeded rice. Jeevika trains women to use machinery and run CHCs with SI-related machinery, making it more readily available

Table 3.6: Precision agriculture companies, services, and states of functioning				
Company	Business Model	Function	Estd. Year	Presence
Cropin	B2B	Monitors fields, weather, and harvesting-related data	2010	Delhi, Karnataka
Aibono	B2B, B2C	Offers soil and nutrient check, vertical e-commerce	2014	Tamil Nadu
Agnext	B2B	Uses AI and advanced data sciences to track food quality along the supply chain	2015	Uttar Pradesh (Ghaziabad, Noida, and Greater Noida)
KrishiHub	B2C	Advisory platform to help farmers get customized information	2016	Maharashtra, Karnataka, Chhattisgarh, Madhya Pradesh, Tamil Nadu, and Andhra Pradesh
Fasal	B2C, B2B	Offers field sensor array to farmers to measure crop variables, insights	2018	Maharashtra, Karnataka, Chhattisgarh, Madhya Pradesh, Tamil Nadu, and Andhra Pradesh
Stellapps	B2B	Offers end-to-end dairy technology solutions	2011	Tamil Nadu, Bihar, and other states
BharatAgri	B2B, B2C	Offers personalized farm solutions	2017	Maharashtra
Eruvaka	B2B	Real-time monitoring of ponds in fisheries, voice call alert, cloud analytics	2012	Andhra Pradesh
Intello Labs	B2B	Provides quality evaluation data to retailers	2016	Karnataka, Gujarat, Jharkhand, Odisha, Punjab, Kerala, Delhi, and other metro cities
Fyllo	B2C, B2B	Helps in on-farm decisions using data	2019	Maharashtra, Karnataka, Tamil Nadu

Source: Inc42 (2020)

to women. The initiative is also a testimony to the relevance of collective action in SI approaches.

SUSTAINABLE INTENSIFICATION THROUGH THE POWER OF STAKEHOLDER AGGREGATION

With over 80% of all farms in India being less than 2 hectares, emerging FaaS, input services, and precision agriculture start-ups can address smallholders' information and service access constraints. Limiting environmental externalities of production and judicious use of scarce resources, such as water and green cover, require other interventions. Natural resource management interventions, such as agroforestry and watershed management, may not make sufficient ecological impact at a small farm level. Aggregation models in the form of Farmer Producer Organizations (FPOs) and self-help groups (SHGs) have the potential to enable joint access to scale-sensitive technologies for the benefit of producer groups. The success of SHGs in empowering women to access credit, manage water resources, and access mechanization is well documented (Deininger and Liu 2013; Desai and Joshi 2014; Raghunathan, Kannan, and Quisumbing 2019). FPOs are being promoted in large numbers, backed by government, civil society organizations, international donors, and corporations for their potential to enable small farm commercialization (Pingali et al. 2019). These aggregation models can capitalize on the existing group-level social capital to jointly access censor and drone technologies for implementing SI effectively.

Collective action initiatives, in which individuals jointly manage and distribute scarce CPR, have had a history of success in India, especially with water and forest resources (Wade 1994; Uphoff 2000; Agrawal and Ostrom 2001; Jodha 2002; Krishna 2002). SI interventions, such as agroforestry and watershed management, can also be carried out using similar institutional arrangements to help small farm adoption. SI interventions can also be community-based, requiring social capital to prevent collective action problems. Effective institutions for aggregation are essential to carrying out activities like community-led agroforestry and watershed management through water user groups. Successful collective action is achieved in groups with high social capital, preventing free-rider problems.[2] ICTs have been shown to have the capacity to organize group activities (Cardoso, Boudreau, M.-C., Carvalho 2019); disseminate information for social and economic change (Urquhart, Liyanage, and Kah 2008); monitor to prevent free-rider problems, build cohesion through social capital, and also allocate resources effectively (Hu et al. 2014).

Farmers' WhatsApp groups have been recognized for solving information asymmetry problems during the COVID-19 pandemic. The agriculture departments have used the platform to provide information to farmers in Himachal Pradesh (LiveMint.com 2020) and Maharashtra (*Indian Express* 2020) and FPOs to organize sales to consumers in Karnataka directly (Kamila 2020). This points to the fact that social media platforms can allow groups to adapt to immediate situations. The scope of such platforms is still yet to be tapped to its full potential. However, as a medium, it remains a powerful option to enable collective action, strengthen aggregation models and their activities in SI at reduced costs. Numerous factors complicate the introduction and usage of farm management technologies. Although the primary aim of introducing any technology should be to increase efficiency, reduce drudgery, and mitigate environmental risks, it is vital to consider the sociocultural and economic factors that can enable or hinder its adoption. Using social media platforms to spread information and increase network strengths between farmers and other stakeholders can increase technology adoption and economic opportunities through better market access.

THE WAY FORWARD

Increasing productivity while limiting the environmental impact through SI is knowledge-intensive and not always scale-neutral. The rapid development of ICT infrastructure combined with increased mobile phone usage has expanded the scope for addressing information availability and asymmetry problems, and technology access issues of smallholders. Increasing commercialization of the agricultural sector has incentivized the emergence of start-ups in FaaS, precision agriculture, and input service provision. The current investment in farm service provision enterprises is still low, despite the high potential for investment and growth.

- FaaS, precision agriculture, and farm input service start-ups are emerging mainly in urbanizing and agriculture-led states. The emergence of such services is slower

[2] Mancur Olson (1965) in his famous thesis on collective action postulates that provision of collective goods is difficult because rational individuals have a tendency to free ride or acquire benefits from group action without contributing to it. Olson suggests that smaller groups are more successful in collective action, as individuals are more easily monitored and sanctioned for free-riding.

in lagging states. Models to deliver services to these states—where food insecurity is the starkest—is essential.

- Higher commercialization through market linkages is necessary to incentivize farmers to accept FaaS and precision agriculture services in lagging areas. Better market access creates and makes such services viable. Increasing market access is critical to improving farm management practices and mechanization.
- Aggregate data at state and national levels on weather patterns, infrastructure availability, regional cropping patterns, adoption rates, and advance production estimates that can inform spot and future markets and policy all remain squarely with the state. Here, GIS, satellite imagery and machine learning algorithms will significantly enhance the collection ease and availability of these data. Integrating these technologies will be critical to addressing aggregate-level data and supporting farm-level service delivery and precision agriculture. The state plays a vital role in collecting aggregate-level data.
- Crop research and R&D through the Indian Council of Agricultural Research (ICAR) and state agricultural universities (SAUs) are necessary for production improvements in lagging areas. Crop- and location-specific extension services can be better disseminated through data sharing public–private partnership (PPPs). Start-ups linked to university systems can aid innovation.
- Although technology service mechanisms such as FaaS can address some of the scale disadvantages of small farms, CA for agroforestry and watershed management systems still require collective action. Technology to monitor resource use, reduce collective action problems, and create social capital, which limits the propensity to free-ride in larger groups, is needed.
- In lagging states, aggregation models can exist in the form of FPOs, as increasing linkages to markets can incentivize and provide ICT-based farm management services that the private sector fails to deliver. Support and innovation to enable these linkages is an area that requires attention.

4 • PREVENTING FOOD LOSS AND WASTE—TECHNOLOGY IN HARVEST AND POSTHARVEST SYSTEMS

In subsistence-based agricultural systems, harvest and postharvest methods were designed to gather and store food, feed, and seed within the household for use until the next harvest. Much of the storage preparation and storage procedures were energy neutral and varied for nonperishables, semi-perishables, and perishables. In the absence of cooling systems to preserve perishables, sun drying, and pickling were the dominant preservation forms. The use of storage systems has been to keep food safe from spoilage by microbes and foodborne pathogens and protect against pests, such as insects and rodents. It prevents excessive moisture, maintains suitable temperatures, and provides a protective physical barrier against microbial and pest infestation. In commercialized agricultural systems, the farm-level surpluses increase, raising the demand for labor and infrastructure for harvest and postharvest activities. Postharvest management includes grading, sorting, drying, packaging, storage, and transportation.

It is estimated that almost 20% of India's food loss and waster (FLW) occurs in the harvest and postharvest stages (NAAS 2019). Moreover, according to a report prepared by the Indian Council of Agricultural Research (ICAR), farmers collectively lose about Rs 92,651 crores (at wholesale prices of 2014) on lost produce due to improper storage each year (Jha et al. 2016). Technology to improve harvest and postharvest management practices serve three critical functions: (1) preservation to enhance agricultural product transportability to reduce FLW and improve food availability and accessibility; (2) ensuring grades and standards and food safety in the agricultural value chain; and (3) enabling value addition to improve agricultural produce marketability and smallholder incomes.

With the rising demand for safe, nutritious, and diverse foods that has resulted from socioeconomic and demographic changes, addressing FLW in the harvest and postharvest stages can ease productivity pressures on the food system. Investments in value chains for connectivity to markets, storage facilities, and behavior change to reduce food waste at all food value chain steps are essential (Abraham and Pingali 2020). Meeting these requirements requires higher capital investments and higher energy consumption. While efficient harvest and postharvest practices are necessary for reducing hunger by way of improving food availability, it is critical to ensuring good health through food safety standards. Harvest and postharvest management will also be critical to addressing climate, as the need for energy-efficient storage and preservation processes (refrigeration, drying, transport, etc.) remains a focus.

In the next part of this chapter, we define FLW and look at the stages and extent of FLW at harvest and postharvest stages. We assess the status of India's storage facilities and storage challenges for both perishables and nonperishables, emphasizing the need for more energy-efficient cold storage facilities for the growing horticulture sector. The last section examines the role that new technologies can play to improve storage and transportation facilities to reduce food loss, ensure safety, reduce emissions, and enable sustainable production and consumption.

FOOD LOSS AND SAFETY AND STORAGE IN INDIAN FOOD SYSTEMS

The Food and Agriculture Organization of the United Nations (FAO) defines food loss as the decline of edible food availability during production, postharvest, and processing, and food waste as food discarded by consumers and retailers (FAO 2014). Spang et al. (2019), in a review of literature on FLW, points out that the definition of this term varies depending on (1) the stage it is on the food supply chain (harvesting, handling, storage and transportation, retail, consumption); (2) its destination (human consumption, animal feed, or landfill); and (3) avoidability (parts of plants and animals that are and are not consumed sometimes are socioculturally defined—for example, peels of vegetables). Food materials not included in the human food supply chain, such as food materials intended for animal feed or biofuel feedstock, are generally not included in the definition of FWL (Spang et al. 2019). To define food loss in the context of harvest and postharvest management, we consider food loss as food intended for human consumption left unharvested or food diverted away from intended human consumption during storage or transportation to markets.

Harvest and postharvest management include handling practices as well as storage practices. Handling practices include harvest practices (harvest maturity, the timing of picking), collection, threshing, winnowing or cleaning, drying, packaging, and transportation for nonperishable produce, such as staple grains, coarse grains, and pulses. Steps of threshing, winnowing, and drying are absent for perishables. Storage practices involve storing at the household level and warehousing before taking the produce to the markets. Postharvest losses in India stem from a range of factors, including lack of postharvest infrastructure for storage and transportation, limited technical knowledge of acceptable agricultural practices among supply chain actors, imperfect market knowledge, and inadequate market access (NAAS 2019). The postharvest losses vary widely for perishables and nonperishables.

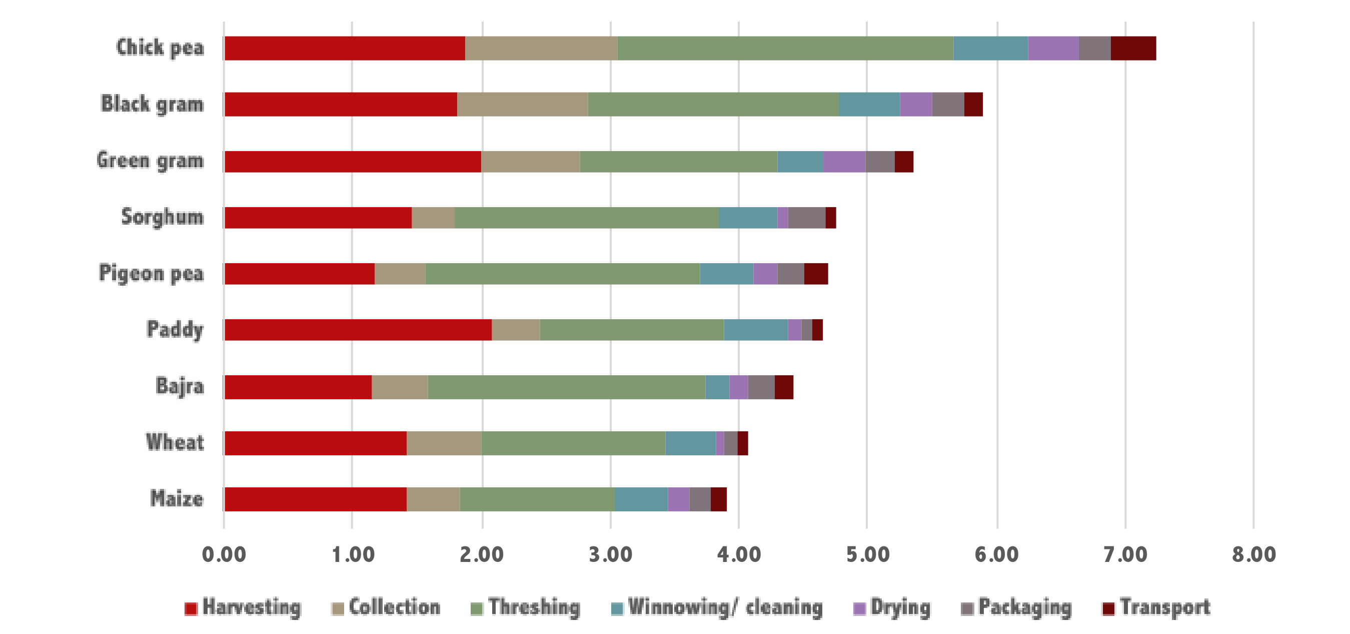
HANDLING AND STORAGE LOSS IN NONPERISHABLE COMMODITIES IN INDIA

The “Report on Assessment of Quantitative Harvest and Post-Harvest Losses of Major Crops/Commodities in India,” by ICAR and the Ministry of Food Processing Industries (Jha et al. 2016), looks comprehensively at food loss at the farm operation and storage stages. **Figure 4.1** shows the different stages of food loss for various nonperishable grains and pulses in India. Across crops, the harvesting and the threshing (separation of grain/seed from husk) stages show the highest levels of loss, while the losses at other stages were relatively low. Harvesting losses result from the harvest and weather-related phenomena, such as storms or rain at the time of harvest.

Paddy showed the highest loss in the harvesting stage (2.08%). Pulses and coarse grains showed the highest losses during threshing and in chickpea cultivation (2.60%). The report states that inferior threshing methods—such as the use of wheat threshers for pulses without changing a thresher’s setting or laying harvested coarse grains like pearl millet on the road—were the main reasons for loss (Jha et al. 2016). The total loss for cereals during harvest and postharvest handling averaged around 4%, while pulses averaged close to 6%, with chickpeas having the highest losses. Delay in harvesting and inferior threshing methods, leading to damaged seeds, were the main reason.

