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Agricultural Technologies in India: A Review

P K Joshi and Deepak Varshney

दृष्टि

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सहभागिता, संधारणीयता और समानता पर आधारित
वित्तीय और गैर–वित्तीय सहयोगों, नवोन्मेषों,
प्रौद्योगिकी और संस्थागत विकास के माध्यम से समृद्धि
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Promote sustainable and equitable agriculture and rural development through participative financial and non-financial interventions, innovations, technology and institutional development for securing prosperity

NABARD Research and Policy Series No. 5/2022

भारत में कृषि तकनीक: एक समीक्षा
Agricultural Technologies in India: A Review

पी के जोशी, दीपक वार्ष्णेय
P K Joshi and Deepak Varshney

NABARD

आर्थिक विश्लेषण और अनुसंधान विभाग
Department of Economic Analysis and Research
राष्ट्रीय कृषि और ग्रामीण विकास बैंक, मुंबई
National Bank for Agriculture and Rural Development, Mumbai

Agricultural Technologies in India: A Review

National Bank for Agriculture and Rural Development

Office Address
National Bank for Agriculture and Rural Development
Plot No. C-24. 'G' Block, Bandra-Kurla Complex
Bandra (E), Mumbai - 400051
Email : dear@nabard.org
Website : www.nabard.org

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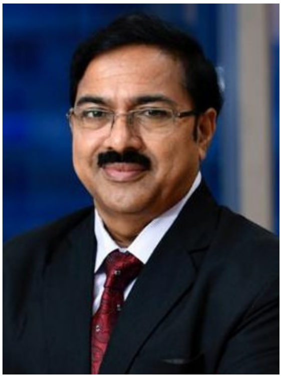
Chairman's Message



Academic research can inform policy making. However, since each piece of research may cover certain aspects of an issue, a comprehensive review of research may help collate the findings that may lead to policy recommendations. Further, the research available may be often very technical and less communicative to the policy makers. NABARD commenced the "Research and Policy" series to commission review papers on various themes to bring research findings on a given theme in a capsule form.

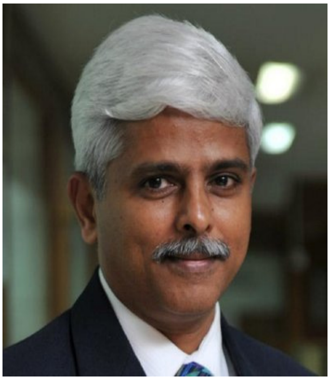
With this series, veteran scholars in different fields of specialisation have been requested to document research in their field highlighting various issues, policy relevance and prescriptions, and suggestions for future research. I am glad to present the paper on "Agricultural Technologies in India: A Review" by Dr. P. K. Joshi who has been an authority on the subject. Dr. Deepak Varshney has co-authored the paper.

The series will present more such authoritative papers on various issues ranging from climate change to agricultural policy in the coming months. I hope that series will be beneficial to academicians, researchers and policy makers for use at the ground level.

My best wishes to the authors and the Department of Economic Analysis and Research (DEAR) for initiating such a wonderful series.

Dr. G. R. Chintala

Foreword



There is a vast body of research available on topics related to agriculture and rural development in the academic world. But, most of it is in the technical realm and not in a form which could feed into the policy. Research must first lead to better understanding of a subject and then into a robust policy, wherever it can, so that it touches the multitude of Indians across the length and breadth of our country through better public policy and efficient services. Discussion with my colleagues on this issue leads to this new series "Research & Policy". We wish that this series will provide the breadth and depth of research into an area topped up by a lucid presentation for the policy makers.

I am happy to present the fifth publication in this series on "Agricultural Technologies in India: A Review" written by Dr. P. K. Joshi and Dr. Deepak Varshney.

I wish this new series acts as a bridge between the researchers and policy makers.

P. V. S. Suryakumar
Deputy Managing Director

Preface

Agriculture sector proved a silver lining in the pandemic period registering a positive growth in the covid times. Yet it faces various structural challenges to be addressed to make it profitable. For, the majority of the population is still dependent on the sector. As we all know, investing in research is one of the best strategies to address problems of agriculture. Equally important is to communicate the research findings to policy makers to design and tweak policies that matter. During one of our meetings with Shri P. V. S. Suryakumar, our DMD, we had loud thinking if we can commission a few review papers on a select themes. We thought that it is appropriate to request veteran scholars who spent prime of their life on a given research theme to attempt such a work where they will distil their understanding and the research done on the theme in a short paper. Duly encouraged by DMD and Chairman, we wrote to a dozen eminent scholars. And the response was overwhelming resulting in Department of Economic Analysis and Research (DEAR), the research wing of NABARD, initiating the 'Research and Policy Series'. The motivation is, thus, to get a few handles from research that can help effective policy intervention. This series will be useful to policy makers and researchers alike.

The 'Research and Policy' series is an attempt to get a glimpse of hardcore research findings in a capsule form thereby making it more effective and communicative to policy makers. The group of researchers who agreed to prepare a review of research have spent their life in the field of agricultural research. Our purpose here, as we communicated to them, was not just to get literature survey but to get researcher's heart and their experience which they gained during their long passionate innings. The paper is expected to highlight various issues, policy relevance, prescription, and suggestion for future papers on the themes of interest to NABARD.

Throughout history, technological innovations have had a significant impact on agriculture. At a time when policy debates are still centred on the agricultural sector's low and stagnant income, the current paper on 'Agricultural Technologies in India: A Review' written by Dr. P. K. Joshi, former Director, South Asia, International Food

Policy Research Institute (IFPRI), Washington D.C. and Dr. Deepak Varshney, Assistant Professor at the Development Planning Centre, Institute of Economic Growth, New Delhi, assumes importance. Dr. Joshi and Dr. Varshney have a distinguished academic career, with research interests in technology policy, market and institutional economics.

This paper aims to analyse the level of adoption pattern of different technologies, as well as the constraints in scaling up these technologies across various commodities, and geographies. It goes on to highlight key conditions for the successful adoption and implementation of agricultural technologies, and how these technologies have impacted farmers' income, natural resource management, input use efficiencies, employment generation, and so on. The paper uses cross-country evidence to demonstrate how investments in agricultural research and development have enormous potential; it also impresses on the rate of return on investments in various agricultural sectors. Finally, the authors discuss how the agricultural research policies should be taken forward to address emerging agricultural challenges. Overall, the paper provides readers with food for thought.

In bringing this series as planned, we would like to express our sincere gratitude to Dr. G. R. Chintala, Chairman, NABARD for his inspiring leadership, unstinted support and guidance. We also wish to express our sincere thanks to Shri P. V. S. Suryakumar, DMD, for being the inspiration and the driving force behind the publication of this first of its kind series. We are grateful to the authors of this series who agreed to write on themes relevant to NABARD in such a short period of time. Indeed, it has been a great privilege for us.

I also acknowledge the contributions of the officers of DEAR, NABARD especially Dr. Ashutosh Kumar, DGM; Mrs. Geeta Acharya, Manager; Ms Neha Gupta, Shri Vinay Jadhav, Assistant Managers, and others who coordinated with the authors and the editor to bring out the series as envisaged.

Thanks are due to Dr. J. Dennis Rajakumar, Director, EPWRF and his team for their contribution in copy editing and bringing uniformity to the document.

K. J. Satyasai
Chief General Manager
Department of Economic Analysis and Research (DEAR)
NABARD, Mumbai-400051

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P. K. Joshi
Former Director
South Asia - International Food Policy Research Institute
New Delhi

Deepak Varshney
Assistant Professor
Development Planning Centre
Institute of Economic Growth
New Delhi

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Abbreviations

ARI	Acute Respiratory Infection
ATMA	Agricultural Technology Management Agency
CCAFS	Climate Change, Agriculture and Food Security
CGIAR	Consultative Group on International Agricultural Research
CSA	Climate Smart Agriculture
DEAR	Department of Economic Analysis and Research
DNA	Deoxyribonucleic Acid
FAO	Food and Agriculture Organization
FPO	Farmer Producer Organisation
GDP	Gross Domestic Product
GIS	Global Information System
GM	Genetically Modified
GPS	Global Positioning System
GVA	Groos Value Added
HYVs	High Yielding Varieties
ICAR	Indian Council of Agricultural Research
IPCC	Inter-Governmental Panel on Climate Change
IRRI	International Rice Research Institute
IT	Information technology
KCC	Kisan Credit Card

(Contd.....)

Abbreviations *(Concluded)*

KVK	Krishi Vigyan Kendra
LLL	Laser Land Levelling
MSP	Minimum Support Price
MSSRF	M S Swaminathan Research Foundation
NABARD	National Bank for Agriculture and Rural Development
NAFED	National Agricultural Cooperative Marketing Federation of India
NARS	National Agricultural Research System
NATP	National Agricultural Technology Project
NPK	Nitrogen, Phosphorous and Potassium
PDS	Public Distribution System
R&D	Research and Development
SAUs	State Agricultural Universities
T&V	Training and Visit
TFP	Total Factor Productivity
TNPFP	Tamil Nadu Precision Farming Project
WTP	Willingness To Pay

Executive Summary

Agriculture sector in India is a primary source of livelihood for a majority of the population. Low and stagnant income in the sector remains a focal point of policy debate in India. The most prominent pathways to enhance farmers' income is the adoption of improved agricultural technologies. This study documents the current state of agriculture technologies in India. The main objectives are: (a) What are the adoption levels of improved technologies and their impact on farmers' income, agricultural production, natural resources and environment? (b) What are the constraints in up-scaling improved technologies and the conditions for success of their adoption? (c) What are the rate of return on agriculture research and extension system? and (d) What can be learnt from the global perspective on agriculture research and extension services?