Storage losses for nonperishable crops were the highest at the farm level, mostly due to inadequate storage facilities and little information about acceptable practices

Figure 4.1: Food loss at farm operation and handling stages for nonperishables in 2016 (%)



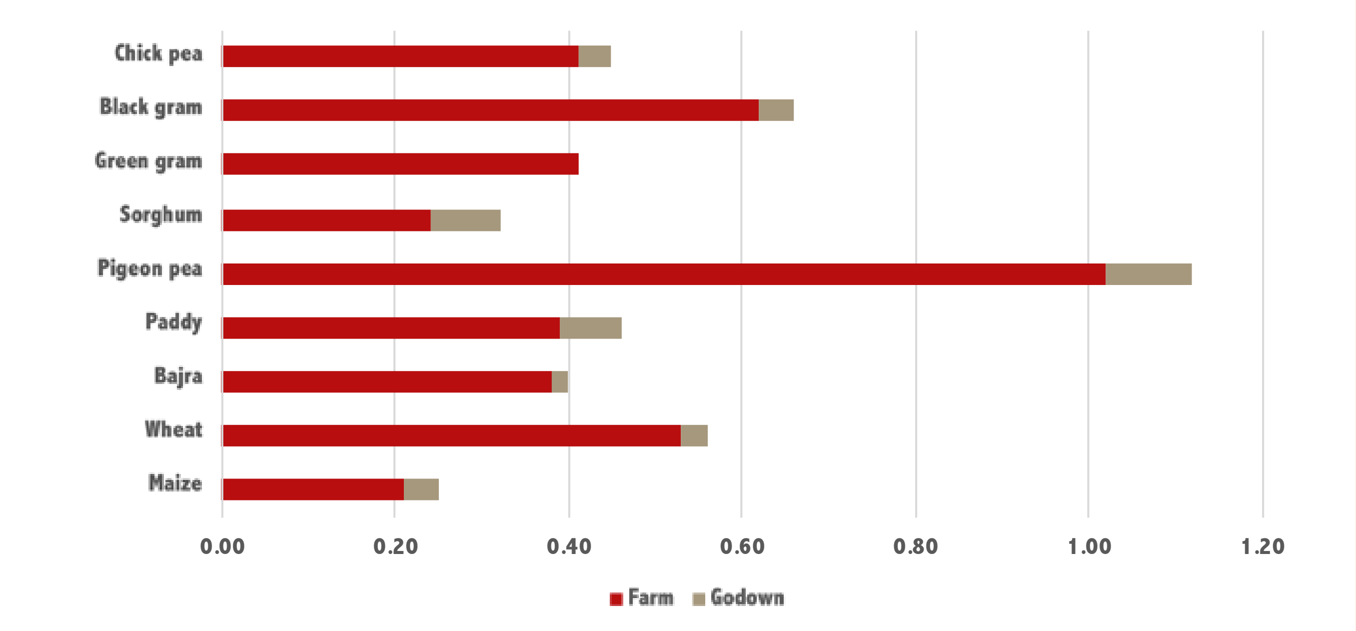
Source: Constructed using data from the ICAR report by Jha et al. (2016)

(**Figure 4.2**). Insufficient knowledge of storage procedures and facilities, such as cemented platforms, storage bins, and moisture meters, leads to poor practices, such as not maintaining moisture levels below 13% and storing in poorly ventilated rooms, leading to pests, mycotoxins, and fungi infestations (Khapre and Pawar 2015). The indigenous storage structures are made of locally available materials (grass, wood, mud, etc.) without any scientific design and cannot protect crops against pests (Kumar and Kalita 2017). Poor storage practices also lead to contamination of grains that can have adverse health impacts.

In a study funded by Tata–Cornell Institute (TCI) to identify household risk factors associated with aflatoxin contamination within and across diverse Indian food systems, Wenndt (2020a) sampled 595 cereals, pulses, and oilseeds from 160 households and found between 30% and 80% of households yielded at least one contaminated sample. Grain washing, sack-based storage systems, and cultivation status (farming or nonfarming) were the most influential factors. Grain storage within the household affects not only harvested grains and pulses but also food bought at the market or received through the Public Distribution System and stored at home.

The ICAR report also finds that food loss from storage is the highest in pulses (**Figure 4.2**). Poor storage facilities, which were inadequate for storage than extended more than three months, was cited as the main reason for insect damage in these crops. Bruchids or weevil damage was the most significant cause of pigeon pea loss during storage. Insect and other pest damages are easier to spot and report as a loss. In contrast, aflatoxin and other microbial damages can be harder to detect but have lasting health impacts on consumers. It is critical to improve farm-level storage facilities to enhance phytosanitary conditions and health. In commercial agricultural operations, where regulatory standards are monitored and enforced, mycotoxins and inconspicuous microbial contaminants, as well as toxic produce, are detected and removed. However, smallholder producers and consumers lack regulatory capacity and, therefore, often handle, store, and consume food without knowing its toxicity status.

Figure 4.2: Food loss during farm storage for nonperishables in 2016 (%)



Source: Constructed using data from the ICAR report by Jha et al. (2016)

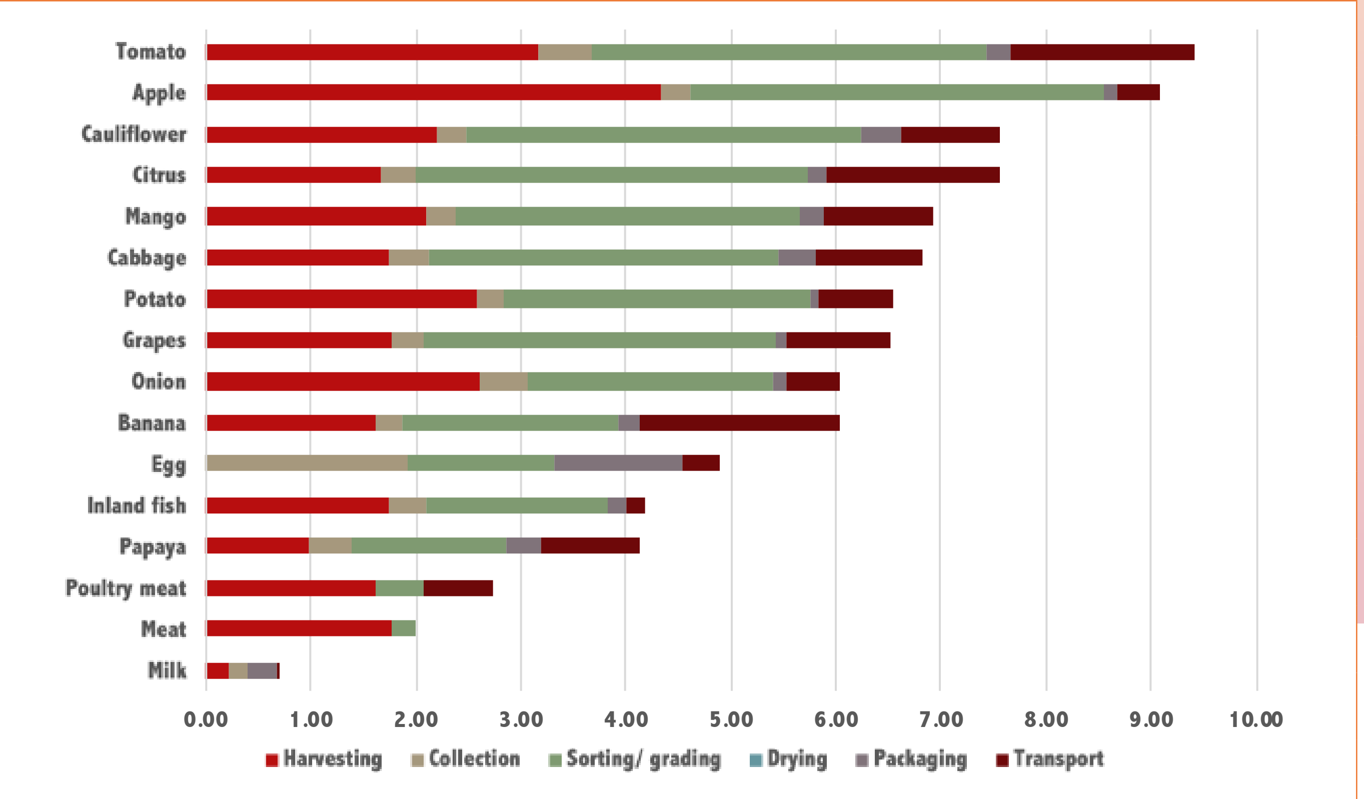
HANDLING AND STORAGE LOSSES IN PERISHABLE COMMODITIES

Handling and storage practices in perishables, such as fruits and vegetables and animal products, are different, and often losses are much higher. The high moisture content (70–95%), soft texture, and increased respiration and transpiration rates imply that most fruits and vegetables are at a greater risk of spoilage than cereals and pulses, especially in the absence of proper storage, handling, and transportation facilities. Jha et al. (2016) showed that losses are highest during the harvest and sorting and grading stages for most fruits and vegetables (**Figure 4.3**). Transportation is another segment that has high losses. Among perishable commodities, tomatoes (9.41%) and apples (9.08%) show the highest overall loss, with harvesting, and sorting, and grading losses the main contributors. The timing of harvesting is critical for perishable commodities. If the products have a longer transportation distance, they need to be plucked less ripe. If the consumers are local, the picking needs to be adjusted accordingly. Suppose the time difference between plucking and transportation to the market increases, grading and sorting losses also increase. In apples, orchards are located in Jammu and Kashmir, Himachal Pradesh, and Uttarakhand, while markets are often far away. Poor connectivity and linkages to markets make transportation expensive and influence loss (Jha et al. 2016). Spoilage in milk has been low due to good infrastructure through cold chains. Milk cooperative collection centers are usually equipped with bulk milk coolers, allowing for better preservation and reduction in spoilage.

Preliminary results from a TCI project by Jocelyn Boiteau on the tomato value chain in Madanapalle in the Chittoor district of Andhra Pradesh show that farmers usually store their tomatoes for short periods (usually overnight) before selling them in the market. **Figure 4.4** shows that semi-perishables, such as onions, potatoes, and a few other crops like bananas, cauliflower, and apples, are stored before sales. The storage-level losses are much lower than in the handling stages, as perishables are sold more quickly. For most crops, cold storage is not used, or facilities are not available, which determines the method of sale, options, and bargaining power. The ICAR report finds that the lack of access to multicrop cold storage was the factor that contributed the most to losses. It also found that market gluts, such as those during harvesting seasons, and lack of planning to handle the surge led to increased farm operations losses (Jha et al. 2016). Infrastructure, awareness, and incentives are required to improve practices and encourage uptake of infrastructure for storage.

The ICAR report finds that losses for both perishables and nonperishable crops are much higher at the farm and storage levels than at the retail level (**Figure 4.5**). The losses are understandably higher in perishables, and at the retail level, poultry meat had a higher loss than at the farm level.

Figure 4.3: Food loss during farm operation and handling stages for perishables in 2016 (%)

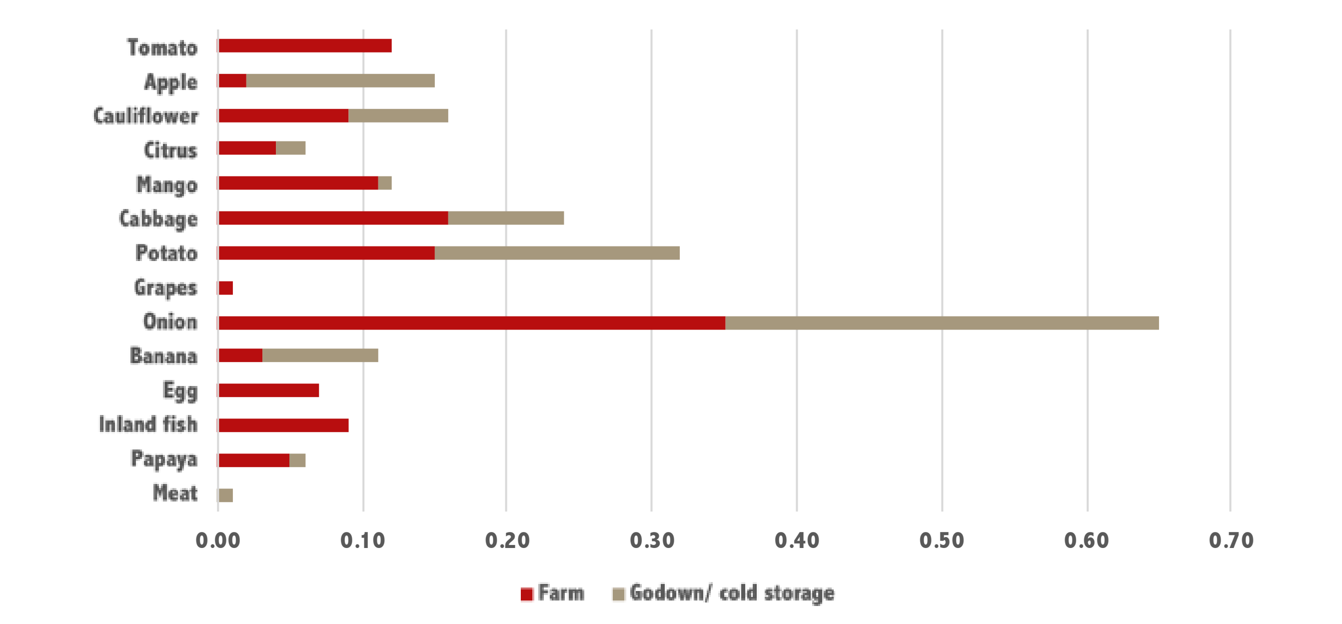


Source: Constructed using data from the ICAR report by Jha et al. (2016)

STORAGE INFRASTRUCTURE FOR PERISHABLES IN INDIA

As demand for higher value agricultural products grows, the total area, production, and yields of horticulture crops are rising. Between 2001–2 and 2018–19, the total area under horticulture crops grew 51%, from 16.5 million ha to 25 million

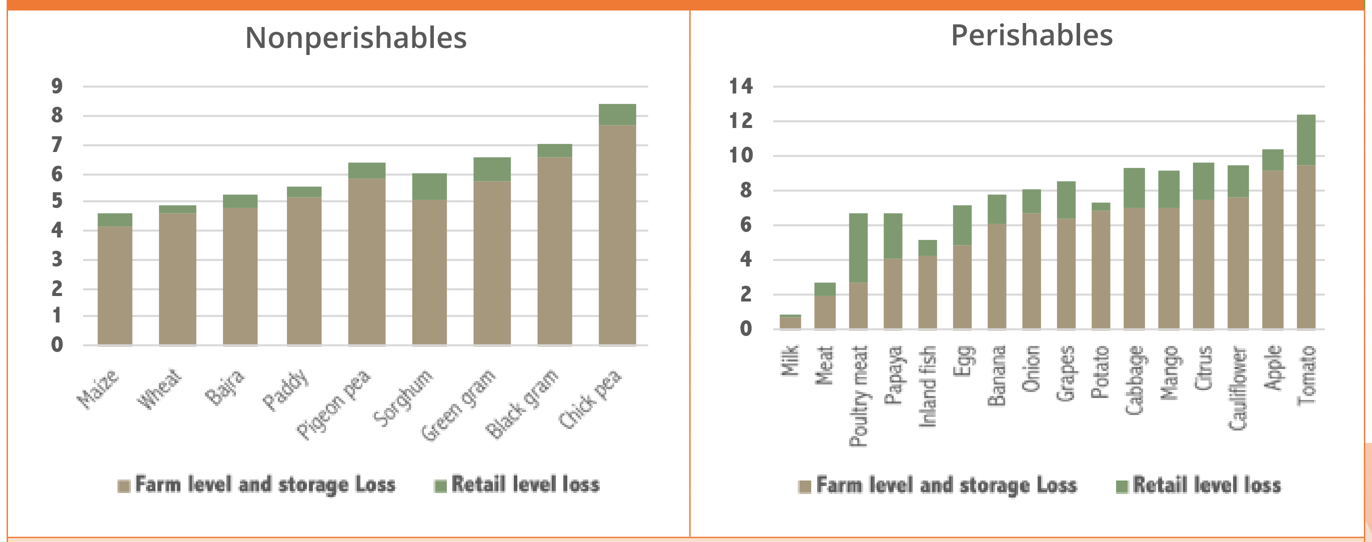
Figure 4.4: Food loss during storage for perishables in 2016 (%)
(excluding market and retail level)



Source: Constructed using data from the ICAR report by Jha et al. (2016)

ha. Production increased by 115% from 146 to 313.8 MT, and yields rose by 37% from 8.97 to 12.31 metric tons per hectare (Ministry of Agriculture & Farmers' Welfare 2018). India produced more horticulture crops (313.8 MT) than food grains (284.95 MT) in 2018–19. If there is no corresponding infrastructure growth, the loss is expected to be close to US$10.6 billion (NAAS 2019; Chauhan 2020). Thus, addressing FLW issues can play an essential role in addressing the interlinked