The study includes the technologies related to: (i) genetic enhancement, (ii) natural resource management, (iii) farm mechanisation, (iv) conservation agriculture, (v) climate smart agriculture, (vi) biotechnology and genetic modification, (vii) biofortification, (viii) frontier technologies, and (ix) digital technologies. It shows that the adoption of improved technologies varied across technologies, commodities and geography. Adoption of improved technologies have shown an unambiguous positive impact on agricultural productivity and agricultural production. More specifically, these have had an impact on increasing farmers' income, income diversification, conserving natural resources, improving input use efficiencies, generating employment opportunities and promoting diversification. At the same time, defective policies and incentives have led to degradation of natural resources, especially a fall in water table and deterioration of soil health. Demand and supply side factors, such as extension, credit, human capital, technology traits, institutional barriers and enabling environment, play a crucial role in the adoption of improved technologies. Small and fragmented size of land holdings, the education level of the farmers, access to knowledge systems and availability of irrigation also determine adoption of improved technologies. Therefore, land consolidation through institutional reforms, connecting farmers with technology delivery systems and markets, and strengthening agricultural credit system are to be addressed for a faster and wider adoption of improved technologies.

Recent studies on agriculture extension highlight the salient role of targeting based approaches, including social networks, for the faster adoption of improved technologies. There is a need to connect farmers in a network mode with a targeted approach by taking farmers' aspirations and needs. It is suggested that the social networking should be a part of the strategy for promoting improved technologies. The study also notes that a perfect symphony is needed amongst technology traits, policies, institutions and infrastructure for the accelerated adoption of improved technologies.

The study highlights key conditions for the successful adoption and implementation of improved agricultural technologies, which includes an effective agriculture extension system, access to credit, human capital and direct benefit transfers. To enable small and marginal farmers for easy access to information and credit, the role of public sector programmes such as Krishi Vigyan Kendras (KVKs) and the Kisan Credit Card (KCC) scheme are crucial. Education and skill development matter for all aspects of technological interventions starting from the choice of technology to its appropriate implementation. Social safety nets such as PM-KISAN can play an instrumental role in providing assistance to marginal and small farmers to improve the investment capacity of farmers to achieve the long-term goals of farmers' welfare.

Investment in agricultural research and extension significantly contribute to increasing productivity and agricultural growth in India. For instance, the recent studies on the returns of frontline extension system reveal a very high benefit-cost ratio of 8 to 12. But the agriculture spending in agricultural research and extension in India is much lower compared to the neighbouring and competing countries, especially China. This largely explains the slow agricultural growth in the country compared to China. The cross-country evidence highlights that the investment in the agriculture research and development have a huge potential in gaining the marginal returns. Therefore, there is a need to strategize the investment in agriculture research and extension to generate and disseminate improved technologies to different agro-climatic regions.

Emerging challenges, such as climate change, degradation of natural resources and undernourishment, need a different approach and higher research resources. It appears that future agricultural research would be more capital intensive, which would require modern tools, infrastructure and upgraded skills. Next-generation technologies, such as climate smart agriculture, frontier technologies and digital agriculture, require a different approach in technology generation and their dissemination. There is a need to reform the agricultural research and extension system by allocating more financial resources, improving capacity of human resources, creating an enabling management structure, promoting multi-disciplinary and multi-institutional research, strengthening public-private partnership, and developing appropriate research infrastructure.

Agricultural Technologies in India: A Review

1. Introduction

India is home to 1.3 billion people, and globally ranks second in terms of the agricultural output. The agriculture, forestry and fishing sector accounted for 16.4% of the gross value added (GVA) in 2021. In contrast, the sector is serving as a primary source of livelihood for more than 50% of the country's population. Low and stagnant income across these sectors remains a focal point of policy debate in India. These sectors accounts for the majority of the poor of the country. Recent estimates show that about 220 million people are poor in India. One of the most prominent pathways to enhance farmers' income is the adoption of improved agricultural technologies. The literature reveals that adoption of improved technologies is the key to increase agricultural productivity and farmers' income (Matushcke *et al.* 2007; Subramanian and Qaim 2009; Duflo *et al.* 2011; Mason and Smale 2013; Kumar *et al.* 2020. Despite a very strong impact on the well-being of farmers, the adoption of improved technologies is low, especially in the context of developing regions and countries.

Both demand and supply side factors play a crucial role for the adoption and diffusion of improved agricultural technologies. Demand side factors include awareness and knowledge about technology, access to credit and relevant inputs, risk implications and marginal returns (Feder *et al.* 1985; Besley and Case 1993; Morris *et al.* 2007; Barrett *et al.* 2010; Duflo *et al.* 2011; Kumar *et al.* 2017; Varshney *et al.* 2019a). Supply side factors include policy support, investment in agricultural research and extension system, availability of infrastructure, and institutional arrangements for the delivery and benefit sharing of technologies. A perfect blending of demand and supply side factors accelerate the penetration rate of improved technologies for achieving desired outcomes. In India, the public sector agriculture research system is primarily responsible for the development and dissemination of improved technologies. With the passage of time, the private sector is gradually contributing to developing and marketing of improved technologies. Delivery of improved technologies through agricultural extension mechanisms play a key role in their up-scaling and out-scaling. In fact, agricultural extension system addresses demand side factors such as awareness creation, risk reduction and proficiency improvement (Babu *et al.* 2013; Gulati *et al.* 2018). All these factors are significant in the widespread adoption and dissemination of improved technologies.

There is considerable literature on the adoption of agricultural technologies in India varied by the type of technologies, crops, natural resources and specific contexts, such as pest and disease management (Chakravarti 1973; Prahlachadar 1982; Hazal and Ramasamy 1991; Evenson and Gollin 2003; Munshi 2004; Jat *et al.* 2006; Varma and Namara 2006; Spielman *et al.* 2013; Veettil *et al.* 2021). The present study is a compilation of most of the studies addressing various types of improved technologies. In particular, the study provides a comprehensive review on adoption of improved technologies, their adoption processes, conditions for their successes and their economic, social and environmental impact. It is in this backdrop that the present paper responds to the following questions:

(1) What are the adoption levels of different technologies and their impact on farmers?

(2) What are the constraints in adoption of improved technologies and the conditions for their success?

(3) What is the rate of return of agriculture research and extension systems?

(4) What lessons can be drawn from the global experiences?

The paper is organised as follows. The second section of the paper documents the status of adoption of improved technologies, and their impact by crops and type of technologies. The third section presents the conditions for the successful adoption of agricultural technologies. The fourth section investigates whether India is investing enough in agricultural research and the development of agricultural technologies? This section compares the investment in agricultural research and extension with that in other countries. Moreover, the section studies the returns to the investment in agriculture research and extension systems. The fifth section documents the lessons learnt from the international experiences and attempts to identify the best practices in agriculture research and extension systems globally. The paper ends with conclusions and policy implications.

2. Agricultural Technologies in India: Adoption and their Impact

This section provides an assessment of the agricultural technologies in India. Our review includes the technologies related to: (i) genetic enhancement, (ii) natural resource management, (iii) farm mechanisation, (iv) conservation agriculture, (v) climate smart agriculture, (vi) biotechnology and genetic modification, (vii) biofortification, (viii) frontier technologies and (ix) digital technologies. We explore the adoption of such technologies through the lens of identifying adoption barriers, and how the adoption of such technologies impacted the agriculture sector, farmers' welfare, natural resources and the environment.

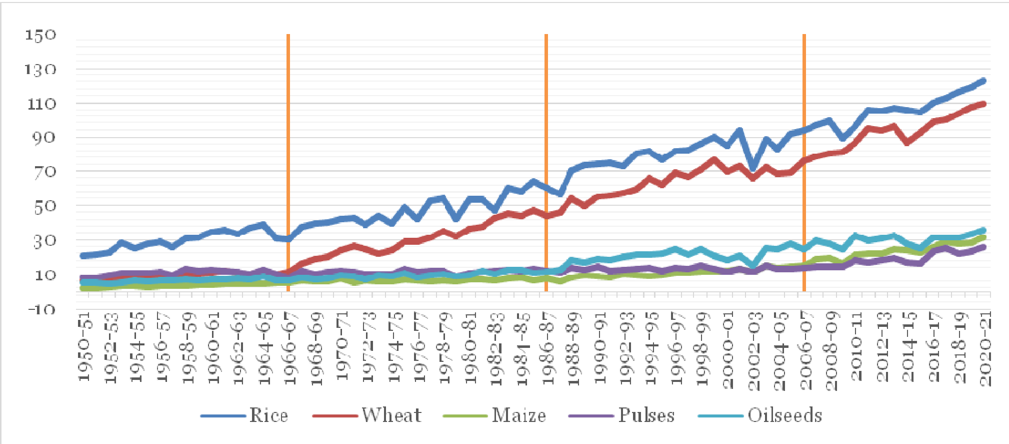
2.1 Genetic Enhancement

Genetic enhancement research in major agricultural commodities has received the highest priority in India. Over the years, the genetic enhancement research addressed different challenges in different phases: (1) yield enhancement, (2) resistance against biotic and abiotic stresses, (3) product quality improvement, (4) adapt and mitigate climate change, (5) fortification of nutrients, and (6) genetically modified commodities. The research efforts yielded positive dividends in terms of ensuring food security, increasing incomes of farmers, reducing poverty, generating employment opportunities and enhancing export of agricultural commodities (Joshi *et al.* 2005).

(a) Adoption Patterns of Key Technologies

Evolution of genetically improved technologies started significantly with the Green Revolution through the introduction of dwarf and high yielding varieties (HYVs) of rice and wheat.[1] Their yield potential was much higher than the traditional varieties. Later, the technological progress has been to (i) develop resistance against various biotic and abiotic stresses, (ii) reduce length of growing season and crop duration, (iii) improve quality traits for better tastes and prices, and (iv) build resilience against climate change. During the early phase, rice variety IR-8 and the semi-dwarf HYV of wheat HYV (Kalyan Sona and Sonalika), were introduced for the large-scale adoption by the farmers.[2] Adoption of improved varieties, especially of rice and wheat, increased rapidly; their area increased by 57% and 83%, respectively, between 1967-68 and 1984-85 (Duraisamy 1989). Prior to the breakthrough of the Green Revolution, India was deficit in rice and wheat, and dependent on imports and foreign aid. The situation has turned around with the advent of dwarf and HYVs of rice and wheat. The rice production, which was less than 30 million tons (mt) prior to 1966-67 increased dramatically and reached to 121.46 mt in 2020-21. The corresponding increase in production of wheat has been from 11 mt to 109.5 mt (Figure 1). This has

Figure 1: Trends in Production of Foodgrains and Oilseeds (in Million Tons)



Source: Ministry of Agriculture and Farmers Welfare, *Agriculture Statistics At a Glance*, Government of India, New Delhi, Various issues.

been possible due to a perfect symphony between technologies, effective policies, innovative institutions and required infrastructure. The quantum jump in production, led by improved varieties, enabled the government to launch various social safety-net programmes for poor and food insecure population. These include the subsidised ration to the poor under the public distribution system (PDS). At present the 'National Food Security Act' covers about 65% of the population of the country with subsidised rice and wheat. Even during Covid-19, the government provided free rations (rice or wheat) to 65% of the population initially for eight months in the first wave and then extended it till November 2021. This was possible due to the massive increase in production and availability of sufficient buffer stocks of rice and wheat.

In rice, the research efforts to improve the yield potential of the traditional basmati variety has also paid high dividends to the farmers as well as government. The improved 'Pusa Basmati' gives yield of 4.0 metric tons per hectare (mt/ha) over 2.5 mt/ha of traditional basmati varieties, which requires 15-20 days less growing period facilitating early sowing of wheat (Kumar and Pal 2020). The improved Pusa basmati has become an important export commodity, earning roughly Rs. 18,000 crore of foreign exchange every year.

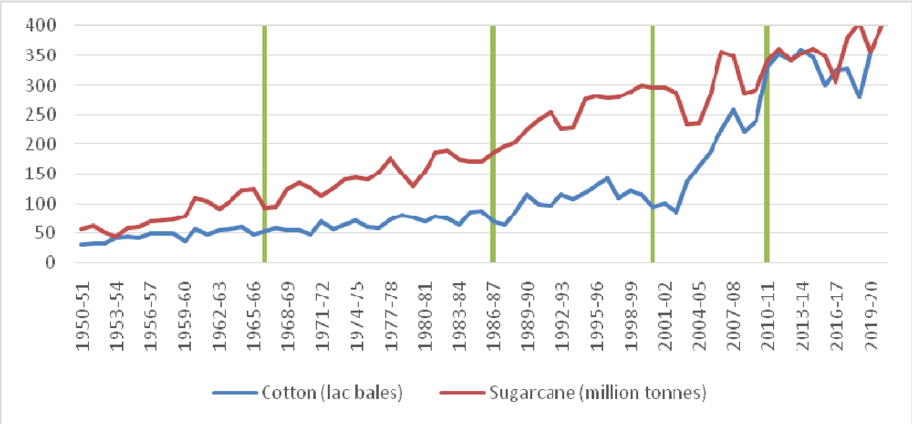
To further push the yield potential of rice, efforts were made to develop hybrids. The hybrids have shown high promise during demonstrations on farmers' fields in Eastern India. The rice productivity increased by 34% in eastern Uttar Pradesh and 24% in Chhattisgarh (Janiah *et al.* 2010). But the hybrids could not become popular among farmers due to undesirable traits for processing and for cooking purposes. Spielman *et al.* (2013) estimated that hybrid rice in Bihar was selling at a price 10%-20% lower than that of coarse rice due to quality issues. The authors also documented other constraints in adoption of hybrid rice: (i) lack of awareness and access of seeds, (ii) higher seed prices, (iii) lack of suitable land, and (iv) shortage of water. The estimates show that only 3 million hectares (ha) area is under hybrid rice, which is approximately 6.8% of the total rice area in Bihar.

Contrary to rice, hybrid maize has become a big success that completely transformed the maize sector. The transformation was from improved varieties to composites to double cross hybrid and, finally, single cross hybrids. The yields increased dramatically in different agro-ecoregions. At the national level, the average yield, which used to be less than 1.5 mt/ha till 1990s has doubled by 2020. Maize production has reached to 30 mt in 2020, which used to be less than 10 mt before 1996 (Figure 1). It was also noted that the maize cultivation also penetrated in the non-traditional areas like Andhra Pradesh and Karnataka. Such a remarkable increase in maize production significantly contributed to the flourishing poultry industry. Maize is an important source of feed for poultry and accounts for about 60% of the total maize production.

Technological change in the pulse sector is of different kind. The improved technologies initially were geared to build resistance against insects and pests. The estimates show that roughly 30% yield losses in pulses were due to infestations of insects and pests (Lal and Verma 2007). Therefore, the early research on pulses during the 1960s and 1970s were mainly to develop resistance against diseases, such as wilt, blight and root rot. Later, the priority shifted to develop varieties which can adapt to a hot and dry climate. The Green Revolution has led to an expansion in area under rice and wheat at the cost of pulses. The pulses find their new niches from north and east India to south and west India. The evidence show that pulses moved from north to south and east to west with a huge hub in central India (Joshi and Saxena 2002). For example, one-third of the total pulses production was coming from Madhya Pradesh by 2000. And, chickpea production has moved to hot and dry climate zones, which contribute more than 70% of the total chickpea production in the country (Joshi *et* *al.* 2005). Later, the research efforts were to reduce the crop duration from long to short, and extra-short duration varieties of chickpea and pigeon pea. It is astonishing that pigeon pea, which used to be grown as a long-duration crop of about 300 days, has varieties of 90-120 days duration (Singh *et al.* 1996). These varieties enabled to suitably fit them in the crop rotation and provided twin benefits of increasing cropping intensity and higher pulses production. Similarly, varieties developed for green gram and black gram find a niche in irrigated areas during the summer season. All these efforts, with appropriate government policies, led to an increase in production of pulses. Their production, which was hovering between 10 and 12 mt till 1966-67 reached to 25 mt in 2017-18. The area under pulses during corresponding years went up from 22 million ha to 29 million ha (Appendix Figure A1). Since 2016, after a steep price rise of pulses, the government launched a multipronged strategy to increase their production. These included (i) large scale demonstration of improved pulse varieties through Krishi Vigyan Kendra's (KVKs), (ii) development of pulse seed hubs for easy access of improved varieties, (iii) considerable increase in minimum support prices (MSP), and (iv) assured procurement through National Agricultural Cooperative Marketing Federation of India (NAFED). These efforts were so successful that pulse production witnessed a quantum jump of 7 mt in one year from 16 mt in 2015-16 to 23 mt in 2016-17, and further to 25 mt in 2017-18. This helped the country to become self-sufficient in pulses. Continued technological and policy efforts is likely to transform the pulse sector from a deficit to a surplus regime.

Oilseed production, which was less than 10 mt prior to 1981-82 and 12 mt in 1987-88, when government launched the Oilseeds and Pulses Mission in 1987, steeply increased to 18 mt in 1988-89 and to 24 mt in 1998-99 and, finally, reached to 36 mt in 2020-21. Such a remarkable increase in production was due to expansion in the area and yield of soybean and rapeseed and mustard (R&M). Despite the significant increase in the production of oilseeds, India is the largest edible oil importing country in the world. The momentum of technology and innovation was not sustained after the reduction in tariff rates of edible oils and import of cheap oil palm. India is importing as much as 56% of its edible oil requirement; 54% of which is the palm oil. Recently, the government launched a National Mission on Edible Oils-Oil Palm, which targets for an additional area cover of 6.5 lakh ha by 2025-26 with an ultimate target of one million ha with special focus on north-eastern states and Andaman & Nicobar Islands.[3] This would help in easing import of palm oil. However, a technological breakthrough is needed in

Figure 2: Trends in Production of Cotton (lakh bales) and Sugarcane (million tons)



Source: Same as Figure 1.

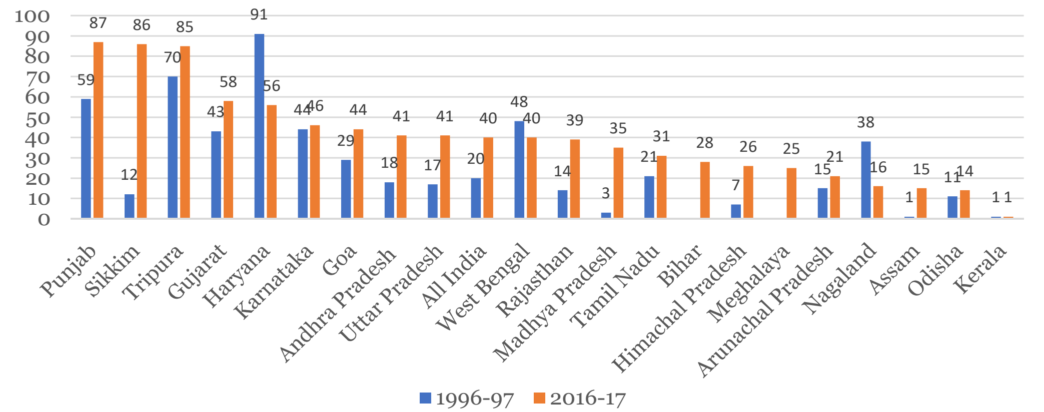
other oilseeds for increasing edible oil production. Technologies are also needed in non-traditional edible oils, such as rice bran oil, corn oil, olive oil, among others.

Cotton is another success story of improved technologies. The technological shift has been from hybrids to genetically modified varieties/hybrids. The Bt cotton, a genetically modified crop, was officially approved for commercial production in the country in 2002. This has led to a remarkable breakthrough in cotton production, more than doubling output from 13.6 million bales in 2002/03 to 37.5 million bales in 2019/20 (Figure 2). The Bt technology contributed in (i) controlling the pest infestation, especially of pod borer, (ii) reducing use of insecticides, and (iii) increasing area and production of cotton.