Figure 4.5: Percentage loss in selected perishable and nonperishable crops
at the farm and market levels

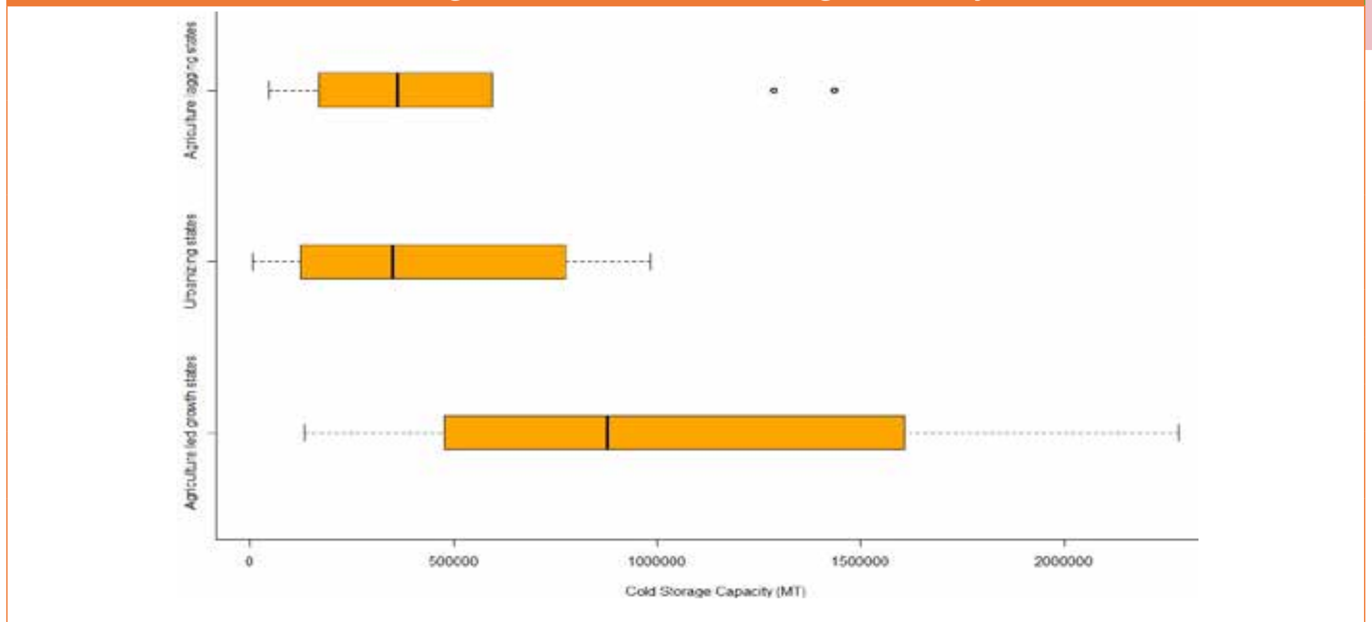


Source: Constructed using data from the ICAR report by Jha et al. (2016)

problems of hunger, malnourishment, and environmental degradation.

The National Centre for Cold Chain Development (NCCD) was established to develop cold storage and cold chains in India. In 2019, India had 8,038 cold storage facilities with a total capacity of 36.77 million MT. Over 66% of the storage capacity is in the states of Uttar Pradesh (39.54%), West Bengal (16.12%), and Gujarat (10.30%), and 75% of cold storage capacity is used for a single crop—potatoes (NAAS 2019; Directorate of Economics and Statistics 2020). Uttar Pradesh, West Bengal, and Gujarat are three of the four largest potato-growing states. **Figure 4.6** shows the distribution of cold storage capacity in agriculture-led, urbanizing, and lagging states, excluding the outlier states of Uttar Pradesh, West Bengal, and Gujarat. The median in agriculture-led states is 0.8 million MT, with Punjab having the highest capacity of 2.2 million MT. In urbanizing states, the median capacity is 0.35 million MT, with Maharashtra having a capacity of 0.98 million MT. In lagging states, Bihar, the third-largest potato-growing state after Uttar Pradesh and West Bengal, has a capacity of 1.43 million MT, while the median capacity is 0.36 million MT.

Figure 4.6: Distribution of cold storage capacity in different regions
(excluding Uttar Pradesh, West Bengal, and Gujarat)



Source: Constructed using data from the ICAR report by Jha et al. (2016)

The inequitable distribution of facilities across the country and low-capacity utilization (as most facilities are used for a single crop) characterize India's cold storage. Low utilization also results from facilities left unused because of lack of access to ancillary facilities, such as integrated packing houses, reefer trucks, and ripening units that form the cold chain (Pandey 2018). The high energy requirements, coupled with unreliable electricity supply and poor road infrastructure, make these facilities unaffordable to most smallholder farmers (Emerson Climate Technologies 2015; NAAS 2019). Even though states like Uttar Pradesh, West Bengal, and Punjab are leading in cold storage capacity, lack of transportation infrastructure implies that losses during transportation are as high as 24% of the total losses in some cases (Negi and Anand 2016). Moreover, the current transport refrigeration units (TRU) in use are mostly diesel-powered, consuming 20% of the trucks' fuel and emitting 29 times as much particulate matter (PM) and 6 times more NO2 in a year, as compared to a modern diesel engine (Birmingham Energy Institute 2014).

An associated challenge with India's storage infrastructure is that around 80% of handling and warehousing facilities are not mechanized, and traditional loading, unloading, and handling methods are used (FAO 2019). The poor handling of food products—mainly due to poorly trained staff with limited skills to properly use handling equipment, or lack of availability of such equipment, including gloves and reusable plastic crates—also results in a considerable quantity of food loss at the storage level, especially for fruits and vegetables (FAO 2019).

In addition to increased physical losses, improper handling of the produce during transportation and storage often elevates food safety and nutrition loss concerns. Factors, such as poor hygiene practices, lack of preventive controls during food processing, incorrect use of chemical fumigants, and inappropriate technologies, can contribute to these concerns (Uçar, Yilmaz, and Çakırğlu 2016). Furthermore, lack of scientific and safe storage facilities, with adequate ventilation and technologies to maintain proper temperature and moisture, significantly affect the quality and quantity of the food, with high probabilities that the food products will be infested by molds or insects (Randhawa and Chaudhry 2016). Thus, there is a vast information gap regarding proper hygiene standards for different commodities and agriculture produced along the supply chain.

The harvest and postharvest management stages of India's food value chain face enormous challenges due to a lack of infrastructure, such as storage and transportation facilities, which is further compounded due to a lack of information and awareness among the different supply chain actors. Improving access to cold chain facilities for perishables can drastically check FLW. A concerted approach for understanding and training farmers and other actors is needed to identify and address the key bottlenecks.

ROLE OF TECHNOLOGY IN HARVEST AND POSTHARVEST MANAGEMENT

Technology in the harvest and postharvest stages of the food system prevent food loss, ensure consumers' food safety and health, and reduce the impact these processes have on the environment. Access to technology and acceptable management practices at the farm, household, and transportation levels are critical. Here, we look at household- and community-level interventions for both perishables and nonperishables to prevent FLW, adapted by smallholder producers. First, we look at interventions at the operational, handling, and household storage stages, especially for nonperishables. Second, we look at technologies for drying and cooling in two sections. Cooling and drying are energy-intensive, low-cost, and energy-efficient technologies that can prevent FLW, improve smallholder incomes, and increase marketing opportunities. Operational handling and household-level storage are not independent of cooling and drying processes, but integrated processes support each other.

INTERVENTIONS IN THE OPERATIONAL, HANDLING, AND HOUSEHOLD STORAGE SPACES FOR NONPERISHABLES

Adopting new technologies for a better harvest and postharvest management requires reliable information access and awareness among the supply chain actors. We see the losses are significant at the harvesting and the threshing stages for nonperishables and sorting stages for perishables. Harvesting practices in both groups are labor-intensive, non-mechanized (except for wheat and rice in agriculture-led states), and handling practices, especially threshing in grains and pulses, are inefficient. Options for mechanization are higher for nonperishables compared to perishables. However, access to capital intensive machinery is low for smallholders. Mechanization for harvesting and threshing is low for coarse grains and pulses, making them labor-intensive. However, wheat harvesters can be adapted to harvest pulses, maize, pearl millets, and mustard, among other crops (Lal and Verman 2007; Damodaran 2020).

Similarly, handheld threshers used for threshing paddy and wheat threshers can be used in pigeon peas and other pulses as well. Making these machineries available to small farms at specifications for multicrop use, again, is a challenge. Access to harvesters and threshers, through Custom Hiring Centers (CHCs) and coordination through apps, described in Chapter 3, applies to harvesting and postharvest stages.

Information and awareness to make critical harvest decisions can also reduce loss in perishables and nonperishables. Information on practices to prevent late harvest and improper threshing, information about market demand and grades and standards, and critical weather information can help timed harvest and avoid losses at grading and sorting stages. In perishable commodities, such as tomatoes and chiles, the harvest is done in 3–4 pickings each season. Farmers must time pickings to get a maximum harvest at required grades, and pickings can result in different ripeness and grade levels. Coordination with cooling sheds and cold storages can slow down ripening to prevent grade losses and help consolidate pickings. The use of information communication technologies (ICTs) through mobile phones and Internet-enabled technologies connects diverse user groups and provides them with better information through Short Message Service (SMS), phone calls, and multimedia content. The health and economic benefits of minimized food losses and preservation of the nutritious value of the food supply will outweigh the cost of accessing technology, knowledge, and information.

Household-level storage facilities are primarily for nonperishable food grains and pulses grown by the household or bought at market. Metal bins or silos are often suggested as one of the easiest methods to improve food grain storage. Silos constructed out of galvanized iron or stainless steel are robust, hermetic, and water-resistant units that can store grains for long periods. Evaluations in Uganda have shown that metal silos have a short payback period of 2.5 harvests and have additional benefits such as reduced farmers' losses compared with the traditional methods (Costa 2014). Moreover, they do not require pesticides, are rodent and pest-proof, and are easy to recycle. Their only disadvantages are that they have a high initial cost compared to other technologies, are challenging to transport, and often require structural adjustments in farmers' houses before installation.

The use of low-cost hermetic bags that are waterproof and airtight to store grains at the household level are cheaper ways to reduce loss. Leveraging a storage system already familiar to farmers (that is, gunny sacks), using airtight hermetic liners halts microbes and pest growth. It substantially reduces spoilage without relying on dangerous pesticides or fumigants. Wenndt's research in Uttar Pradesh, where participatory research methods were used to educate households about the benefits of using hermetic bags as a food safety intervention, has shown that participatory hermetic storage interventions can reduce mold contamination and spoilage of stored grain (Wenndt 2020a). The research points to the need for community mobilization and building of awareness through participatory research methods, even for simple interventions that are not capital intensive to improve uptake (Wenndt 2020b). Acceptable practices before storage also play an essential role in reducing food loss, and drying in this regard is critical.

DRYING TECHNOLOGIES TO PREVENT POSTHARVEST FOOD LOSS IN PERISHABLES AND NONPERISHABLES

Drying is often required to reduce the moisture content in nonperishables to levels where it can be safely stored without microorganism growth and moisture-intermediated spoilage, resulting from enzymatic reactions, pigmentation, and oxidation lipids, among others (Kumar and Tiwari 2007; Udomkun et al. 2020). The process is used in perishables, such as fish, sweet potatoes, chiles, and other vegetables, to transform and preserve them at the household level. Drying is an energy-intensive but cost-effective way of preserving or storing agricultural produce, and sun-drying is the most common form of drying used by smallholder farmers. However, sun-drying potentially exposes produce to dust, rain, pests, and rodent contamination, leading to losses at the farm level. The alternative forms of drying are active, passive, and hybrid drying, all of which are closed and ventilated. All three forms use solar radiation for heat transfer. In passive drying, smaller box driers or greenhouse dryers are used. Greenhouse driers are easy to construct as cheap, transparent (glass, polyethylene, or polycarbonate sheet) sheds, where air circulation occurs naturally and humidity is ventilated through chimneys (Seveda and Jhajharia 2012; Ghaffari and Mehdipour 2015; Chauhan and Rathod 2020). Greenhouse dryers are the cheapest and most convenient structures that can be adopted at the farm level and are ideal for drying nonperishable produce.

The major shortcoming of passive dryers is that the temperatures cannot be controlled, and overheating can lead to quality loss, especially in fruits and vegetables. Active dryers, in which temperature can be regulated through electric fans and blowers that circulate air, are more suitable for fruits and vegetables (Chua and Chou 2003; Tiwari, Tiwari, and Al-Helal 2016). The energy required to run circulation systems with solar power can make active dryers energy neutral. Solar bubble dryers (SDB), jointly developed by the International Rice Research Institute (IRRI), Grainpro, and the University of Hohenheim, feature a low-cost space-saving drying tunnel, which uses a solar-powered photovoltaic system to power a blower to circulate air (**Figure 4.7**). The SDB can be easily set up and dismantled when not in use and can be a useful tool.

Hybrid dryers also use stored heat when solar energy is absent. Heating air using gas before circulating it in the dryers is, however, energy-intensive and leads to emissions. A number of local, farmer-friendly innovations have been pioneered in efforts to minimize the cost to farmers of active drying, while also not producing excess gas emissions for drying alone. For example, there is evidence that waste heat from the engine exhaust of other farm machinery (that is, diesel engines used in threshing, pumping, etc.) can be recovered and utilized for grain drying at no extra cost to farmers (Akhter, Nabi, and Afroz 2007; Pati, Hotta, and Mahanta 2015). In India, where annual radiation ranges from 1,200 to 2,300 kilowatt/m2 (Yadav, Kumar, and Yadav 2015), active and passive heaters are sufficient. The fan for forced ventilation accounts for only 5% of energy consumption (Liu, Wang, and Li 2015).

Figure 4.7: Solar bubble dryers

Source: The International Rice Research Institute, CC BY-NC-SA 2.0

The drying process has also been shown to preserve the nutritional properties of food when carried out under ideal temperatures, compared to open-air drying. Retention of provitamin A in the leafy vegetables, amaranth and fenugreek, at 65° (Negi and Roy 2000); provitamin A and trans-ß-carotene in orange-fleshed sweet potato (Bengtsson et al. 2008; Bechoff et al. 2009); flavonoids, polyphenols, vitamin A, and vitamin C in bitter gourd and capsicum (Mehta et al., 2017); and vitamin C in Indian gooseberry (Prajapati, Nema, and Rathore 2011) are good examples (Udomkun et al. 2020). At the household level, using smaller passive box dryers, kitchen garden produce or fruits and vegetables bought from the market can be preserved without nutrient loss for stable access to the produce throughout the year.

Along with fruits and vegetables, drying fish is also a way of preserving and transporting fish effectively. In Odisha, WorldFish has collaborated with the Mid Day Meal Scheme (MDMS) and Integrated Child Development Services (ICDS) programs to provide nutrition-rich dried fish to schools and *anganwadis* (Letondot 2019). The fish is made available through women's self-help groups (SHGs) involved in village-level aquaculture and drying of fish. While drying does not transform nonperishables products such as grains, in the case of fruits, vegetables, and fish, drying transforms the product into a different food groups. For example, dried chiles and fresh chiles are two other food categories that are not substitutable. Preservation strategies for fish, livestock products, fresh fruits, and vegetables, without transforming them, involves cold storage and cold chain development.

DEVELOPING COLD CHAINS FOR PERISHABLE COMMODITIES IN

INDIAN FOOD SYSTEMS

Cooling and refrigeration are energy-intensive activities that require high energy inputs and generate emissions from refrigerants, such as ammonia and hydrocarbons (propane or isobutane), hydrofluorocarbons (HFCs), and insulation material when not properly recycled.[3] According to the Kigali Cooling Efficiency Program, cooling currently accounts for about 7% of GHG emissions (Kigali Cooling Efficiency Program 2018). As the need for air-conditioned living spaces and buildings, transport air conditioning, refrigeration, and cold chains increase with rising temperatures, cooling requirements will also rise.

The Montreal Protocol on Substances that Deplete the Ozone Layer of 1987 was the first global effort to reduce the use of chlorofluorocarbon (CFC) gases in cooling to protect ozone's depletion layer. Although less harmful than CFCs, the HFC-substituting CFC is still a more potent greenhouse gas (GHG) than carbon dioxide (CO2). The Kigali Amendment of 2016, which went into force on January 1, 2019, has tasked the 197 ratifying countries to reduce their HFC footprint. India is tasked to reduce its HFC with global warming potential (GWP) by 85% by 2047. India is one of the first countries to release their comprehensive India Cooling Action Plan (ICAP)—a framework to set and achieve targets between 2017–18 to 2037–38. Compared to space cooling, transport air conditioning, refrigeration, and cold chains represent a small cooling portion. The demand is, however, expected to grow rapidly because of transforming value chains.

A cold chain is the link between farm and consumer involving storage, packaging, transportation, and food distribution while preventing spoilage, weight and water loss, quality loss, and damaged perishables, such as fruits and vegetables and livestock products. The four crucial nodal points of a cold chain are packing houses, or the source point; reefer transport, cold storages, and ripening chambers for some fruits (MoEFCC 2019). As frozen foods are more industry-driven and have a post-processing/manufacturing activity requiring higher energy utilization, they are not given attention here. **Table 4.1** shows the current and future projected cold chain capacity needs in India. In the next 10 years, the projected capacity growth in packing houses will be the highest, and reefer vehicles and ripening chambers will also see high growth.

Packing houses are the gateways into the cold chain, where sorting and grading, washing, drying, packaging, and precooling for perishables occur. Precooling removes the field heat from the product and is often energy-intensive and needs to be done rapidly. While active cooling mechanisms through forced air, hydro, vacuum, room cooling, and other energy-intensive methods are used, passive cooling techniques that use shading, glazing, cool roofs, and proper ventilation can decrease costs and energy use.[4] Net-zero cooling, where energy is drawn from solar power coupled with passive cooling, can make packing houses efficient. Packing houses in India are expected to grow at 60.1% compound annual growth rate (CAGR) in the next 10 years. Net-zero cooling supported by passive cooling will reduce emissions and help off-grid packing houses set up, especially in lagging states. Access to packing houses at low costs will incentivize diversification, as FWL can be minimized. Solar-powered cold storage can increase shelf life by up to 20 days at the cost of Rs. 0.006 per kg of produce per day (Sharma and Kumar 2018).

Passive cooling technologies would be ideal for ripening chambers, wherein the temperature needs to be controlled at 15–20oC, with elevated humidity. Ripening chambers are critical for ripening bananas and climacteric fruits, such as mangoes and papayas, degreening of citrus fruits, and maturation of tomatoes and pears (MoEFCC 2019). These chambers can be easily set up as off-grid, net-zero cooling units at farm levels to improve grades and standards, allowing for value addition and standardization, as required by the organized retail segment.

Table 4.1: Current and future projected capacity needs of cold chains in India (2017–2038)

	2017-18	2022-23	2027-28	CAGR*	2037-38	CAGR*
Packing houses (unit)	500	17,500	55,000	60.1	125,000	8.56
Reefer vehicles (unit)	13,500	55,000	135,000	25.89	400,000	11.47
Cold storage (million MT)	35	39.5	43	2.08	47.5	1
Ripening chamber (unit)	1,050	2,750	8,750	23.62	13,500	4.43
Domestic refrigerator (Million units)	100	129.5	173	5.63	309	5.97
Commercial refrigeration (Million TR)	8.4	11.6	17.5	7.62	47.5	10.5

Note: CAGR = Compounded annual growth rate
Source: Ministry of Environment, Forest & Climate Change (2019)

Reefer transport vehicles or reefer containers with a fixed insulated bodies, equipped with active refrigeration to transport produce from packing houses and ripening chambers to markets or other bulk and cold storages, are critical to reducing loss. The reefer transport segment is another segment that will see high growth over the next 10 years. According to ICAP projections, it is expected to grow at about 26% CAGR. Logistics in cold chains and cold storage technologies at aggregate levels, as bulk and hub storage, are capital-intensive and are infrastructures that need extensive technological support from the state and the private sector. When agricultural markets are unrestricted, private sector investment enters the value chain. With the rising demand for horticulture produce, there will be volumes and incentives for such investments from the private sector. Protocols laid out by ICAP in line with the Kigali Amendment will require emerging technology to be very efficient with low GWP, by focusing on net-zero cooling.

Both drying and cooling technologies, like most farm management and harvesting technologies, are not scale neutral. Smallholders' cost to build or access cold storage, or access harvesting and threshing machines, active and passive dryers, packing houses, and ripening units, may be challenging without aggregation through farmer producer organizations (FPOs). Aggregation through FPOs can reduce high fixed costs of cooling, drying, and storage and allow for better market linkages through contract farming, where quality, volumes, and prices are prespecified, allowing for better incentives. Contract farming-driven vertical coordination of value

[3] https://unfccc.int/files/methods/other_methodological_issues/interactions_with_ozone_layer/application/pdf/epeebroc.pdf
[4] https://coolcoalition.org/climate-action-pathway-net-zero-cooling-executive-summary/

chains, where the number of intermediaries is reduced, can allow for private sector investment of cold chains, similar to that of milk. In the vertical coordination of dairy, the processor creates collection centers at the village level with bulk milk coolers to prevent spoilage. Aggregation is also essential for better traceability, sanitary and phytosanitary standard enforcement, certification, and quality control. Aggregation ideally can facilitate vertical coordination in value chains more efficiently, helping the private sector link backward to farms, invest in infrastructure, and incentivize diversification.

THE WAY FORWARD

Efficient harvest and postharvest management are critical for preventing FLW and ensuring food safety at the farm and household levels, thereby playing a crucial role in meeting hunger, poverty, responsible consumption, and food safety. Technological focus to aid harvest and postharvest loss in perishable commodities will help diversify and improve commercialization. **Table 4.2** looks at the harvest and postharvest characteristics that influence technological adoption in perishable and nonperishable commodities. Variations in economic risk, monitoring intensity, cost of storage, and transportation differentiate capital and knowledge intensity for technological intervention. Specialized storage, logistics, and allied services in perishable value chains also present nonfarm employment growth opportunities. For nonperishables, technological interventions can be cost-efficient, innovative, low-tech interventions in passive dryers, and safe, moisture-free storage systems. For perishables, however, addressing economic risk, monitoring intensity, and cost of storage and transportation is critical to ensuring smallholder participation.

Table 4.2: Harvest and postharvest characteristics that influence technological adoption in perishables and nonperishables

Characteristics	Perishables	Nonperishables
Economic risk	High risk and high return—the need for well-functioning markets	Low risk and moderate returns. Spillovers from efficient markets will aid the marketing of perishables
Cost of storage and transportation	Specialized storage and transportation systems are capital- and energy-intensive. High energy requirement—the need for energy-neutral innovations and economies of scale	Necessary infrastructures required at farm level for storage to prevent moisture and pest damage
Monitoring intensity	High monitoring and traceability requirements at harvest and postharvest are knowledge-intensive	Lower monitoring at harvest and postharvest storage, but susceptible to contamination
Nonfarm employment	Logistics, specialized storage, and allied activities require human resources, and thereby, nonfarm employment opportunities	No specialized infrastructure at the farm and transportation levels. Limited skilled employment opportunities

Specifically, the main concerns requiring attention are:

- Diversification to higher value agriculture is a high risk—high return proposition. With the right market incentives and sufficient infrastructure to limit FLW, the risks can be reduced. Well-functioning markets with low transaction costs, while increasing participation, will encourage a private sector response in the harvest and postharvest space.
- Cold storage is energy- and information-intensive, increasing the cost of use and the produce. Economies of scale can reduce the high fixed costs in storage, and transportation is essential. Aggregation through FPOs and vertical coordination, whereby retailers buy directly from farms, can reduce smallholder costs when the distance to markets is considerable. Concomitantly, innovation in energy-efficient, small-scale cooling technologies can rectify scale problems.
- Infrastructure for connectivity is a public good and the responsibility of the state. In contrast, technological interventions, as private goods or club goods, will be the private sector's responsibility. Public–private partnership (PPPs) for developing cold chains can reduce risks and improve participation, especially in lagging regions where private sector participation and vertical coordination initiatives are limited.
- Logistics, cold chain management, monitoring, and the emergence of allied activities around value chains create nonfarm employment opportunities in rural areas. Targeting youth and individuals, such as intermediaries displaced through value chain integration, for these jobs can prove essential.

5 • NEW MARKET PLATFORMS AND TECHNOLOGY TO IMPROVE SMALLHOLDER PARTICIPATION

While the farm-to-agricultural market link is the last step in the commercialization process, the intent to participate in markets influences almost all decisions, such as seeds, the nature of farm inputs, and harvest and postharvest practices. Agricultural markets, in which farmers sell their surplus produce in line with consumer demand, incentivize commercialization. Well-functioning agricultural markets have two fundamental functions: one, to signal the demand for goods to producers, and two, to enable smallholders to respond to demand through reduced market frictions in the form of transaction costs. Despite changing demand for food driven by urbanization, population growth, and income growth, the farm sector has not responded adequately. Smallholder production systems in India are disadvantaged in regard to economies of scale and liquidity constraints, influencing small farmers' decisions to participate in markets. When the surplus volume is low, marketing costs, low bargaining power, search costs in finding suitable buyers, and factors such as inadequate information and connectivity, will add to smallholders' cost of market participation or transaction costs. Reducing these transaction costs is critical for smallholder commercialization and response to changing demand, with resulting welfare gains at the household level.

In the past two decades, alternative platforms to traditional agricultural markets have emerged in Indian agriculture. Commodity futures platforms, warehousing systems, and most recently, electronic markets are examples of such platforms with the potential to reduce transaction costs and increase smallholder participation. Commodity futures provide farmers with alternative markets to sell their produce while hedging some of their risks related to price fluctuations. In commodity futures, a producer or aggregator can agree to sell agricultural produce at a predetermined fixed price at a future date and a designated location to a buyer. In recent years, commodity futures through farmer producer organizations (FPOs) are being tried out in various parts of India, allowing for better price discovery and reduced transaction costs (Rajib 2015). Negotiable Warehouse Receipt (NWR) systems, in which farmers can store their grain in warehouses and use their receipts to access short-term loans, can improve credit access and enhance bargaining power (Shalendra et al. 2016). Commodity futures and receipt systems are more conducive for growers of nonperishables, such as grains, pulses, and oilseeds.

Electronic markets, as virtual spaces where buyers and sellers interact, have revolutionized e-commerce for goods and services globally. For agricultural commodities, electronic platforms enable the seller to position their graded and standardized agricultural produce on an electronic platform on which buyers from anywhere in the country can bid for the crop. Based on the final bid, farmers are paid electronically, and the product is stored in the market for collection by the buyer. In principle, electronic markets are suited for marketing perishables, reducing information asymmetry and transaction costs, such as bargaining and search costs, as their grades, standards, and prices are objectively determined. The Indian government launched the e-National Agricultural Market (e-NAM) initiative in 2016 to link all agricultural markets in a state, and eventually, the whole country under one unified agricultural market. Despite the policy push and setting up of electronic platforms, the uptake and integration of these platforms have been less than optimal and have concentrated on nonperishables.

Two integral factors are essential for the implementation of alternative markets. First is the institutional environment, consisting of laws, rules, and regulations for the emergence of these markets. Second, systems, infrastructure, and technology reduce information asymmetry and allow for uptake and increased participation. In the first part of this chapter, we discuss the challenges of the institutional environment in agricultural marketing and how they influence smallholders' market participation. We will look at markets in the context of the farm bills of 2020 that removed market restrictions, which will allow for the emergence of a unified market platform. In the second part of this chapter, we will look at the technological interventions to reduce information asymmetries and connectivity disadvantages and improve bargaining power critical to increased participation. Agricultural market reforms and progress in information communication technology (ICT), made possible by mobile phone penetration and cheap data availability, creates conditions rife for interventions to improve information access and market participation.

AGRICULTURAL MARKETS, SMALLHOLDER PARTICIPATION, AND CONDITIONS FOR ALTERNATIVE MARKETS

Agricultural marketing in India takes place through the Agricultural Produce Marketing Committees (APMCs), regulated by the Agricultural Produce Markets Regulation (APMR) Acts formulated during the 1960s. As agriculture is regulated by both the state and central governments, APMC laws differ from state to state. Until 2020, there have been no significant reforms in the APMC laws. During the economic reform period in the early 1990s, as the economy was liberalizing, direct reforms in the agricultural markets were mostly absent. While changes in the World Trade Organization's (WTO) Agreement on Agriculture (AoA) and liberalization of the seed sector, and removal of restrictions on foreign direct investment (FDI) in organized retail sales were taking place, the agricultural sector and agricultural marketing, particularly, was left untouched. This section looks at the crop and location specificities of transaction costs and technology's scope to address them.

CROP SPECIFICITY OF AGRICULTURAL MARKETING

The AMPC Act, under the jurisdiction of various states where the AMPCs were enacted (some states do not have APMCs), mandated farmers to sell their produce to designated markets in their locality to traders and buyers registered in the local APMCs. The Acts granted a marketing monopoly to the state, preventing private investment in agricultural markets and restricting farmers from making direct contact with any processor or manufacturer through strict regulations. While the intent was to protect farmers, over the years, it made farmers dependent on intermediaries, financiers, and other intermediaries that became increasingly powerful (Narayanan 2020). Furthermore, highly fragmented supply chains with many intermediaries led to marketing malpractices (for example, poor weighing practices and no grades or standards), low price realization, and insufficient signaling. Intermediaries mean an average of four to six transactions occur before the product reaches the final consumer (Chand 2012; Pingali et al. 2019). For higher margins at each intermediary level, transaction processes were opaque, and traders showed oligopsonistic behavior through collusion to keep buying prices low (Banerji and Meenakshi 2008; Abraham and Pingali 2021).

The regulated market worked in the post-Green Revolution period when grains needed to be procured from farmers by the state for grain reserves and distribution in the Public Distribution System (PDS). Regulated markets also allowed the central government to impose restrictions on the storage and movement of certain crops through the Essential Commodities Act (1955) to prevent hoarding and provide minimum support prices (MSPs) to farmers, thereby incentivizing production. For commodities other than food grains, the APMC market conditions have been limiting. **Table 5.1** depicts the difference between the marketing of nonperishables (especially, food grains and pulses) and higher value agricultural products. Higher value commodities are highly differentiated, requiring capital-intensive infrastructure and systems to ensure food safety and standards and storage facilities much different from food grains (Pingali et al. 2019). Not many APMC, especially in remote markets, have these facilities.

Table 5.1: Marketing characteristics of perishables and nonperishables

Characteristics	Perishables	Nonperishables
Market information	Highly differentiated—varieties, nutrient characteristics, and value, making information important	Not highly differentiated
Price stability	Prices can be volatile with huge seasonal variations.	Prices are relatively stable and are often supported by minimum support prices (MSPs)
Asset specificity	Higher capital investment in value chains, storage, etc., with limited transferability	Lower capital investments and better transferability of capital
Perishability	Products are highly perishable, making the timing of supply important	Can be stored for long periods and may not perish quickly
Quality, grades, and standards	Highly differentiated with large quality, grades and standard differences	Low differentiation leads to minimum grades and standards variation

Source: Pingali et al. (2019)

According to the Ministry of Agriculture and Farmers Welfare (2017), covered and open auction platforms exist in only 66% of the regulated markets, drying platforms in only 29% of markets, cold storage units in less than 15% of the markets, and grading facilities in only 22% of the markets. Only half the APMC markets had proper weighing facilities. Despite having inadequate facilities, APMCs collect market fees, ranging between 0.30% and 2.0% of each product's sale value. Also, commission charges vary from 1% to 2.5% in food grains and 4% to 8% in high-value crops, like fruits and vegetables (Ministry of Agriculture and Farmers' Welfare, 2017, 36). In addition to these mandatory charges, other charges, such as purchase tax, weighing charges, and labor charges, must also be paid. In some states, the total charges sometimes reach a level of about 15%, to be borne by the farmers (Chatterjee and Kapur 2017; Ministry of Agriculture and Farmers' Welfare 2017). Infrastructural inadequacies, information asymmetry, and high marketing costs disincentivize market participation. These conditions are especially stark for higher value agricultural products and perishables.