Sugarcane also witnessed a sharp increase in production. Its production prior to 1988-89 was less than 200 mt, which doubled to 400 mt in 2018-19 (Figure 2). The technological progress was to enhance yield, conserve water, improve management practices, reduce crop duration, and finally to improve the sugar recovery rate. The yields went up from 60 mt/ha in 1988-89 to almost 80 mt/ha in 2018-19. Studies have shown that 50% to 70% of the increase in yield has been due to HYVs (Joshi *et al.* 2005). Early maturing varieties (like Co J 64, Co C 671) have spread fast in states like Punjab, Gujarat, Tamil Nadu and Andhra Pradesh. The technological advances in improving sugar content and recovery have made a significant contribution in enhancing sugar production in the country. The higher sugar content/recovery varieties (especially Co 86032) led to production of additional 412 thousand tons sugar. The variety has additionally produced by-products of 5.43 mt of molasses and 33.6 mt of bagasse (Kumar and Pal 2020).

Several studies have been undertaken on the adoption of improved varieties of different crops. Initial trends showed a remarkable progress in the adoption of HYVs. For example, the adoption of HYVs of rice has increased to 38.8% in 1976-77 from 2.5% in 1966-67, and the corresponding increase for wheat was 72% in 1976-77 from 7% in 1966-67 (Chakravarti 1973; Prahlachadar 1982). For the period 1965 to 1994, the study by Mckinsey and Evenson (2003) estimated the adoption of HYVs, measured in terms of the percentage of the crop planted to HYVs released after 1964, and observed a significant increase in the adoption of HYVs for rice and wheat (for more details, see Table 1). These studies argued that though the HYVs were widely adopted, their adoption patterns were heterogeneous across states and farm sizes (Chakravarti 1973; Bhalla 1974; Hazal and Ramasamy 1991). In particular, the rainfed areas were not benefited much by the Green Revolution, and could not take advantage of the improved varieties initially. These studies also suggests that inter-regional inequality has widened, and this is explained by the levels of infrastructure across regions. Slowly, there was a spillover of HYVs from irrigated to rainfed areas during 1980s (Janiah 2006). One of the possible explanations of the successful spillover in rainfed areas is the expansion of irrigation facilities during the mid-1980s. Some progress in the lagging regions was witnessed, but the huge regional differences in the adoption patterns persisted. Using expert elicitation method, Pavithra *et al.* (2017) reveal that wheat varietal turnover was the highest in Punjab (7.5 years) and the lowest in Rajasthan (19.25 years). A recent study by Kumar *et al.* (2020) based on the nation-wide varietal mapping survey also found similar patterns. Using estimates from this study, we present the adoption patterns for the new paddy cultivar across states and for India in Figure 3. At the all-India level, there are only 26% farmers who are adopting new paddy cultivars, while 74% are still adopting old cultivars.[4] It shows that the highest adoption of new paddy cultivars is in Haryana (82% of all farmers) and Punjab (65%). The eastern states show a very low adoption of new cultivars. For example, only 14% farmers in Odisha have adopted new paddy cultivars, while the remaining 86% farmers are adopting old/traditional paddy cultivars. Several paddy growing states such as Karnataka, Odisha, Andhra Pradesh, Telangana, Tamil Nadu and West Bengal are lagging in the adoption of new paddy cultivars.

Figure 3: Trends in Adoption of Certified Seeds (% of All Farmers)



Notes: Andhra Pradesh includes Telangana State, Uttar Pradesh includes Uttarakhand, Madhya Pradesh includes Chhattisgarh and Bihar includes Jharkhand.
Source: Same as Figure 1.

(b) Adoption Patterns based on Secondary Data

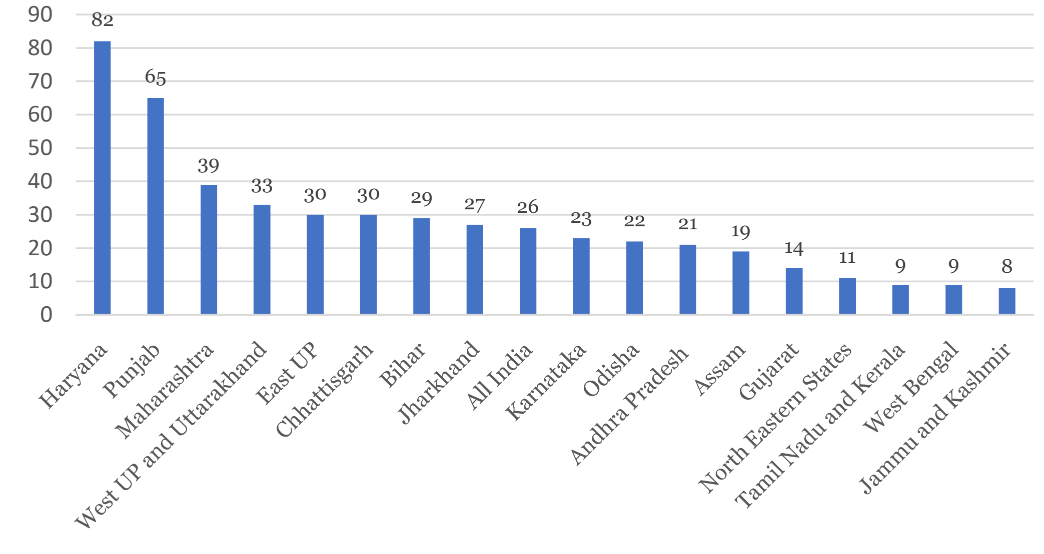
We use the agricultural input survey to assess the trends in the adoption of certified seeds over the period from 1996-97 to 2016-17. Figure 3 presents the trends in the adoption of certified seeds across the states over the period 1996-97 to 2016-17. At the all-India level, the adoption of certified seeds increased from 20% to 40% over the period 1996-97 to 2016-17. At the same time, the Figure 4 suggests a heterogeneous adoption patterns of certified seeds across states. Joshi and Khan (2017) pitched a Green Revolution for eastern India focusing on an integrated approach including agriculture technologies, policies and agriculture infrastructure.

Figure 5 presents the sources of purchase of certified seeds in 2016-17. It is noted that the private sector accounts for the most of the purchase (57% farmers). The Department of Agriculture and Department of Seed Corporations account for 21% and 7%, respectively. It means that the role of private sector in seed supplies is quite salient.

(c) Impact on Agricultural Productivity, Income, Employment and Total Factor Productivity

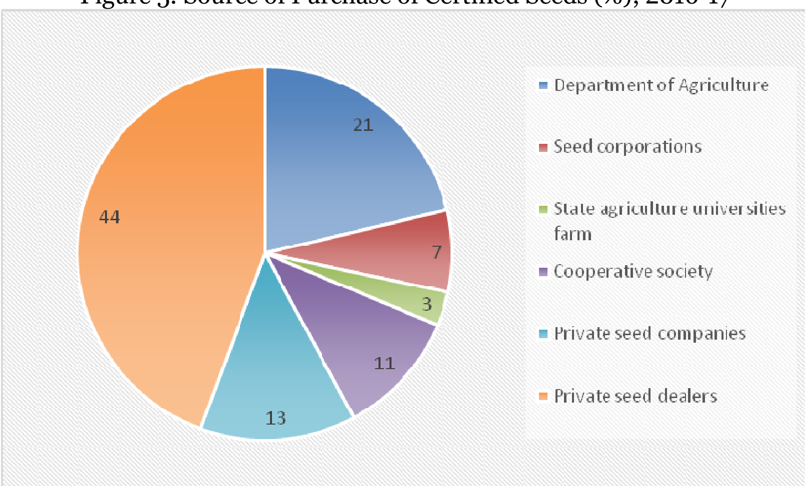
Adoption of improved varieties impact the agriculture sector in multiple ways. Based on selected studies, Table 1 documents the impact of adoption on a range of indicators — yields, production, farm income, inequality and employment.

Figure 4: Adoption of New Paddy Cultivars (% Farmers), 2017-18



Notes: Andhra Pradesh includes Telangana State and UP is Uttar Pradesh.
Source: Kumar *et al.* (2020).

Figure 5: Source of Purchase of Certified Seeds (%), 2016-17



Source: Same as Figure 1.