LOCATION-SPECIFIC CHALLENGES OF AGRICULTURAL MARKETS

The crop-specific factors influencing transaction costs and marketing are further accentuated by location-specific challenges, inadequate marketing facilities, and connectivity. The geographical distribution of agricultural markets in India is highly skewed. The principal wheat- and rice-producing belt of northern India has a higher density of agricultural markets than other regions. According to the *State of Indian Agriculture, 2015–16*, the area served by each regulated market among the large states varies from 116 km^2 in Punjab to 11,215 km^2 in Meghalaya (Directorate of Economics & Statistics 2016). The average coverage of an APMC market in India is currently 496 km^2, much larger than the National Commission on Farmers' (2004) recommended coverage of 80 km^2, reflecting the inadequacy of marketing facilities.[5] In a study of agricultural markets in Punjab, Bihar, and Odisha, Chatterjee et al. (2020) found that farm location in relation to market determines the price farmers receive for their produce. The study found that farmers in remote locations received lower prices due to costlier transportation and the buyer's exertion of monopsonist power, knowing that farmers have limited selling options.

The National Sample Survey (70th round) found market participation varies by crops and states (**Table 5.2**). In the agriculture-led states of Punjab and Haryana, wheat and rice sales in markets are high. Direct procurement by the state and high market density enable higher market participation. In all other states and in many other crops, the rate of market participation is low. Transaction costs at the market level, resulting from insufficient information, low bargaining power, high transportation costs, and increased marketing costs discourage market participation. Smallholders sell to intermediaries at farm gate, often at the lowest competitive price (Abraham and Pingali 2019).

Regional variations in market and transport infrastructure affect transaction costs. The two states of Punjab and Haryana, accounting for more than 20% of the country's total regulated markets, face lower costs and market connectivity risks. These farmers generally benefit from better transport, communication infrastructure, and direct government procurement of wheat and rice—hence, the farmers have relatively lower search and information costs and higher market participation for nonperishables. Where road density is low (often in lagging states), transaction costs associated with accessing markets and information tend to be high. The price that farmers receive for their produce will be net of some of these costs, thus reducing incentives to enter commercial agriculture. Farmers will not enter markets when the value of participating is outweighed by the costs of undertaking the transaction, including the costs mentioned here (Sadoulet and de Janvry 1995). Therefore, farmers, usually in lagging states, will bear a higher cost of market access (Marieswaran and Kalaivannan 2017), limiting the potential to diversify to growing perishables and commercialization.

The highly regulated agricultural market structure, tuned predominantly to the procurement of wheat and rice and nonperishables, influences small farms to effectively respond to changing demand for higher value farm products through urban growth, rising incomes, and population growth. In the past, the need for reforms led to the APMC Act of 2003 to increase private sector participation in marketing and processing. Its most significant provision was permitting contract

[5] Filling up the deficit of physical markets are more than 22,000 largely unregulated Rural Periodical Markets or Grameen Haats, under the control of local bodies, panchayats, and councils.

Table 5.2: Sale of selected crops in the market and outside in various states

Crops	State Name	Extra-market sales	Market sales
Paddy	Tamil Nadu	63%	37.50%
	Andhra Pradesh	96%	4.45%
	Haryana	0%	100.00%
	Punjab	0%	100.00%
	Odisha	45%	54.52%
	Bihar	100%	0.00%
	Uttar Pradesh	66%	34.48%
Wheat	Karnataka	29%	70.57%
	Haryana	21%	78.94%
	Punjab	14%	86.21%
	Uttar Pradesh	52%	48.11%
	Bihar	90%	9.73%
	Odisha	100%	0.00%
Sorghum	Andhra Pradesh	50%	50.36%
	Tamil Nadu	92%	8.39%
	Karnataka	46%	54.35%
	Maharashtra	73%	27.22%
	Odisha	100%	0.00%
Pigeon pea	Andhra Pradesh	100%	0.00%
	Karnataka	100%	0.00%
	Maharashtra	21%	79.20%
	Tamil Nadu	100%	0.00%
	Bihar	100%	0.00%
	Odisha	100%	0.00%
	Uttar Pradesh	59%	40.67%
Potatoes	Haryana	100%	0.00%
	Punjab	69%	31.09%
	Maharashtra	74%	26.36%
	Tamil Nadu	68%	32.01%
	Odisha	91%	8.50%
	Bihar	97%	2.41%
	Uttar Pradesh	40%	60.47%
Onions	Andhra Pradesh	0%	100.00%
	Haryana	40%	60.00%
	Tamil Nadu	100%	0.00%
	Karnataka	45%	55.26%
	Maharashtra	37%	63.23%
	Bihar	100%	0.00%
	Odisha	92%	8.46%
	Uttar Pradesh	84%	15.94%

Source: Based on analysis of National Sample Survey (NSS, 70th round) data

farming. The APMCs were still in control and had to record the contract, resolve disputes, and charge marketing fees. The uptake of contract farming in India has been limited, except for a few crops such as cotton, barley, poultry, and seeds. The significant challenges have been collective action problems of forming contracts, with hundreds of small farmers in informal groups, poor contract compliance by buyer or seller with low accountability, and the limitation of procuring from the area of a particular market's jurisdiction. While the Model APMC Act of 2003 aimed to increase private sector participation in marketing and processing, the absence of real reforms to remove sales restrictions, enforceable grades and standards, and infrastructure, has made the link between farms and organized retail challenging.

ONE NATION, ONE MARKET: ELECTRONIC MARKETS AND SUPPORTING REFORMS

In principle, electronic platforms enable the seller to position their graded and standardized agricultural produce on an electronic platform where buyers from anywhere in the country can bid for the produce. When bids are finalized, payment is made electronically to farmers, and the product is stored in the market for collection by the buyer. Well-functioning electronic markets will reduce information asymmetry and bargaining costs, as their grades, standards, and prices are objectively determined. Transaction costs will decrease with the lower intermediaries and without the search cost of finding buyers. The collusion by buyers to set prices low will be reduced with high transparency in sales in the market. The resulting changes should help in price discovery and also incentivize increased commercialization in developing countries.

The Indian government launched the e-NAM initiative in 2016 to link all agricultural markets in a state and, eventually, the whole country under one unified agricultural market. Although a unified market platform (UMP) is the intention, the platform currently connects only about 1,000 AMPCs (13% of markets) in 18 states. Despite the policy push and setting up of electronic platforms, the uptake and integration to these platforms have been less than optimal. The two significant reasons that have limited the uptake of e-market uptake in India are restrictive markets and the lack of market and back-end infrastructure and systems for electronic marketing. If buyers' and sellers' market participation is limited to specific markets and locations, the linking of markets to form a UMP will not make sense.

If the movement of goods is limited through variable taxation in different states, a unified market will not make sense.[6] Similarly, if the market density is low, effective market participation options, especially in lagging states, are absent. Electronic markets will not be able to connect remote regions. The lack of back-end infrastructure for quality testing, storage, and transportation leads to low information and scope for quality and price discovery, again mooting electronic markets' functioning, as reliable price and quality information is critical for their functioning. Therefore, interventions to implement the electronic market to create a UMP are first conditioned on the institutional environment, allowing favorable policies to remove

[6] The goods and services tax (GST) law of 2017 deregulated interstate movement of goods and services by introducing a multistage, destination-based comprehensive tax that allows for more free movement of goods, including agricultural commodities. Before the GST, multiple taxes such as value-added tax (VAT), excise duty and service taxes were levied, and they differed from state to state. Moving commodities across states was problematic. In principle, GST, as a single tax bracket, frees up ambiguity of taxes and different levels.

market restrictions. Second, infrastructure and technologies allow for the emergence of systems that enable e-markets participation.

The farm bills of 2020, especially the Farmers Produce Trade and Commerce (Promotion and Facilitation) Act, 2020 (FPTC), allowing farmers to sell their produce outside any APMC is much needed for a unified market. The FPTC removes intrastate and interstate trade restrictions and enables the creation of "trade areas," where any buyer, such as corporate retail chains, processers, private traders, or agri-entrepreneurs, can buy directly from farmers without state levies. In regions where market density is low, private players can set up markets to procure agricultural commodities without relying on the state. Private markets can compete with AMPCs, allowing for effective price discovery, bring in market-required grades and standards, and build infrastructure for higher value produce marketing. Maharashtra was the first state to allow private markets in 2005–06 by issuing Direct Marketing Licenses (DMLs). Commodities like chickpea, pigeon pea, soybean, cotton, fruits and vegetables, onions, and potatoes are traded in over 58 private markets. The state government has also issued DMLs to FPOs to procure produce from farms and supply processors, thereby competing with large traders.

Table 5.3 summarizes the different phases of agricultural market evolution in India from 1950 to 2020. It is only in the last 5 years that concrete market reforms have been put in place. While removing restrictions allows a UMP emergence and can improve e-market participation, provisions for linking all e-market,c itics have also pointed out that market reforms do not address connectivity problems and small farmers' bargaining power limitations. While trade areas will benefit aggregators by freeing them from the regulations of AMPCs, increasing the bargaining power and market participation of individual farmers will require other interventions. Strong aggregation models at the farm level, technology, and infrastructure will reduce connectivity constraints and information asymmetry, allowing for price discovery and increased vital e-market participation.

TECHNOLOGICAL INTERVENTIONS TO INCREASE MARKETING OPTIONS—ELECTRONIC MARKETS AND COMMODITY FUTURES AND WAREHOUSING

Just as in harvest and postharvest practices, the marketing practices of perishables and nonperishable commodities vary greatly depending on crop characteristics. The three main factors that influence transaction costs, and differently so for perishables and nonperishables, are information availability, connectivity to markets, and bargaining power. Perishables and high-value agricultural products are highly differentiated, and their grades and standards that determine their quality vary greatly. They are susceptible to spoilage, and health and safety concerns are more pronounced than with nonperishables. These characteristics make them more information-intensive at the marketing stages, making the availability of information and access to it critical. Information availability on prices, quality, and buyers can reduce costs to the seller and improve grades and standards-based transaction and price realization.

The perishable nature of crops warrants the need for specialized supply chains. Cold storage and reefer transportation to markets if the distances are large, infrastructure such as a covered shed, and cooling storage systems to reduce FLW is critical. These processes add to the cost of marketing compared to nonperishables.

Table 5.3: Phases of agricultural market evolution in India (1950–2020)

Phase	Status and approach	Remarks
Phase I: Pre-Green Revolution period (1950–65)	Status: Deficit in food production Approach: Marketing system designed to handle the deficit, regulate trade, and manage food security.	– Improved food security through agrarian reforms and large-scale investment in irrigation and power. – Enacted Zamindari Abolition Act (1950) to organize agriculture and animal husbandry on modern, scientific lines
Phase II: Green Revolution period (1965–80)	Status: Self-sufficiency in food grains, the start of "Operation Flood" Approach: Marketing system to incentivize output and manage its distribution through procurement.	– The advent of the Green Revolution (distribution of high-yielding varieties (HYVs) – Number of essential institutions set up during 1960 and 1970 (Food Corporation of India, Commission for Agricultural Costs and Prices (CACP), Central Water Commission (CWC), and state nationalization of commercial banks – National Bank for Agriculture and Rural Development (NABARD) and Regional Rural Banks (RRBs) established – Cooperative Credit Societies strengthened
Phase III: Post-Green Revolution period (1980–91)	Status: Diversification Approach: Expansion of echnology to other produce types and regions	– Diversification toward high value produce – Focus on commercial horticulture, setting up of Coconut Development Board and National Horticulture Board
Phase IV: Economic reforms period (1991–2015)	Status: Approaching surplus Approach: Liberalization and toward greater international market access	– Improving the functioning of markets and liberalizing agriculture trade. – Model APMC Act 2003 to increase private sector participation in marketing and processing. – The signing of the Agreement on Agriculture (AoA) of the World Trade Organization (WTO) – Legalization of futures trading in agricultural commodities
Phase V: One nation, one market, one tax (2015–2020)	Status: Food secure, but the problem of plenty emerges Approach: Toward a national unified market	– Electronic National Agricultural Market – Model Agriculture Produce and Livestock Marketing (APLM) Act, 2017, allowing for – Operation of alternate markets and unified national markets – GST rollout, streamline of interstate trade.
Phase VI: Deregulating agricultural trade (2020 onward)	Status: Slowdown due to economic factors and COVID-19 Approach: Removing gluts in the agriculture sector by removing trade barriers	– Reduced oversight of APMCs in agriculture trade: Farmers (Empowerment and Protection) Agreement on Price Assurance and Farm Services Act, 2020 (FAPAFS) – Removing quantity restrictions on storage and handling of agriculture commodities: Essential Commodities Act, 2020 (ECA) – Promoting contract farming: Farmers' Produce Trade and Commerce Act, 2020 (FPTC)

Source: Adapted from Ministry of Agriculture and Farmers' Welfare (2017)

Good connectivity through roads and communication systems and the availability of markets near fields can address connectivity problems and reduce transaction costs. Bargaining power in markets is influenced by access to information, distance to markets, and perishability. Higher value crops with low storage options and high perishability have higher associated hold-up costs (Mugwagwa, Bijman, and Trienekens 2020). Similarly, smallholder producers of nonperishables face liquidity constraints for the next sowing and are subject to distress sales, at which they sell at the lowest competitive prices, reducing price realization. **Table 5.4** summarizes the various challenges of information availability, connectivity to markets, and bargaining power in perishable and nonperishable commodities that lead to transaction costs.

Table 5.4: Institutional and technology requirements for marketing of perishable and nonperishable agricultural commodities

Characteristics	Perishables	Nonperishables
Information availability	Highly differentiated products with stringent grades, standards, and safety requirements requiring reliable information. *Technology requirement:* rapid quality assessment technology for an objective price assessment. Information communication technologies (ICTs) for the dissemination of price and demand information.	Less stringent grades and standards requirement but requiring reliable price and quality information. *Technology requirement:* low tech quality assessment through physical assessment of grain and seed quality and moisture content. ICTs for the dissemination of price and demand information.
Connectivity	Distance to market and marketing infrastructure determine food loss and waster (FLW), energy requirement, and transportation infrastructure. *Institutional requirement:* roads and cold storage infrastructure investments at farm and market levels. *Technology requirement:* Specialized supply chain depending on the distance to the market. After-sales storage for buyer flexibility in collection. Virtual markets for direct purchase from farms.	Distance to market influences the fixed cost of transportation. Less vulnerable to FLW. *Institutional requirement:* roads and storage infrastructure investments at farm and market levels. *Technology requirement:* good storage facilities and warehousing.
Bargaining power	High perishability and smallholder liquidity constraints can lead to hold-up cost and increase vulnerability to distress sales. *Institutional requirement:* electronic markets and virtual platforms for the sale of perishable commodities. *Technological requirements:* ICTs for information regarding price and quality requirements.	Liquidity constraints of smallholder farmers, reducing bargaining power, and increasing distress sale. *Institutional requirement:* warehousing facilities and commodity futures trading platform and linkages through farmer producer organizations (FPOs). *Technological requirements:* quick assaying of grades to standardize produce stored. ICT technology to determine demand and prices allowing for long- or short-term hedging.

Digital initiatives, such as Agricultural Marketing Information Network (AGMARKNET) launched in 2000, currently link 7,000 APMCs for price information exchange regarding commodity arrivals and price data (Ghosh, Rajeshwor, and Vinit 2020). With mobile phone proliferation, the transmission of price data through Short Message Service (SMS) is cited as aiding smallholders in India and other developing countries (Fafchamps and Minten 2012; Aker and Fafchamps 2015; Baumüller 2015). Evidence of information improving price realization is limited, however. At the farm level, price information, without corresponding improvement in marketing systems to reduce connectivity disadvantages and bargaining power, will limit price information availability. Marketing system changes through electronic markets, commodity futures platforms, and NWR systems-conditioned technology for rapid object quality assessment can rectify information, connectivity, and bargaining power limitations in perishable and nonperishable commodities.

ELECTRONIC MARKETS AND DIGITAL PLATFORMS FOR MARKETING OF PERISHABLES

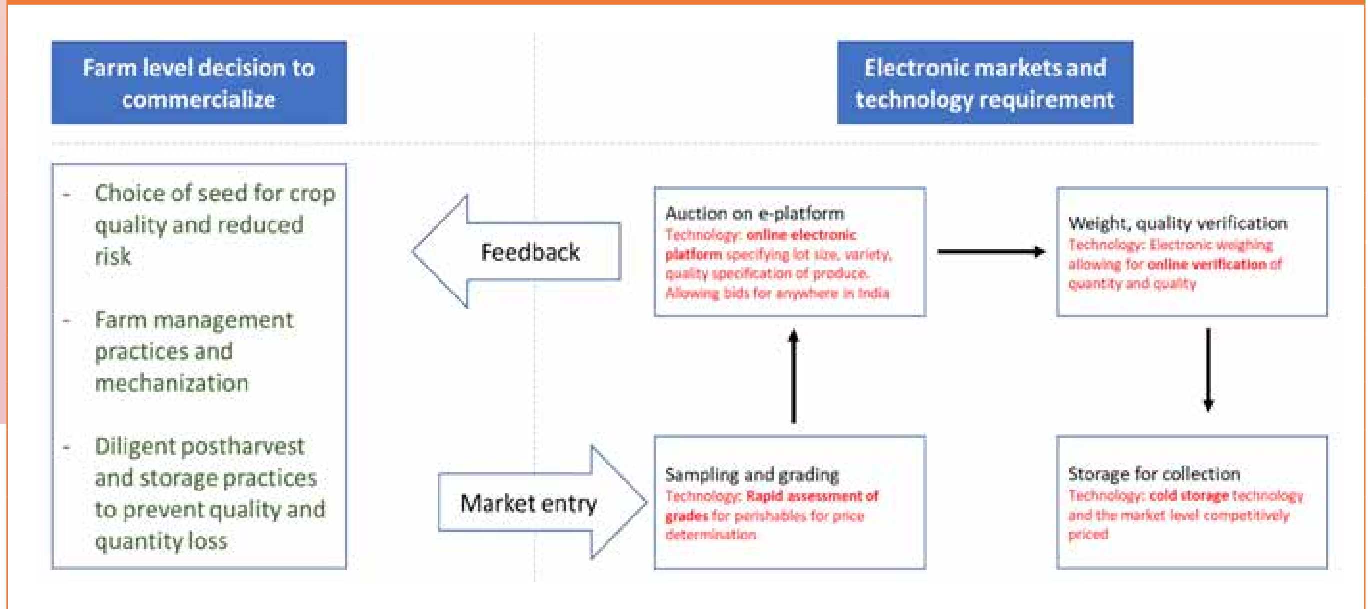
The empirical literature on the benefits and challenges of e-market platforms for developing country agriculture is still scarce. While there is a focus on creating a multitude of apps for price discovery and acquiring market information, market platform creation seems to remain within the ambit of the state in developing countries for reasons of low incentives. With the underlying physical infrastructure in place through e-NAM since 2016 and FPTC removing market restrictions to allow for a unified market, the critical challenge is to create systems and additional infrastructure to enable widespread adoption on the platform for agricultural sales development.

Karnataka's Rashtriya eMarkets Services Pvt. Ltd., (ReMS), a joint venture between the Karnataka government and the National Commodity & Derivatives Exchange (NCDEX) eMarkets Limited, was the first unified and digitized marketing platform to emerge in India in 2013. Proprietary software developed by NCDEX created the electronic platform to register entry and exit of goods, inventory, e-tendering, invoice generation, and settlement function (Aggarwal, Jain, and Narayanan 2017). Farmers reported their commodities on the platform, traders then submitted their bids online, the winning bid was determined, and the farmer was notified by SMS on the winning bid (Levi et al. 2020). Currently, 157 of the 162 APMCs in Karnataka come under this unified platform. The platform increased market bids in auctions, reduced collusion among traders and cartels, increased transparency in transactions, and reduced delays in payments compared to non-e-markets (Reddy 2017). Levi et al. (2020) found that a UMP increased modal prices by an average of 5.1%, 3.6%, and 3.5% for paddy, groundnut, and maize, respectively, but did not find significant change for cotton, green gram, and pigeon pea.

In their study on ReMS, Aggarwal, Jain, and Narayanan (2017) found that although transactions have become fast and convenient, benefits such as reduced transaction costs and increased market arrivals have not occurred. The study points out that centers for quality determination are missing in most markets; traders and farmers are skeptical about quality assessments and rely on physical verification; not all the lots are placed on the electronic platform; and most sales took place through traditional bidding. In the absence of object quality assessment, traders do not bid on lots in distant markets, and the marketing of perishables is mostly missing from the electronic platform. Opposition from intermediaries that the UMP intends to replace is also a significant concern cited in studies (Aggarwal, Jain, and Narayanan 2017; Reddy 2017; Levi et al. 2020).

Figure 5.1 depicts a scenario of unified markets that can potentially address information asymmetry and reduce transaction costs in the market. Central to electronic market functioning is the availability of technology for the rapid assaying of quality for both perishables and nonperishables. Quality assessment and listing of grades and standards on the platform allow bids to occur remotely as buyers participate remotely. Verifiable quality assessment and the corresponding price realization will provide feedback to farmers on the importance of quality for the price, giving feedback to change production practices from the choice of seeds, farm management, and mechanization, as well as diligent harvest and postharvest practices. The need for storage facilities is also critical for the functioning of electronics markets as platforms for perishable commodities. Once sold on the electronic platform, the produce can be stored for pick-up when there is an inexpensive cold storage present.

Figure 5.1: Technological needs in marketing perishables on electronic platforms



Timely reporting of objective and verifiable produce quality is central to the functioning of agricultural electronic markets. Quality criteria are usually based on a product information classification framework known as Search, Experience, and Credence (SEC) classification (Girard and Dion 2010). In traditional agricultural markets, search information is most critical and involves visual quality (for example, color, size, shape, defects) and touch (for example, firmness) descriptors. Experience and credence information is only generated once the food is consumed or later tested, respectively. Thus, this information is delayed during selection and may not be considered unless received before the next purchase opportunity.

Advances in computer vision, artificial intelligence, machine learning, acoustic measurements, and near-infrared (NIR) have emerged to aid in the low cost, non-destructive quality assessment of horticulture crops (Hidekazu 2004; Sun 2016; Yan et al. 2019; Nturambirwe and Opara 2020). Computer or machine vision utilizing digital camera technology—used to inspect electronics, automobiles, and pharmaceuticals—can detect the color, shape, size, and defects of horticulture crops (Patel and Jain 2012). The easy availability of digital cameras on smartphones makes assaying easily accessible to determine the main search or visual quality characteristics. Portable acoustic sensors that transmit an acoustic signal onto fruit, with the reflected signals captured to determine the firmness of a fruit or vegetable, is another technology used to determine ripeness and storability (Vasighi-Shojae et al. 2018).

Experiential characteristics of horticulture crops, such as fiber content, sweetness, and water content, have traditionally been hard to determine at the market level in short periods. NIR spectroscopy can now be used to assess soluble solids, dry matter, water content, acidity, fiber, crude protein, and crude fat, among others (Hidekazu 2004). Earlier NIR techniques were costly to implement, but handheld NIR devices are portable and easy to use with the advance in technology. Quality of details and standard assessments can be carried out and uploaded onto digital platforms in minutes. Rapid quality assessment helps with traceability and transmission of objectively assessed grades across markets, allowing remote participation in agricultural markets. However, along with subsystems that enable information flows in quality and price, better back-end infrastructure for storage and transportation, along with adequate policy support, can help make these markets more effective. The Farm Bills ease trade barriers and remove pricing restrictions, providing a push for electronic markets.

Although electronic markets with rapid testing facilities will allow for the reduction of information asymmetry and the resulting "lemon" problem where the absence of grades and standards leads to undervaluing of commodities due to quality uncertainties (Akerlof 1970), it may do little to address the transaction and transportation costs arising from low connectivity. Again, aggregation models in the form of FPOs play a critical role in market access. Aggregation at the farm level to jointly sell in markets will reduce transportation costs and increase bargaining power. The Farmers (Empowerment and Protection) Agreement on Price Assurance and Farm Services Bill, 2020 (FAPAFS), enabling contract farming on fair terms, can increase backward linkages by allowing contracts specifying crop quality and quantity and sale at the farm gate. The FPTC Bill, 2020, allowing farmers to sell outside the APMC, can help private electronic markets emerge, especially in regions with low market density. The presence of rapid quality assessment technologies and Internet connectivity can support entirely virtual agricultural markets. FPOs can post the quality, volume, and harvest time for bidding or negotiation with buyers. When the sale is finalized, it can be stored at the farm level for collection by the buyer.

Direct procurement from farms with and without contracts outside markets is rapidly emerging—start-ups, such as Crofarm, NinjaCart, MeraKisan, and Go4Fresh, among many others, that have captured this space. Table 5.5 lists some of the market linkage start-up that have emerged in India over the past 15 years. Since 2014, these start-ups, procuring directly from farms, have acquired over US$305 million in funding, or close to 65% of all start-up funding, in the agriculture technology space (Inc42 2020). Go4Fresh, for example, operates through a network of farm collection centers that are responsible for coordinating with smallholder farmers directly procuring their produce. Buyers, such as export companies, resellers, grocers, supermarkets, and individual retail customers, can place their orders on the Go4Fresh platform, and produce will be delivered to them within two days. The predetermined buying and selling contracts help Go4Fresh limit its inventory and minimize losses. The farmers are assured of payments in their bank accounts immediately or within 15 days, according to the nature of the transaction (Tinsley and Agapitova 2018). The procurement start-up space is most prominent in Maharashtra and Karnataka, which had reformed its marketing laws to allow for sale outside the APMC. They are also primarily concentrated in high potential areas or areas close to urban markets with high connectivity. The spot markets will remain an essential method of sale in low potential areas.

Table 5.5: Market linkage start-ups in India and their locations of functioning			
Company	Estd. year	Total funding raised (in $ mn)	Presence
Waycool	2015	19.6	Tamil Nadu, Karnataka, and Telangana
Origo	2010	10.9	15 states
NinjaCart	2015	198.5	Tamil Nadu, Delhi, Gurugram, Maharashtra, Karnataka, and Telangana
Go4fresh	2013	undisclosed	Maharashtra
Ecozen Solutions	2010	1.9	Maharashtra, Chhattisgarh
FarmLink	2014	3	Maharashtra
Crofarm	2016	2.7	Maharashtra, Karnataka, National Capital Region, Delhi
MeraKisan	2016	N/A	14 States
Aker Foods	2019	0.095	Maharashtra
Farmers Fresh Zone	2015	0.9	Kerala
Kisan Network	2015	3.49	16 states
SuperZop	2016	1.21	Maharashtra

Source: INC42: India's Agritech Market Landscape Report (2020), company websites and reports

COMMODITY TRADING ON FUTURES EXCHANGES AND WAREHOUSING OPTIONS FOR NONPERISHABLES

A futures contract is one in which a producer or aggregator agrees to sell their produce at a predetermined fixed price at a future date and a designated location to a particular buyer. Commodity exchanges are platforms on which futures contracts are made, enforced, and traded through licensed brokers as derivatives. India banned futures trading in 1966, but reintroduced commodity derivatives trading in 2002–03. Unlike in spot markets, there are no transaction costs or risks resulting from hold-up, high search costs, or low bargaining power. Prices are agreed upon and locked. Hedgers cover their price risks and encourage competition from other traders who possess market information and price judgment (Mishra 2008). Linking farmers to future markets allows for efficient price discovery and hedging risks at planting time and has worked well in China, a small farm-based agricultural system (Chatterjee, Raghunathan, and Gulati 2019). Profit and loss from the commodity increasing or decreasing in value is borne by the buyer, while the seller remains protected.

Currently, the major commodity exchanges are the National Spot Exchange Limited (NSEL), Indian Commodity Exchange Limited (ICEX), Multi-Commodity Exchange (MCX), NCDEX, National Multi-Commodity Exchange of India Ltd. (NMCE), Ace Derivatives & Commodity Exchange Limited and Universal Commodity Exchange (UCX), among others. NCDEX, the largest commodity exchange in India, works with 246 FPOs with 4.6 lakh farmers in 13 states and 17 nonperishable commodities (NCDEX 2019). While FPOs form just a minute fraction of the NCDEX commodity trading, measures to increase participation are being carried out. Using case studies, Chatterjee Chatterjee, Raghunathan, and Gulati (2019) found that in addition to a poor understanding of how futures markets work, risk aversion leading to the reluctance to hedging, infrastructural constraints, and low quality to be the main barriers. The absence of grading and sorting facilities at the farm level resulted in producers not meeting the quality required and a high rejection rate of commodities. As farms and FPOs are diverse and dispersed, a limited number of delivery centers also limit futures market adoption. As FPOs are the only mechanism through which farmers can participate in the futures markets, the management and competence of FPOs also determine the linkages to futures markets.

Alternatively, for nonperishables, the warehouse receipt system is another instrument that has been cited for increasing smallholder bargaining power and improves their access to institutional credit (USAID 2013; IFC 2015; Shalendra et al. 2016). An NWR is a certified warehouse document stating that a specific commodity of a certain quantity and quality has been stored by the farmer for the receipt holder. When a regulatory authority legitimizes the receipt system, it becomes a derivative or a financial instrument that can be traded or used as collateral (Miranda, Mulangu, and Kemeze 2019). Low village-level storage and liquidity constraints for small farms necessitate the sale of crops immediately after harvest, often when prices are the lowest, to finance the next cycle of sowing and for repayment of credit or household budgetary requirements. An NWR can ease liquidity constraints, improving bargaining power and price realization.

Since the passing of the Warehousing (Development and Regulation) Act 2007 and the government's efforts to increase participation in warehouse receipt systems, farmer participation has been low. Since 2011–12, the cumulative value of commodities stored under NWR has been valued at 6,200 crores, and the loan disbursement against these receipts has been 1,705 crores (Biswas 2020). The main reason for low uptake has been low confidence in warehouse management as storage facilities, and low signaling of quality make banks reluctant to lend against the receipt (RBI 2005; Shalendra et al. 2016). Interlocked contracts, by which traders lend money on sales conditional to them, also prevent the farmer from availing services from the warehouse receipt systems (Bhaduri 1986; Subramanian and Qaim 2011).

Efficient warehouses, where crops are sorted, graded, dried, and stored at optimal conditions, can raise service costs. If the price of produce at the sale is not higher than the cost of storage, the incentives to hold them through warehousing systems are low (Miranda, Mulangu, and Kemeze 2019). Three critical factors are necessary for the effective functioning of NWR: established and enforced grades and standards at the collection points, efficient storage systems, and well-functioning markets. Enforced grades and standards to ensure the quality of stored goods and efficient storage systems ensure minimal food loss and waster (FLW) during storage. Assurances of quality signal the validity of the derivatives, which the banks are confident of supporting. Technological requirements here are in methods to assay grades and standards quickly, and also, quality storage facilities to reduce FLW.

Electronic warehouse receipts, or e-NWR, was launched in 2018, and in her 2020–21 budget speech, the Finance Minister spoke about provisions to integrate e-NWR to e-NAM (Bhayani 2020). The linking of warehouses to the market allows the receipts to be traded without moving the commodities, and thus, incurring transaction and transportation costs. Central Depository Services (India) Limited (CDSL), promoted by the CDSL Commodity Repository Limited (CCRL), and National e-Repository Limited (NERL) by the NCDEX are repositories that provide e-NWR to farmers and traders, guaranteeing quality. e-NWRs allow tracking of receipts across integrated platforms and enable the trading of receipts in markets. A significant challenge that will soon emerge is getting various smallholders to buy into e-NWRs as an option. FPOs, especially in Maharashtra, have begun looking into NWR and e-NWR as options for better price realization and bargaining power.