There is a consensus among studies about the positive impact of adoption of improved varieties on the agricultural production and productivity (Chakravarti 1973; Prahladachar 1982; Mckinsey and Evenson 2003). Between 1950-51 and 1969-70, there is a significant increase in the food grain production from 51 mt to 100 mt,

Table 1: Adoption of Improved Varieties and their Impact

	Adoption of HYVs		Impact of HYVs				
Authors	Year	Adoption pattern	Outcome variable	Year	Crops	Impact	Study region
Chakra-varti (1973)	1966-67 and 1968-69	Rice (2.5% and 7.2%) Wheat (4.1% and 30%) Maize(4.1% and 6.8%)	Production	1950-51 to 1969-70	Foodgrains	51 mt to 100 mt	All India
Prahla-dachar (1982)	1976-77	Rice (38.8%), Wheat (72.1%), Jowar (18.4%), Pearl millet (23.6%), and Maize (20.5%)	Production	1967-70 to 1976-79	Foodgrains	4%-69%	Andhra Pradesh (25%), Assam (15%), Bihar (15%), Gujarat (39%), Haryana (47%), Karnataka (25%), Kerala (1%), Madhya Pradesh (13%), Maharashtra (44%), Odisha (4%), Punjab(68%), Rajasthan (46%), Tamil Nadu (69%), Uttar Pradesh (26%) and West Bengal (19%)
Mckinsey and Evenson (2003)	1965 and 1994 (Adoption of HYV is measured as the percentage of the crop planted to HYVs released after 1964). Indicator= logarithm (HYV/(1-HYV))	Rice (-3.9 and 0.69), Wheat (-3.9 and 2.21), Maize (-3.9 and -1.09), Sorghum (-3.9 and -0.47), and Pearl millets (-3.9 and 0.24)	Yield	1965 to 1994	Rice, Wheat, Maize, Sorghum and Pearl Millet	Rice (0.68 mt/ha, Wheat (0.84), Maize (0.46) Sorghum (0.74), Pearl millet (0.41)	All India
Matushcke *et al.* (2007)	2001 and 2005	Wheat (0.4% and 1.8%)	Yield	2003-4	Wheat	34%	Maharashtra
Subramanian and Qaim (2009)	2003-4	Cotton (7.5%)	Yield	2004-5	Bt. Cotton	34%	Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu
Foster and Rosenzweig (1995)	1968 and 1970	Rice and wheat combined (19% and 42%)	Profit	1968-1970	Rice and Wheat	21%-22%	India
Matushcke *et al.* (2007)	n.a	n.a.	Net income	2003-04	Wheat	Rs. 1,852 per acre	Maharashtra (@ 2003-4 prices)
Janiah *et al.* (2010)	2008-9 (purposive sampling)	Hybrid rice : Chhattisgarh (68%), UP (73%), and Haryana (23%)	Yield	2008	Rice hybrid	36% (EUP) and 24% (CHH)	Eastern Uttar Pradesh (EUP) and Chhattisgarh (CHH)
Janiah *et al.* (2010)	n.a.	n.a.	Profit	2008	Rice hybrid	34% (EUP) and 13% (CHH)	Eastern Uttar Pradesh and Chhattisgarh
Janiah *et al.* (2010)	n.a.	n.a.	Yield and profit	2008	Rice hybrid	Insignificant	Haryana
Kumar *et al.* (2020)	2017-18 (Adoption of new cultivars)	Rice (26%)	Yield	2017-18	Rice	1.20%	India
Bannorr *et al.* (2020)	2017-18 (purposive sampling)	New rice varieties (0.84)	Consumption expenditure	2017-18	Rice	Rs. 3,222 per month to Rs. 3,853 per month	Odisha
Subramanian and Qaim (2009)	n.a.	n.a.	Insecticide risk	2004-5	Bt. Cotton	-50%	Maharashtra, Karnataka, Andhra Pradesh, and Tamil Nadu

Note: 'n.a.' is not applicable.

Source: Compiled by authors

as a consequence to the Green Revolution. Between 1967-70 and 1976-79, the study by Prahlachadar (1982) notes that the increase in food grain production has varied across states. For instance, northern states like Punjab registered a 68% increase in foodgrain production, followed by Haryana (47% increase), but a mere 15% increase was noticed in Bihar and 4% in Odisha. These results are consistent with the adoption of HYVs across the states.

This rise in production is mainly driven by the increase in agricultural productivity as a consequence of the adoption of HYVs (Hazal and Ramasamy 1991; Mckinsey and Evenson 2003; Evenson and Gollin 2003; Matushcke *et al.* 2007; Subramanian and Qaim 2009; Janiah and Xie 2010). Between 1965 and 1994, the yield levels increased phenomenally. The yield of rice almost doubled from 860 kg/ha in 1965-66 to 1,911kg/ha in 1998-99. In case of wheat, the increase was much steeper; from 827 kg/ha to 2,560 kg/ha during the same period (an increase of about 1,733 kg/ha). Yield levels of rice and wheat have reached 2,660 kg/ha and 3,421 kg/ha, respectively, in 2019-20 (Appendix Figure A1). The improvement in agricultural productivity as a result of improved varieties have raised the profitability and farm incomes (Foster and Rosenzweig 1995; Matushcke *et al.* 2007; Janiah and Xie 2010). These studies showed that the adoption of modern varieties raised the farmers' income between 14% and 34%, though varied by technology type and geography (for more detail, see Table 1). Adoption of improved varieties also reduced the risks of cultivation. For instance, adoption of disease and insect resistant varieties reduced the risk and application of pesticides by 50% (Subramanian and Qaim 2009). On the consumption side, increased production of foodgrains and incomes of farmers also led to a rise in consumption expenditure. Bannorr *et al.* (2020) estimate that consumption expenditure of the farmers increased in the range of Rs. 3,222 per month to Rs. 3,853 per month. In terms of prices, Evenson and Gollin (2003) showed that the consumers benefited mainly through reduction in prices, and farmers benefited when cost reductions exceeded a fall in prices. On employment, the Green Revolution period generated huge on-farm employment opportunities to farm laborers. Gradually with the mechanisation, the labor demand declined, and this encouraged the surplus labor to shift away to non-farm employment, especially to the construction sector.

The total factor productivity (TFP), which generally reflects the contribution of improved technologies, also reveals a quantum jump. The World Bank estimates

Table 2: Total Factor Productivity Growth

	Janaiah *et al.* (2006)			Chand I (2012)	
	1970-1985	1986-2000	1970-2000	1975-2005	
	Rice			Wheat	
Andhra Pradesh	0.7	2	1.3	0.5%-1%	n.a.
Karnataka	1	-0.4	0.2	0.5%-1%	n.a.
Punjab	3.6	-0.8	1.2	>2%	1%-2%
Uttar Pradesh	2.5	0.6	1.4	1%-2%	1%-2%
Assam	0.8	0.7	0.7	0.5%-1%	
Bihar	-1	4.4	0.5	<0.5%	0.5%-1%
Madhya Pradesh	1.1	-0.6	0.3	<0.5%	0.5%-1%
Orissa	0.2	2.4	1.2	<0.5%	
West Bengal	1.9	0.9	1.4	<0.5%	0.5%-1%
Haryana	n.a.	n.a.	n.a.	<0.5%	1%-2%
Tamil Nadu	n.a.	n.a.	n.a.	1%-2%	
Rajasthan	n.a.	n.a.	n.a.	n.a.	0.5%-1%
Gujarat	n.a.	n.a.	n.a.	n.a.	1%-2%
Himachal Pradesh	n.a.	n.a.	n.a.	n.a.	Negative
All India	n.a.	n.a.	n.a.	n.a.	n.a.

Note: 'n.a.' is not available
Source: Compiled by authors

the TFP growth at 1.3% during 1980-2009 (World Bank, 2014). It increases from 0.9% during 1997-2003 to 1.7% during the 2003-2009 period. Recent estimates for the period 2005-12 show a very high TFP growth of 5.4% (Jain *et al.*, 2017). Table 2 summarises the estimates of TFP growth made by a few studies (Janaiah *et al.* 2006; Chand *et al.* 2012). Table 2 reveals that the annual TFP growth rates of wheat in Punjab, Haryana, Uttar Pradesh and Gujarat are between 1% and 2%. And for lagging states, namely, Bihar, Rajasthan and Madhya Pradesh, it is between 0.5% and 1%. For paddy (1970s to 2000s), the TFP growth rate has been in the range of 1.2% (Janiah *et al.* 2006) to 2% (Chand *et al.* 2012). The lagging states, namely, Bihar, West Bengal, Madhya Pradesh and Odisha, show a TFP growth of less than 0.5% (Chand *et al.* 2012). Janiah *et al.* (2006) further reports that the TFP of rainfed rice has been gradually picking up during 1986-2000 and showing spillover effects from the north-west regions to southern regions, especially in the rainfed areas. More research is needed to expand the analysis of TFP for the recent period and for other commodities by different regions.

(d) Impact on Inequality and Sustainability

Unequivocally, the improved and HYVs were widely adopted, and they significantly increased production and agricultural productivity. Consistent with the adoption patterns, the impact was heterogenous across farm size and agro-ecoregions (Chakravarti 1973; Bhalla 1974; Hazal and Ramasamy 1991). Some studies also argued that the Green Revolution made poor farmers poorer and led to widening income disparities (Bowonder 1979 and Freebrain 1995). Although the inequality in adoption patterns is also noted for the recent period by Kumar *et al.* (2020), there is a need to assess the contribution of technologies in explaining the extent of regional inequality in terms of agricultural productivity and farm incomes.

There are serious concerns about the sustainability of natural resources. Most of the studies on the impact of improved technologies on sustainability of natural resources reported that adoption of improved and HYVs has led to inappropriate application of fertilizers, pesticides and irrigation that deteriorated soil health, nutritional imbalance and natural hydrology (Chaudhary and Aneja 1991). Absence of appropriate institutional arrangements in managing natural resources led to deterioration of soil and water resources (Marothia 2003; Marothia 2009). There are reports that the Green Revolution belt, which excessively used the ground water, is now exhibiting second-generation problems owing to over-exploitation and mis-management of soil and water resources (NAAS 2009). These negative externalities can be grouped into three broad areas: (i) affecting soil health because of imbalance and excessive use of inorga-nic fertilizers, (ii) depleting groundwater as a result of excessive and injudicious use of groundwater, and (iii) polluting air quality due to crop residue burning.

There are several studies that have concluded that the soil health has deteriorated due to disproportionate use of inorganic fertilisers and less application of organic manure (Chand and Pandey 2008). The partial factor productivity of fertilisers during the last three and a half decades showed a sharp declining trend from 48 kg foodgrains per kg of nitrogen, phosphorus and potassium (NPK) in 1970-71 to 10 kg foodgrains/kg NPK in 2007-08 (NAAS 2009). The recently introduced ‘Soil Health Card Scheme’,[5] if implemented effectively, will play an important role in saving inorganic fertilisers and improving soil health, which would eventually reduce the fertiliser subsidy burden to a large extent.

A fall in the groundwater table is another serious concern, especially in the irrigated and Green Revolution belt of Punjab and Haryana. The worst affected areas of steeply plunging water table are in most of the irrigated areas, and the deteriorating water quality is more due to leaching of salts and other pollutants (NAAS 2009; ICAR 2011). The excessive use of groundwater has been due to the availability of free or cheap electricity for pumping underground water. Leaching of nutrients is causing higher levels of fluoride and nitrate pollution, and further affecting groundwater quality and yields (Joshi 2015). These are also affecting human health.

Burning of crop residues is a new phenomenon, and has become a serious environmental problem reported from the Green Revolution belt. There are estimates that roughly 92 mt of crop residue is burnt in India, which otherwise have high economic value for several alternative uses (Bhuvaneshwari *et al.* 2019). The extent of residue burning is increasing over time and spreading to other parts of India. Venkatramanan *et al.* (2021) observed the following drivers causing crop residue burning: increase in crop yield, labour scarcity, short time interval between the harvesting of monsoon (Kharif) crop and sowing of winter (Rabi) crop, lack of space to stock/store crop residue, absence of appropriate crop residue management technologies, nutritionally poor rice crop residues, economic resource constraints, social influence and lack of awareness about the public health issues. The private cost of burning crop residue is negligible, but the social cost, in terms of polluting air quality, and thus, contributing to global warming and deteriorating human health, is very high. Chakrabarti *et al.* (2019) estimated that there was a three-fold higher risk of acute respiratory infection (ARI) to those who live in and surrounding areas of crop residue burning. The authors further estimated the value of adjusted life year lost to the tune of $ 1.529 billion over five years. The solution to crop residue burning lies in the effective implementation of sustainable management practices with government interventions and effective policies. Realising the seriousness of the problem, the government launched a 'National Policy for Management of Crop Residue', which consists of (i) organising awareness campaign, (ii) conducting demonstration of technologies to manage and use crop residue, (iii) extending subsidies on implements for managing crop residue, and (iv) declaring residue burning a crime. Despite concerted efforts by the government, the problem is increasing over the years and affecting soil and human health.

There has been a debate on the causes of negative externalities as a result of improved technologies. Some argue that the improved varieties require more water and inorganic fertilizers, which result in deterioration of natural resources and the environment. The others argue that the government policies, especially subsidies on inputs (fertilizer, irrigation and power), are encouraging farmers to excessively and injudiciously use modern inputs to maximise their profits. There are prescriptions that correcting the government policies and incentives, and promoting agricultural diversification towards input-saving (especially water) and more remunerative agricultural commodities are a prerequisite for sustainable transformation and agricultural development.

The following messages can be summarised from the above review:

(i) Improved varieties made a significant impact in transforming Indian agriculture, increasing agricultural production and ensuring food security. This elevated India from a food deficit to food surplus nation on the global map.

(ii) Adoption patterns of improved cultivars varied by the commodity type and geography.

(iii) Adoption of improved cultivars show an unambiguous impact on the agricultural productivity, agricultural production and farmers' incomes.

(iv) Adoption of improved cultivars have implications on employment, equity and poverty.

(v) Negative externalities, especially the adverse impacts on the sustainability of natural resources and environment, are surfacing, and it needs to be better managed through appropriate technologies and effective policies.

(vi) Targeted approach holds the key for quicker and wider diffusion of improved cultivars.

2.2 Natural Resource Management

Promising technologies in natural resource management are related to improving water use efficiency, increasing input use, especially of fertilizer, and conserving soil and water resources.

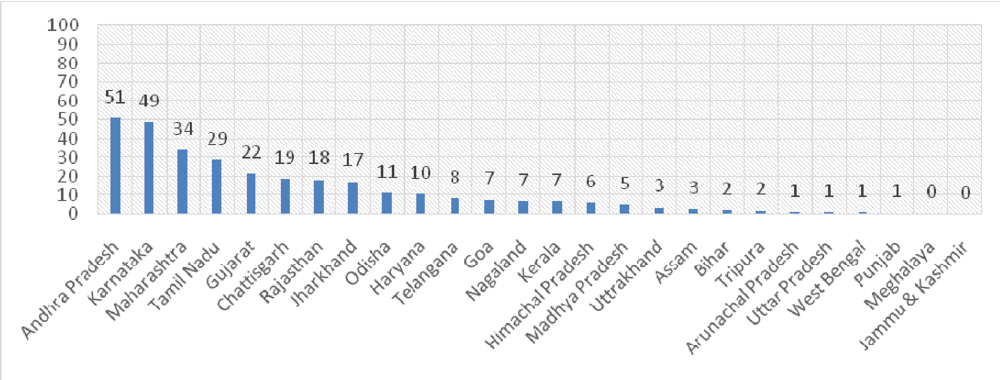
(a) Water use

Water is an essential input for agriculture and allied activities. India accounts for 4% of world's water share and 17% of the world population. The irrigated area has reached to more than 40% through ground, surface, and other sources. Despite abundant availability of water, the World Resource Institute categorised India into the high-water stress category. It is mainly due to the fact that the ground water level is significantly falling in India, and its condition is highly alarming in states such as Punjab and Haryana (Singh *et al.* 2020). In such a situation, conserving ground water and improving water use efficiency are an utmost priority for the sustainability of agriculture. Roughly, two-third of the cultivable land in India is rainfed while the remaining 39 million ha land is irrigated by groundwater and 22 million ha by canals (Dhawan 2017). Adoption of water-efficient technologies is one of the most prominent pathways to address the sustainability of agriculture. This section provides a brief review of key technologies to better understand how these impacted the sustainability of agriculture and farmers' income. The assessment includes micro-irrigation technologies, land-levelling technology, agronomic practices and multiple water use systems to understand the adoption barriers and the potential impact.

Adoption of micro-irrigation technologies such as sprinkler and drip irrigation have a huge potential to improve water use efficiency and increase agricultural productivity (Namara *et al.* 2005; Varma and Namara 2006; Kumar 2016; Bahinipati and Viswanathan 2016; Bahinipati and Viswanathan 2019). These studies show a significant rate of growth in the adoption patterns of micro-irrigation technologies over time. Figure 6 presents the area under micro-irrigation for major states for 2020. The results reveal that top 5 states are Andhra Pradesh (51% of the gross irrigated area), Karnataka (49%), Maharashtra (34%), Tamil Nadu (29%) and Gujarat (22%). Strikingly, the area covered under micro irrigation in Punjab is merely 1% despite the fast-depleting ground water table. In contrast, the neighbouring state Haryana has 10% area under micro-irrigation, especially in areas where groundwater quality is brackish. The low adoption of micro-irrigation technologies in Punjab and Haryana is mainly due to the dominance of rice cultivation. However, it may be pointed out that research is still in progress as to how to use micro-irrigation in rice crop.

In terms of impact, the study by Bahinipati and Viswanathan (2016) found that more than 80% of the surveyed farmers reported improvement in water and agricul-

Figure 6: Area Under Micro-irrigation (% of Gross Irrigated Area), 2020



Source: Ministry of Agriculture and Farmers Welfare, *Agricultural Statistics of India, 2020*, Government of India, New Delhi.

tural productivity. Interestingly, more than 60% of them reported savings in labour and energy use. A study by Namara *et al.* (2005) reported a very high elasticity of the yield in response to the application of micro-irrigation technologies. In the selected crops (banana, groundnut and cotton), the application of micro-irrigation technologies, compared to traditional methods of irrigation, resulted in a significant yield improvement in terms of elasticities in the range of 0.51 to 1.21. Despite saving irrigation water and increasing agricultural productivity, the adoption of micro-irrigation has been very slow.

The main reason for the slow rate of adoption of micro-irrigation systems is the high cost of establishing the system. There are suggestions that low-cost of micro irrigation systems is the precondition for their large-scale adoption. As pointed out by Kumar (2006), there are other constraints, as listed below:

(i) Unreliable access to ground water.

(ii) Less independence across farmers in extracting water.

(iii) Mismatch between micro-irrigation system and existing cropping patterns.

(iv) High opportunity costs of pumping ground water.

(v) Poor knowledge due to weak extension services.

(vi) Fragmented and small size of land holdings.

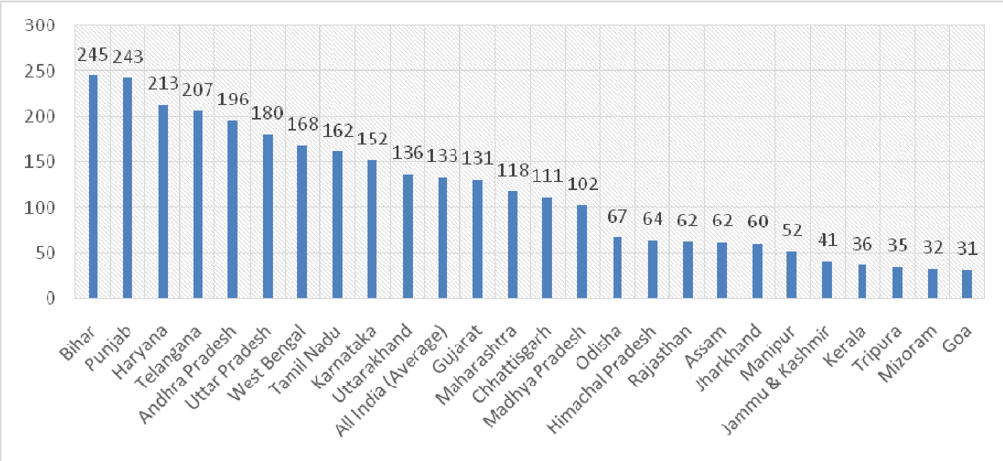
Subsidies in micro-irrigation systems also play an important role in their adoption. To promote micro-irrigation system, the Government of Gujarat has made the following provisions – adoption of micro-irrigation technologies is compulsory for getting new electricity connection and an additional 10% subsidy is extended for the adoption of micro-irrigation technologies. These provisions have increased the adoption of sprinkler and drip irrigation systems (Bahinipati and Viswanathan 2016).