THE WAY FORWARD

Alternative market platforms can increase smallholder commercialization and allow for better response to changing demand for diverse agricultural products. The farm bills have brought about much needed reforms in the institutional environment of agricultural marketing—the most significant the agricultural sector has seen. The laws make up the farm bills—The Farmers (Empowerment and Protection) Agreement on Price Assurance and Farm Services Bill, 2020 (FAPAFS) enabling contract farming on fair terms; FPTC allowing farmers to sell their produce outside the APMC and in any market in India. The Essential Commodities (Amendment) Bill, 2020 (ECA) removed stocking limits on traders in numerous commodities. Collectively referred to as the Farm Bills, the reforms aim to bring sweeping changes to agriculture markets, predominantly structured around staple grain marketing. They will remove interstate trade barriers, encourage direct farm-to-business supply chains through contract farming, and remove agricultural commodity storage restrictions. The Farm Bills together aim to lower entry barriers for new-age social enterprises, organized retailers, and farmer producer organizations (FPOs), and thus, reduce transaction costs for farmers by directly connecting them to end buyers. The main points form the discussion going forward are:

- Electronic markets, commodity futures trading, and NWR systems are not new institutional arrangements. However, for smallholders to access these platforms, institutional and technological innovations will be critical in reducing transaction costs.
- FPTC will allow private markets to function side-by-side to APMC, turning the emphasis to competing markets that provide the best services for farmers. However, to truly reduce transaction costs, the need for high-tech infrastructures, especially in rapid quality assessment, traceability, and storage of perishable commodities, is needed.
- Technology intervention in rapid quality assessment is critical for marketing perishables. Currently, e-markets market only nonperishables due to constraints for grades and standards determination. Infrastructure and systems of quality determination need to be implemented and enforced for the market to diversify.
- While the FPTC has had limited influence in reducing small farm connectivity to markets and the related transaction costs, FAPAFS strengthens provisions to encourage contract farming. Vertical coordination, by which retailers and processors can directly buy from producers, can reduce marketing costs. Again, the need for quality determination and cold storage will help lagging states that are distant from markets.
- For nonperishables commodities, futures trading platforms and NWR systems are options to improve bargaining power and reduce transaction costs. Technology to mitigate farm-level risks and enhance produce quality and infrastructure to collect produce from farms is critical. With NWR, the introduction of e-NWRs, tradable on electronic markets, will be a significant boost to marketing perishables as it can reduce bargaining, transportation, and search costs. The removal of stocking restrictions under the ECA will be critical in enabling this increase in marketing.
- The market linkage segment in the agricultural technology start-up space is the most sought after. Since 2014, start-ups procuring directly from farms have acquired over $US305 million in funding, or close to 65% of all start-up funding in the agriculture technology space, mainly in states with reformed markets that link producers directly to consumers. Government investment in infrastructure for connectivity and other public goods is required for a high private sector response, especially in lagging states.

6. INTEGRATED APPROACHES TO TECHNOLOGICAL INNOVATIONS IN INDIAN FOOD SYSTEMS

As India becomes a nation of 1.51 billion people by 2030, its ability to ensure its citizens' food security will hinge on the ability to feed an additional 150 million people and improve the diets and food access of over 189 million people who are currently food insecure. Additionally, India is urbanizing fast, and with it, food preferences are changing. As incomes rise with urbanization, food demand is moving from staple grains to higher value, nutrition-rich horticulture and animal-based products. The challenge for the Indian food system is to increase production, improve the quality of food, and at the same time, limit the impact productivity, growth, and diversification will have on the environment.

Technology has played a central role in helping economies achieve food security and economic development through intensification. The Green Revolution of the 1960s and 1970s is considered the watershed of technological advancement for Indian agriculture and global food security. The introduction of high-yielding varieties (HYVs) in wheat and rice helped increase yields exponentially, pulling India out of a frame of low productivity, low surpluses, and vulnerability to chronic food shortages in the wake of weather-related risks. In 2020, India had grain surpluses of close to 74 million tons, about two times more than is required. Yet, the paradox of "hunger amidst plenty," as reflected in India's current malnutrition figures, is a stark reminder of the food security challenges ahead.

While the Green Revolution helped achieve food security in a caloric sense, it had limitations. The technologies were limited to major staple crops of wheat and rice, conditioned on high rainfall or irrigation infrastructure. This meant wheat-growing and rice-growing regions with access to irrigation could benefit from the gains, while other regions lagged. Other nutrient-rich crops, such as coarse grains and pulses, were mostly orphaned as the infrastructural, market, and subsidy support focused on major staples and major staple-growing regions. Injudicious use of resources, such as water and inputs, and intense monocropping also led to environmental externalities, land degradation, and water table depletion. Furthermore, regions that the Green Revolution benefited and the regions that diversified into cash crop production achieved poverty reduction. In contrast, the regions that did not benefit from agricultural development saw lower poverty reduction rates and high and persisting adult and child malnutrition levels, comparable to less developed countries in sub-Saharan Africa.

DRIVERS OF TECHNOLOGICAL CHANGE IN INDIAN FOOD SYSTEMS

Technology has again come to the forefront of achieving food security. However, deviating from the Green Revolution's modus operandi, the focus and the challenges have expanded. While increasing yields remain critical, diversification to more nutritious crops and reducing the environmental impact becomes other vital elements to new food security approaches. Acknowledging the Green Revolution's limitations, scholars and scientists have looked at comprehensive strategies that incorporate seed and farming system technologies to achieve intensification while limiting environmental impacts. Centered around the idea that cultivation systems are not separable from ecosystems that situate them, various approaches referring to this embeddedness are described as an evergreen revolution (Swaminathan 2000), agroecological intensification, green food systems (Defra 2012), agroecological intensification (Garbach et al., 2017; Milder et al. 2019), doubly green revolution (Conway 1997), greener revolutions (Snapp et al. 2010), among others. In this report, we used the term sustainable intensification (SI) (Royal Society 2009; Pretty and Bharucha 2018), as we explored the methods and technologies at farm management levels to enable SI.

This report takes SI beyond production and environmental sustainability to look at the supply side of the food systems—from seed and farm management systems to harvest and postharvest and agricultural market systems—to assess the food systems' SI. The emphasis on technologies beyond the farm to the supply side is critical, as seed development and farm management systems influence harvest and postharvest systems, and commercialization and market linkages incentivize production, and practices changes. We identify four main drivers of technological innovation as:

- Environmental challenges and food systems intensification
- Shift from producer orientation to consumer orientation
- Scale disadvantages of smallholder production systems
- Changing private and public sector roles in agriculture

ENVIRONMENTAL CHALLENGES AND FOOD SYSTEMS INTENSIFICATION

The environmental challenges for intensification come from the fact that the agricultural sector influences and is influenced by climate change. Intensification of production is resource- and knowledge-intensive, putting pressure on land and water resources and raising emissions as energy requirements at the production and value chain stages increase. Agriculture is a large emitter of greenhouse gases such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). Agriculture contributes 18% of India's total emissions, and rice and livestock production contribute to 36.9% and 38.9% of greenhouse gases (GHGs), respectively, by way of anaerobic and enteric fermentation (Vetter et al. 2017). While the impact of rising temperatures on staple grains is well studied, less is understood about its effect on other crops, such as millets and sorghum and more nutritious foods, such as fruit, vegetables, pulses, and livestock products (Pingali et al. 2019).

Climate change impacts food and nutrient availability in multiple ways. It can reduce agricultural yields and livestock productivity and increase production uncertainty. Climate change can affect the quality of natural resources, soils, and water, reducing the quality of nutrients in crops. Production uncertainty and crop loss will also lead to price volatility, especially in nutrition-rich perishable crops, accentuating malnutrition problems in economically and socially vulnerable populations. Addressing challenges of climate change is integral to safeguarding crops and livestock production and achieving nutrition security. Climate change will adversely affect rainfed and semi-arid regions exposed to agroclimatic risks (IPCC 2014), and the lagging states in India are the most vulnerable.

Technological innovations are critical for developing adaptation and mitigation strategies to increase the resilience of food systems (**Table 6.1**). Chapter 2 discussed the importance of genetic gains to improve crop tolerance to biotic and abiotic stress, increase nutrition content of food crops, develop biological nitrification inhibition (BNI), and enable early maturation to minimize resource use. Improving the capacity of the National Agricultural Research System (NARS) to deliver higher genetic gains remains vital. Technologies to implement SI methods, such as conservation agriculture (CA) and community-based watershed, tank irrigation, and watershed management practices, are essential adaptation and mitigation strategies at the farm. Farm as a Service (FaaS) provisions for information, extension, and mechanization services through information communication technologies (ICTs) are vital technological interventions to support small farm adaptation of these practices and ensure information dissemination. Reducing food loss and waste at postharvest and marketing stages is integral for food security. Rising temperatures and increased length of value chains make energy-efficient cooling, drying, storage, and transportation systems essential to connecting farms to markets and reducing food loss. As cooling and drying are energy-intensive, net-zero cooling and drying strategies, using renewable energy and efficient insulation for storage and transport will be areas of innovation. As cooling needs increase, energy requirements in cold chains will increase with potential externalities. Therefore, innovations in cold chains to improve energy efficiency and cost-effectiveness will require technology and institutional strategizing.

Table 6.1: Innovations for climate change adaptation and mitigation

	Adaptation Strategies	Mitigation Strategies
Plant Breeding Systems	– Genetic gains to develop crops with biotic and abiotic stress tolerance; early maturing crops that potentially use fewer resources; crops with higher nutrient content	– Developing seeds with biological nitrification inhibition (BNI) traits
Farm Management	– Technology for the conservation of resources—drip irrigation, community-based conservation practices – Information systems through information communication technologies (ICTs), allowing for predictive modeling and early warning systems to aid farm-level decision making	– Farm management strategies for smallholder agriculture – Conservation agriculture practices aided by Farm as a Service (FaaS) models for information, mechanization, and extension service
Harvest, Postharvest, and Marketing	– Energy-efficient cooling infrastructure at farm levels to reduce food loss and waste (FLW) due to high temperatures – Storage of nonperishables to prevent contamination, moisture damage, and loss.	– Net-zero cooling and drying systems – Efficient reefer transportation systems – Advanced insulation innovations to reduce energy use and enable passive cooling

The impact of climate change on the food system and its contribution to climate change determines adaptation and mitigation strategies and technological innovation. Hand-in-hand, policy changes are needed to create an enabling environment for innovation. Policy incentives for clean energy investments and climate smart-infrastructure, along with the removal of lopsided subsidies on inputs, such as nitrogenous fertilizer and energy, will support, supplement and incentivize technological innovations for climate-smart agriculture. The India Cooling Action Plan (ICAP) following the Kigali Amendment of 2016 is an essential step for sustainable cooling solutions. Innovative, cost-effective, and accessible solutions for India's cooling needs in agricultural value chains are urgent. As for removing subsidies, political will and capital are required as any elimination of benefits will meet resistance.

FOOD SYSTEMS SHIFT FROM PRODUCER ORIENTATION TO CONSUMER ORIENTATION

In the past few decades, India has been witnessing rapid urbanization, with growth in megacities and smaller towns and district towns. Along with urbanization and corresponding income growth, diets are also transitioning as consumer preferences diversify away from traditional staples, such as wheat and rice, toward nonstaple foods, such as fruits, vegetables, and livestock products, and from *quantity* to *quality*. The National Sample Survey Organization (NSSO) consumption survey shows a steady decline in the monthly expenditure of cereals and cereal products in the Indian diet from 41% in the 1970s to just over 10% in 2012–12 in rural areas and 23.4% to 6.6% in urban areas during the same period. The diversification of diets to higher value agricultural products has provided new growth opportunities for rural India to provide for growing urban consumption needs. The growth opportunities from diversification to higher value horticulture and livestock products are conditioned on small farms' ability to access market information, quality inputs, meet the required grades and standards of consumers, and access markets through reduced transaction costs.

During the Green Revolution, technology transfer and diffusion led to productivity increases, poverty reduction, and rural development in agriculture-led and urbanizing states. These technologies were producer-oriented and focused on high-yielding variety (HYV) adoption to increase wheat and rice yields in high potential areas with irrigation infrastructure or higher rainfall levels. The "grow more" approach to early agricultural development disregarded supply chains and urban food demand until urbanization and income growths led to the rise of supermarkets, emerging to cater to the changing demand (Reardon and Timmer 2014). In 2019, modern food retail sales in India from supermarkets and hypermarkets grew12%. Although online grocery sales in 2019 were only 5% of total organized grocery retail, they grew by 27%, and sales are expected to grow to 18 billion from the current US$1 billion by 2024.

Harnessing the new growth opportunities means leveraging technological innovations to (1) access quality inputs, information, and extension services; (2) manage resources and risks associated with higher value crops; (3) adopt harvest and postharvest practices to reduce food loss and waste; and (4) minimize transaction costs and information asymmetries to access markets. Increased focus on lagging states, which did not benefit from the Green Revolution and development of technologies, to address production and marketing challenges in these states becomes critical. Table 6.2 summarizes the deviation of new technological approaches from the Green Revolution era for a supply revolution. Technology to aid farmers at the farm level make better production decisions, such as what, when, and how to grow, is vital for optimal output. Information and extension services for diversification becomes critical to reducing risk and improving the quality of the produce. Farm services for mechanization and aggregation are also essential for high-value crops.

At the harvest, postharvest and marketing levels, diversification will bring a drastic change to practices and procedures that may require new infrastructure, knowledge, and information. Mechanization of harvesting of nonperishables and adequate drying facilities is critical for food safety and reduced loss at the farm, household, and market levels. However, with perishables, especially when markets are distant, cold storage and cold chain infrastructure to preserve quality and prevent loss are required. Investment in quality determination technology at the farm level for direct marketing and the market level to reduce information asymmetry will be essential to incentivize diversification and increase price realization. Chapter 5 discusses the various quality determination technologies necessary for the effective marketing of perishable commodities.

Table 6.2: Innovations for demand-driven agricultural growth

Domain	Innovations
Information communication technologies (ICTs) and farm management approaches rectify information intensity	– Technologies to improve aggregate-level data on adoption rates, climate risks, sowing estimates – Farm as a Service (FaaS) models to improve access to mechanization services, information, and input service delivery – Reduce production risk and improve quality of products to meet standards required by the markets
Harvest and postharvest interventions to reduce food loss and waste through net-zero cooling and drying	– Farm service delivery for mechanized harvesting of nonperishables – Cold chains for coordinated picking, storage, and transportation of perishables – Dryers for practical preservation of nonperishables and value addition for perishables
Market access by smallholders through reduced transaction costs	– Technology for the rapid assessment of quality in perishables to improve participation in alternative value chains – Increase sales of perishables on electronic platforms – Increase smallholder participation in commodity futures platforms and warehousing systems.

A tangential shift away from the production-side technology approach will require a change in the policy focus on staple grains and calories, which are remnant of the Green Revolution, toward a market and consumer-oriented approach. Input delivery and farm-level services to support diversification are emerging in the agricultural technology start-up phase. Commercialization, in line with the rapid growth in organized retail in India, will give rise to nonfarm employment opportunities in rural areas, supporting urban-facing agribusinesses that provide back-end aggregation, logistics, storage, and labor support in value chains (Pingali et al. 2019). Market reforms to increase private sector participation, reduction of connectivity constraints through adequate infrastructure, especially in lagging states, and the emergence of farm services will be critical for diversification and linking rural growth to urban growth.