Land levelling is another important intervention to improve input use efficiency, especially of water. Several efforts have been made in the past to promote laser land levelling (LLL), especially in north-west states of India. These efforts have shown a positive and significant impact in (a) adopting micro-irrigation technologies, (b) improving water use efficiencies, and (c) increasing agricultural productivity (Jat *et al.* 2006; Bhatt and Sharma 2009; Sapkal *et al.* 2019). The projections reveal that adoption of LLL in 2 million ha area would conserve 1.5 million hectare-meter of irrigation water and save 200 million litres of diesel (Jat *et al.* 2006). Adoption of LLL also increases cultivated area due to reduction in bunds and channels. The gains of LLL are as high as Rs. 20,000 per ha (Sapkal *et al.* 2019). Main adoption barriers for LLL are: (a) small size of land holdings, (b) high service charges for LLL, (c) scarcity of technical manpower and adequate skills, and (d) lack of adequate knowledge. Further, there are reports that information about technology through farmer-to-farmer communication and private traders, and participation in agricultural training and membership in local agricultural institutions increase the likelihood and the intensity of adoption of LLL (Aryal *et al.* 2018). The LLL is characterised as the precursor technology for resource conservation (Jat *et al.* 2006).

(b) Inorganic fertilizer

Application of inorganic fertilisers and pesticides as per the recommended quantities has contributed to the increase in agricultural productivity and farmers' income. Their application, in combination with improved cultivars and irrigation, has significantly increased agricultural production. However, there is a wide disparity across states (Figure 7) and farm size in the application of fertilizers and pesticides. The better-off states and large farmers are using excessive fertilizers and pesticides, while rainfed areas and small and marginal farmers are using less than the recommended doses. There are three challenges in optimum use of fertilizers and pesticides: (i) affordability of fertilizers and pesticides, (ii) balance and judicious use of fertilizers

Figure 7: Consumption of Fertilizer (N,P and K), 2019-20, (kilogram per hectare)



Source: Ministry of Agriculture and Farmers Welfare, *Agricultural statistics of India, 2020*, Government of India, New Delhi.

and pesticides, and (iii) environmental degradation as a result of their injudicious and indiscriminate use.

To address affordability, the Government of India provides a large amount of subsidy to make fertilizers affordable – it amounted to about Rs. 80,000 crore in 2020-21. According to the government portal, the number of farmers who purchased the fertilizers are about 10.5 crore (out of 14.5 crore farmers), which suggests that only 70% of farmers are applying fertilizers and pesticides for cultivation activities. More detailed studies are to be conducted to better understand the key drivers of not using fertilizers by the remaining 30% of the farmers. Is it because of inaccessibility and/ or affordability? It would be useful to characterise these farmers and develop their typology so that appropriate policy and institutional arrangements can be made.

A large number of farmers in better endowed regions are overusing these inputs. To address the inappropriate use of fertilizers, the Government of India in 2014 initiated a 'Soil Health Card Scheme' so that farmers could apply soil-test based nutrient/fertilizer to maximise their profit. The optimum use of nutrient management has implications on input costs, productivity and profitability (Joshi *et al.* 2019; Cabangon *et al.* 2014; Makadia *et al.* 2017). Role of micro-nutrients, especially Zn and Mn, is also important. A programme, known as *Bhoochetna* was launched by the Government of Karnataka to promote micro-nutrient. The programme was aimed to improve the soil quality and to promote the balanced use of macro- and micro-nutrients. The programme yielded a positive impact on agricultural productivity (Joshi *et al.* 2019). Moreover, the Government of India advised the farming community to reduce fertilizers use and encouraged more zero-budget natural farming and the organic manure for the agricultural sustainability. However, its scientific validity is yet to be confirmed.

Disproportionate use of fertilizers and less application of organic manures has led to deterioration of soil health (Chand and Pandey 2008). Over the years, continuous application of excessive quantity of inorganic fertilizers has been adversely affecting the agricultural productivity and sustainability of agriculture (Baweja *et al.* 2019; Srivastava 2020). The adverse effects of excessive and injudicious use of fertilizers have resulted in the deterioration of soil health, loss of microflora and other organisms, and deterioration in the quality of groundwater. As noted earlier, the partial factor productivity of fertilisers has significantly declined during the last three and a half decades. On-farm experiments further reveal that the current fertiliser management patterns are depleting carbon and micronutrient availability, and thereby, adversely affecting agricultural production and income, and ruining soil health and water quality. Smallholders are more vulnerable to such adverse effects due to disproportionate fertiliser use. Higher subsidies on nitrogenous fertiliser induce greater urea use compared to phosphorous, potash and other micronutrients (like manganese, zinc and boron). The fertiliser subsidy is also thinly distributed to smallholders due to their large number. On a per holding basis, smallholder farmers get about 14 times less fertiliser subsidy than what large farmers get (Government of India 2016). In 2015, entire urea is sold with neem coating. The neem coated urea has multiple benefits of saving urea, improving nitrogen use efficiency and increasing crop yields. Besides, it minimises the leakages of fertilizer from agriculture to the non-agriculture sector, and thereby, reduce the subsidy burden on fertilizer. More research is needed to assess the adoption and impact of neem coated urea on all aspects of agriculture.

(c) Watershed

Watershed technology is considered to be a boon for the rainfed areas. It involves conservation and judicious use of rainwater for increasing agricultural production and controlling soil erosion. Watershed programme in India was designed based on the research efforts made at eight locations by the Indian Council of Agricultural Research (ICAR). The programme involves connecting technologies with institutional arrangements, financial provisions, capacity development for greater people's participation and effective governance for management of watersheds. The programme was designed for rainfed areas with multiple purposes, namely, increasing farmers' income, controlling soil erosion and conserving rain water.

Watershed programme in rainfed areas serves as an important tool for water resources development, groundwater recharge and socio-economic improvement (Sreedevi *et al.* 2006; Joshi *et al.* 2008; Shaheen *et al.* 2009; Soni 2017). Some of the structures and agronomic practices of watershed programme include raised-bed planting, ridge-furrow method of sowing, sub-surface irrigation and precision farming – all of these provide a great potential for improving water use efficiency (Gregory 2004; Singh *et al.* 2014; Dhawan 2017). The better access to irrigation water through rainwater harvesting result in multiple benefits (Joshi *et al.* 2008), such as:

(i) Increasing agricultural production.

(ii) Enhancing cropping intensity and enable two to three crops in a year.

(iii) Improving groundwater availability.

(iv) Facilitating crop diversification towards high-value crops.

(v) Generating employment opportunity.

(vi) Raising farm incomes.

(vii) Improving sustainability of soil and water resources.

Joshi *et al.* (2008) did a meta-analysis of a large number of watersheds to quantify their impact on rainfed agriculture (Table 3). The results reveal that watershed programmes not only increase farmers' income, but improve equity and sustainability of natural resources in rainfed areas. This also increases the likelihood of raising farm income through crop diversification and integration of fish, poultry and other enterprises in the farming system.

Despite the enormous benefits, the watershed programmes could not succeed without government intervention. Joshi *et al.* (2008) documented the conditions for success for watershed programmes. These are:

Table 3: Meta-analysis on the Benefits of Watershed Programmes

Indicator	Particulars	Unit	Number of Studies Evaluated	Mean	t-value
Efficiency	Benefit/Cost ratio	Ratio	128	2.14	21.25
	Internal rate of return	%	40	22.04	6.54
Equity	Employment	Person days/ hectare/year	39	181.5	6.74
Sustainability	Irrigated area	%	97	33.56	11.77
	Cropping intensity	%	115	63.51	12.65
	Rate of runoff	%	36	-13	6.78
	Soil loss	Tons/hectare/year	51	-0.82	39.29

Source: Joshi *et al.* (2008)

(i) Necessity of people's participation, and involvement of local stakeholders in planning, development and execution is crucial.

(ii) Need for demand-driven activities of watershed programme rather than supply driven.

(iii) Active participation of women and landless labour.

(iv) Develop processes for decentralisation of decision making.

(v) Involvement of elected leaders and village heads.

(vi) Visible tangible economic benefits.

(vii) Awareness about the benefits of the programmes and community participation.

(viii) Need to develop linkages with other institutions like credit sector and technology.

(ix) Implement agro-ecoregion specific technologies.

The key messages that emerge from the above review are summarised as follows:

(i) There are positive economic, social and sustainability impacts due to the adoption of technologies related to natural resource management.

(ii) There is a large variation across states or agro-ecoregions in the adoption of technologies related with natural resource management.

(iii) The main adoption barriers are poor access to water, lack of technical knowledge, poor extension services, and small and fragmented land holdings.

(iv) Main drivers of the adoption are the community participation, government subsidy, access to information, and effective coordination among farmers.

(v) Significant benefits of watershed programmes are increasing efficiency, improving equity and enhancing sustainability.

2.3 Farm Mechanisation

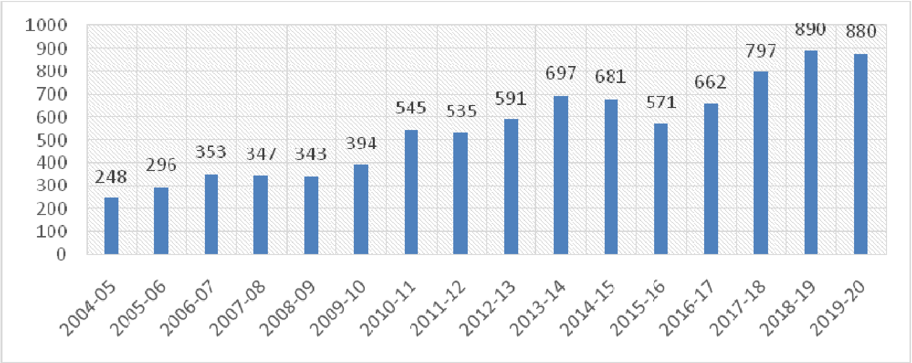
Labour-saving technologies, such as tractors, seed-drills, harvesters, combines, etc., are important not only to reduce costs and drudgery but also to increase labour efficiency and farmers' income (Mehta *et al.* 2014; Ahmad and Goodwin 2016; NABARD 2018; Joshi *et al.* 2019; Sarkar 2020). These studies show that the adoption of labour-saving technologies has the potential to increase agricultural productivity by up to 30% and reduce the cost of cultivation by 20%. At the same time, adoption of such technologies save labour in agriculture, and thereby, release the labour supply to the non-farm sector by 30%. The returns in non-farm sector are higher than in the agriculture sector.