SCALE DISADVANTAGES OF SMALLHOLDER PRODUCTION SYSTEMS

Higher value agricultural products are highly differentiated, requiring higher labor, monitoring, technology, and credit inputs than staple grains. Diversification to higher value crops increases production costs, management inputs, and risks at the production level and specialized storage and transportation at the postharvest and marketing levels due to their high perishability. Economies of scale disadvantages constrain smallholders' ability to access credit, high-quality inputs, information, and technology to diversify and produce for the changing demand and to access specialized value chains. Small farms do have an advantage of higher per capita productivity than large farms due to higher labor utilization, using family labor, and higher input utilization using intensive farming practices, and lower monitoring costs (Sen 1966; Bardhan 1973; Binswanger and Rosenzweig 1986; Eastwood, Lipton, and Newell 2010; Hazell et al. 2010; Poulton, Dorward, and Kydd, 2010). However, small farms are disadvantaged in accessing markets, credit and extension services, technical knowledge, and technology, along with lumpy inputs such as management and asset-specific machinery that are not scale-neutral (Johnson and Ruttan 1994; Hazell et al. 2010; Poulton, Dorward, and Kydd 2010). The small farm productivity advantages, therefore, disappear for commercialization purposes.

At the household level, the capacity of small farms to diversify depends on behavioral characteristics, such as levels of risk aversion and the ability to withstand and manage those risks, access infrastructure, and technology, such as farm machinery, irrigation, and inputs, including credit and quality seeds, fertilizer, and pesticides (Pingali et al. 2019). High information costs, low education levels, and scale-specific disadvantages in the form of inadequate access to capital put small farms at a disadvantage in accessing technology and market participation (Foster and Rosenzweig 2010; Feder, Just, and Zilberman1985; Barrett 2008. Barrett et al. 2019). Higher value agriculture production can benefit from higher resource utilization and better monitoring advantages of small farms, if disadvantages in accessing factor and product markets and technology are rectified. The success of Green Revolution technologies can partly be attributed to the fact that small farms could adopt scale-neutral HYV technologies in areas with favorable agroclimatic conditions and complementary institutional support. In the wake of new technological approaches to meet current food systems challenges, innovations in service delivery that can rectify the problems of scale and institutional innovations in aggregation models will be critical.

ICT advantages—through mobile phone connectivity in rural India that allows for the information and knowledge transfer with certain levels of scale neutrality, and for access to input services, precision agriculture and monitoring technologies, cold storage, and cold chains and markets—require aggregation. Aggregation models can rectify high capital requirements for infrastructure and high fixed costs of transportation and marketing, as well as high monitoring and adherence costs of vertical coordination and contract formation to small farms. In lagging states, collective actions for natural resource management, such as water user groups, watershed management groups, and agroforestry initiatives that have precedent in India, remain relevant and increase SI and technological transfers.

Table 6.3 summarizes innovations at the farm, harvest, postharvest, and markets level to rectify smallholder access problems. At the farm management level, start-ups are emerging that provide services tailored to small farms. Custom hiring centers where smallholders can access types of machinery such as tractors, direct sowing machines, and sprayers can increase mechanization access. ICT through mobile phone and data connectivity in rural India has made it possible for information and knowledge transfer with certain levels of scale neutrality. Access to input services, precision agriculture and monitoring technologies, cold storage, and cold chains can be made more readily available through ICT-enabled services. Farm as a Services is rapidly emerging in the start-up space with custom packages for information, extension, and input service requirements for small farms. These services can help smallholders bypass investments in capital-intensive equipment, and reduce search costs to small farms in accessing extension services and information that will allow them to make better farm-level production and marketing decisions. Models of aggregation through FPOs and services are needed to rectify scale disadvantages at the harvest, postharvest, and marketing levels. Services that can facilitate joint drying and cold storage at the village level can reduce food loss and waste.

Table 6.3: Innovations to rectify scale disadvantages for smallholders

Domain	Innovations
Farm Management	– Custom hiring centers for mechanization – Information communication technology (ICT)-based information dissemination leveraging social media – Farm as a Service rectifying scale disadvantages and reducing the cost of extension service access.
Harvest and postharvest	– Joint drying facilities – Aggregated cold storage facilities
Market access	– Village-level cold storage systems linked directly to the buyer – Quality determination technologies in warehouses for efficient participation in negotiable warehouse receipts and futures market platform – Technology for rapid determination of quality in perishables for reduced information asymmetry and increased e-market participation

For an individual farmer, the capital investment for drying and cold storage facilities is exorbitant; drying and cold storage services for rent will emerge as an opportunity for farmers and entrepreneurs. Access to alternative marketing platforms, such as future markets, negotiable warehouse receipts, and electronic markets require reduced information asymmetry through rapid, objective quality determination. Chapter 5 discusses the technological innovations in rapid quality assessments at the market and storage levels that can reduce information costs, increase smallholder bargaining power, and increase market participation, especially in higher value crops.

FPOs as aggregation models by which smallholders jointly access technology, other inputs, and markets are cited to improve market access and reduce transaction costs (Boselie, Henson, and Weatherspoon 2003; Reardon, Barrett, Berdegué, and Swinnen 2009; Schipmann and Qaim 2010; Bellemare 2012; Briones 2015). In lagging states, where the penetration and incentives for Farm as a Service (FaaS) models and other services are low, FPOs can be instrumental in bringing FaaS model services, aggregated storage, transportation, and marketing services to their members. Supporting FPOs, improving their capacity to adopt technological and provide information services to their members, can emerge as a viable business model, improving their viability. The government has provided a significant push for the promotion of FPOs since 2014. Using FPOs as a vehicle to disseminate technology will be a critical step in improving smallholder viability.

CHANGING ROLES OF THE PRIVATE AND THE PUBLIC SECTORS IN AGRICULTURE— CREATING ENVIRONMENTS FOR INNOVATION

The role of the state was quite central to the uptake of Green Revolution technologies. HYV for staples was created as an international public good by CGIAR and adapted to Indian conditions by NARS. Policy for subsidies, favorable market access, and procurement was put into place to ensure incentives adoption, collection, and distribution. Since 1991, private sector investments in the agricultural sector saw exponential growth. As a proportion of agricultural GDP, private sector investment in research and development (R&D) grew from 4% in the 1980s to 13% in 2013 (Ferroni and Zhou 2017). Public sector investment as a proportion of agricultural GDP in 2013 was 2%. Despite the shifting of scales toward increasing private investments, the public sector is critical agricultural R&D, creating institutional environments to incentivize food system innovations.

Investments in the following segments remain squarely in the ambit of the public sector. (1) R&D in crop technologies for self-pollinated crops, including staple grains, pulses and livestock; (2) information systems for collating satellite and weather and climate-related data; and (3) creation of public goods such as critical infrastructure for communications and road connectivity. Private sector investment in public goods is absent, as returns to investments are negligible. However, the state's public good creation and enabling policy environment can facilitate private sector response in building public–private partnerships (PPP) and investments in R&D and infrastructure in food systems. PPPs are long-term agreements between the government and a private partner, in which the partner funds and delivers public goods or public services (Nielander 2020). Different developed and developing countries use PPP models in which governments access finance, share risk and technology and enable business development for economic growth (Bayliss and Van Waeyenberge 2018; Uddin and Akter 2021). When upfront costs of projects are high, private sector finance and expertise are used, and the costs are eventually recovered through user fees or taxes (Kwak, Chih, and Ibbs 2009).

Table 6.4 highlights the different domains of the private and public sectors and areas where there can be convergence for PPP, such as joint breeding programs for nutritionally relevant crops, like staples, coarse grains, and pulses, in which the public sector shares investments and genetic material and the private sector contributes technology and procedures. The creation of infrastructure to store perishables, cold storage facilities, and cold chains is another area for PPP investments. At the market level, private and public markets can coexist, allowing for competition and better delivery of services. The private sector can deliver services, especially in quality determination, traceability, and storage in public markets, to market higher value agricultural products.

PPP's have also shown to crowd-in investments from the private sector through the created infrastructure and resources (Spraul and Thaler 2020; Uddin and Akter 2021). In the postharvest and market levels, capital and technology-intensive services for cold storage, reefer transportation, quality determination, and establishing traceability systems are scenarios for PPPs to emerge. Agricultural markets availing private sector services for storage, transportation, quality determination, and traceability can usher in technology transfer and essential services, which the state cannot provide. The availability of such services will incentivize private investment in the supply side of the food system.

Table 6.4: Public and private sectors and public–private partnerships as drivers of technological innovation

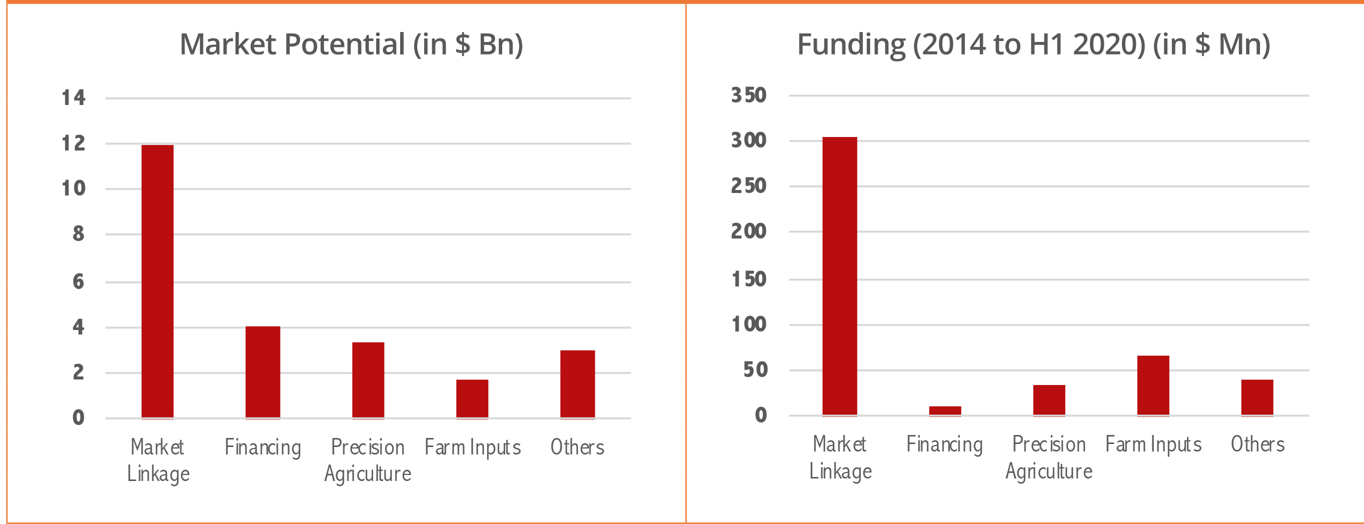
Domain	Private and public sector competence and their convergence
Modern plant breeding	**Public**: germplasm and genetic material **Private**: genomic services, breeding technology, and methods **Public–private partnership (PPP)**: joint breeding programs for nutritionally relevant crops with lower commercial value
Farm management	**Public**: Data and communication infrastructure for satellite and weather-related data. Location-specific extension knowledge through state agricultural universities (SAUs) **Private**: information and service delivery platforms
Harvest and postharvest	**Public**: Policy support, tax breaks to incentivize investments **Private**: Investment in storage, cold storage, and cold chains **PPP**: storage infrastructure for public utilization using private capital.
Markets	**Public**: Agricultural Produce Marketing Committees (APMCs) and electronic market platforms **Private**: private market platforms, vertical integration, and direct farm-to-retail linkages **PPP**: Private sector providing cold storage, quality determination, and traceability systems in public markets

The institutional environment characterized by policy regimes regarding market regulations, price determination, procurement, and infrastructure influences investment and innovation responses in the food system's supply side. The farm bills of 2020 deregulate agricultural markets, allowing for the emergence of unified national markets, which will in turn allow for greater market participation and investments in the food system's supply side. The agricultural technology (agritech) space comprises technology firms delivering services in market linkage and farm inputs, precision agriculture and farm management, quality management and traceability, postharvest and supply chain technologies, and financial services. Currently, the sector has attracted $US454.5 million, a fraction of its agritech market potential (EY 2020). **Figure 6.1** shows the segment-wise market potential of agritech through addressable market opportunity to be US$24 billion. The total market opportunity, according to EY, is close to US$170 billion (EY 2020).

Figure 6.2 shows that agritech investments are highly skewed in favor of Maharashtra, Karnataka, Tamil Nadu, Delhi, and Bihar. In terms of agritech funding by location, Karnataka (Bangalore) start-ups makes up 55% of the financing, and Maharashtra, Tamil Nadu, and Karnataka make up 80%. Thirty-five percent of the start-up hubs are located in Karnataka, and 7 % of all hubs are located in Maharashtra, Karnataka, and Delhi. Among the start-up market linkages, start-ups that directly produce from farmers make up the majority of start-ups. Maharashtra, Karnataka, and Tamil Nadu are states with more liberal Agricultural Produce Marketing Committee (APMC) laws, where the states' sales restrictions are done away with. Bihar does not have an APMC law allowing for direct procurement from the farm or private markets.

The food system's supply-side revolution hinges on responding to consumer demand and shifting the focus from solely production orientation outlook under the Green Revolution, rectifying economies of change challenges of technological access and changes in the public sector role, as well as increasing private sector participation. Food systems are interlinked, and with a supply side highly responsive to the demand changes, consumer behavior change, and activism can redirect supply

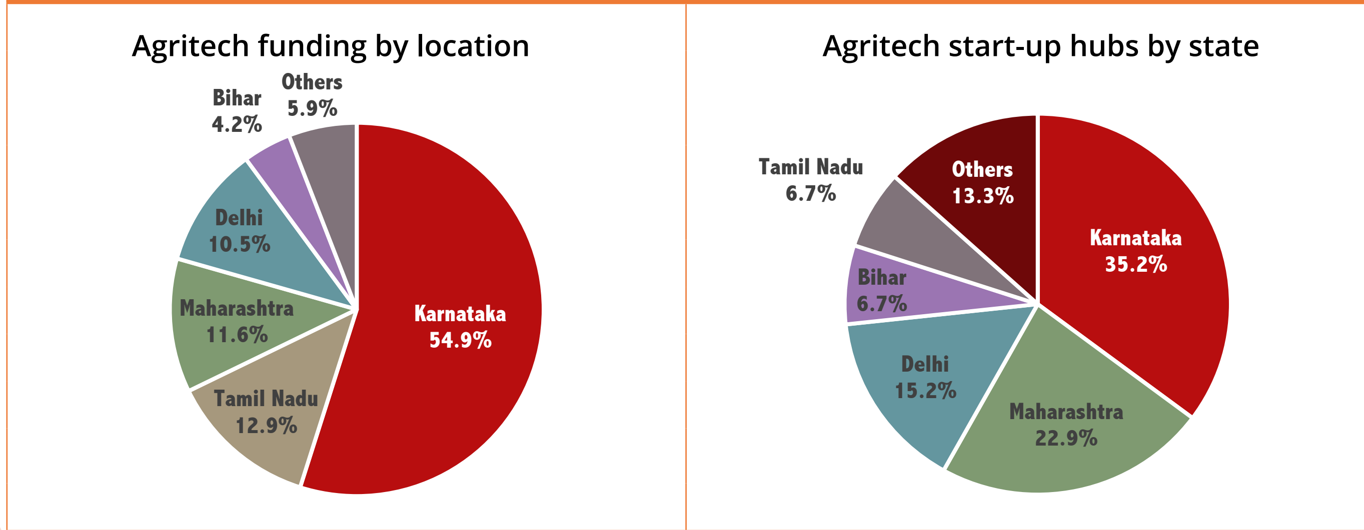
Figure 6.1: Segment-wise funding and market potential of agritech



Source: EY (2020) and Inc42 Plus Analysis (2020)

in the food system. In developed and developing countries, the emerging markets for organic foods, activism for the ethical treatment of animals, and the increasing demand for plant-based meats result from the agricultural sector and food processing industry responding to demand and innovating to ensure supply. The emerging problems of obesity in agriculturally developed states and urbanizing states through changes in consumption, resulting from changing demand and a shift toward consuming processed foods, require behavior change communication interventions in both urban and rural areas. A demand-responsive food system will respond to shifting demand for healthier foods with changes at the farm, market, food processing, and food business levels. Technology will continue to play a role in the supply side, and an improved institutional environment through freer markets is vital for a synchronized food system.

Figure 6.2: Spatial distribution of investment in agritech by state



Source: Inc42 Plus Analysis (2020), based on disclosed funding until H1 2020

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