In India, 85% of the total holdings are small and marginal, where affordability and execution of agriculture machineries is a major challenge. Although custom hire services or the rental markets for agricultural machineries exist, these have their own limitations and complexities. To promote agricultural mechanisation, the Government of India has launched a sub-mission on agricultural mechanisation in 2014-15 focusing on training, testing and demonstration. Yet, the agricultural mechanisation in India is in early stages, and can be seen from the fact (Figure 8) that only 9 million farmers out of 146 million were able to procure tractors during the last 15 years (2004-05 to 2019-20). Figure 9 presents the state-wise sale of tractors in 2019-20, and a huge inter-state variation is noticed.

To promote farm mechanisation, the following steps may be taken-up (Mehta *et al.* 2014; NABARD 2018; Joshi *et al.* 2019; Sarkar 2020):

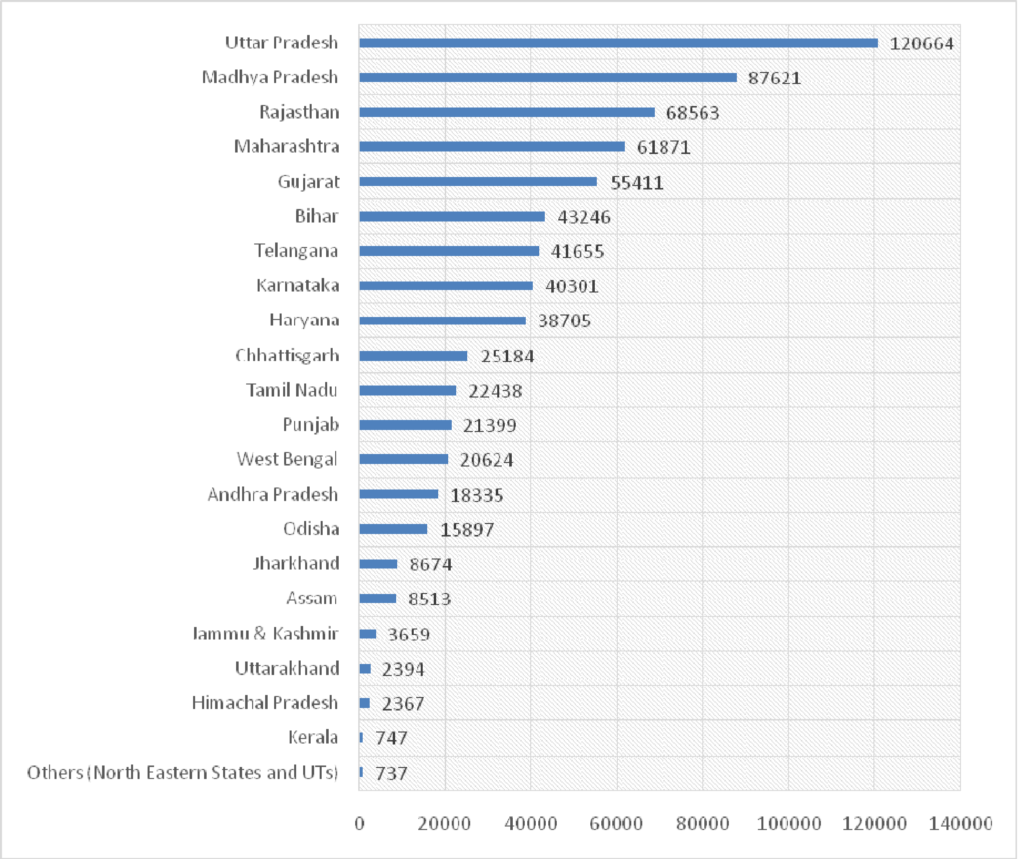
1. Existing machines and implements are pro-large farmers. The smaller land size (about 1.08 ha) in India, compared to Europe (14 ha), limits the adoption of equipment suitable for the large land size. There is a need to de-

Figure 8: Trends in Number of Tractors Sold in India, 2004-5 to 2019-20 (in '000)



Source: Same as Table 7.

Figure 9: State-wise Trends in Number of Tractors Sold in 2019-20 (in '000)



Source: Same as Table 7.

velop and promote suitable farm machines, which suit the requirements of smallholders.

2. High fixed and variable costs of operation (economies of scale) for a smaller and fragmented piece of land limits the ownership of existing farm machines and equipment. Aggregation of farmers through Farmer Producer Organisations (FPOs) would enable them to use farm implements and machines.

3. Need for appropriate agriculture extension services for selection of farm equipment suitable across different farming systems.

4. Relax credit constraints for small and marginal farmers.

5. Hilly regions are way behind in use of available farm machinery and implements, as these are unsuitable to the existing terrain and topography. To promote farm mechanisation in hill regions, suitable implements are needed that suit the terrain and cropping systems.

6. Existing machines and implements are not women-friendly. As agriculture is getting more feminised, new machines and implements need to be more women-friendly.[6]

2.4 Conservation Agriculture

The upper Indo-Gangetic plain is facing serious challenges in terms of depletion of natural resources, especially soil and water. These are related to rising production costs and declining profitability, mainly on account of (a) declining organic matter content and carbon in the soil, (b) extensive tillage and imbalance use of nutrients, (c) growing menace of residue burning, (d) steeply falling ground water table, (e) increasing wages and labour scarcity, and (f) rising fuel prices (Joshi 2010). These factors are adversely affecting soil, water and air, and consequently affecting agricultural productivity, farm income and human health. To overcome these problems arising due to conventional agriculture, the concept of conservation agriculture is promoted. It is a range of soil management practices that minimise effects on composition, structure and natural biodiversity and reduce erosion and degradation (Joshi 2011). The conservation agriculture practices include (a) direct sowing and nil/reduced/minimum tillage, (b) surface – incorporation of crop residues, and (c) establishment of cover crops in both annual and perennial crops. These concepts are confined to improvement in soil health, and do not refer to farm income. To integrate farm income and soil health through conservation agriculture, the Food and Agriculture Organization (FAO) of the United Nations has focused the concept as resource-saving agricultural crop production. As per FAO definition, the conservation agriculture is to (a) achieve acceptable profits, (b) high and sustained production levels, and (c) conserve the environment (FAO 2009).

The most important components of conservation agriculture are laser land levelling, direct seeded rice and zero tillage. The adoption of conservation agriculture is slow in India, but gaining importance in Punjab and Haryana. Several economic and environmental benefits are realised as a result of adopting conservation agriculture practices. These include: (i) yield increase (10%-17%), (ii) water saving (20%-35%), (iii) energy and oil saving (roughly one million barrels if adopted in 3.5 million ha), (iv) high rate of internal rate of return (57%), and (v) improved carbon sequestration and reduction of greenhouse gas emission (Erenstein and Pandey 2006). The adoption constraints include: (i) lack of awareness about the concept, (ii) non-availability of machines and/or services for laser land levelling and zero tillage, (iii) high cost of machines, and (iv) lack of competence for repair of conservation agriculture related machines. The components of conservation agriculture are also adopted in steps and modified by the farmers to suit their skills and resource endowment. In Punjab and Haryana, the adoption of laser land levelling is getting more prominence than the other components. It is followed by direct seeded rice and zero tillage. It is interesting to note a high correlation between adoption of laser land levelling and zero tillage (Joshi 2016). It is more likely to adopt zero tillage if the land is laser leveled. More research in different agro-ecologies and for alternative production systems is needed to scale up the adoption of conservation agriculture.

2.5 Climate Smart Technologies

Climate change has now become a reality. It is adversely affecting agricultural production and pushing the poor to below the poverty line (Pal *et al.* 2019). One of the recent reports of the Inter-Governmental Panel on Climate Change (IPCC) is very scary, and it states that human action has been responsible for climate change. It further elaborates that in the absence of appropriate measures to combat climate change, the damage would be more serious than predicted. The small farm holders are more vulnerable to climate change. This group of framers have the least capacity to overcome the consequences, as they have fewer resources to adapt socially, technologically and financially, and thus, are likely to be the worst affected (Joshi and Tyagi 2019).

To combat impact of climate change, Climate Smart Agriculture (CSA) has been promoted at the global level by the Consultative Group on International Agricultural Research (CGIAR) programme on Climate Change, Agriculture and Food Security (CCAFS). The FAO defines the CSA as, "an approach that helps guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a hanging climate". It is a win-win proposition in the short- and long-run, which contributes to (i) increase in agricultural productivity and farmers' incomes, (ii) adapting to climate change and reducing the risk arising due to climate change, and (iii) improvement in carbon sequestration and/or reduction in greenhouse gas emissions. The CSA incorporates a comprehensive strategy incorporating social, economic and environmental contexts. The CSA consists of a package of practices, which intends to improve efficiency, reduce the risks and enhance sustainability of natural resources and environment. Perez *et al.* (2019) evaluates the effectiveness of CSA practices in mitigating the adverse impact of climate change. The study reveals that the adoption of CSA practices has a huge potential to mitigate the adverse effects of climate change.

There are several components of CSA technologies. These include stress-tolerant cultivars, minimum tillage, laser land levelling, weather advisory, energy management, site-specific nutrient management and crop diversification. Since most of the components are dealing with resource management, their adoption is location specific. Their adoption is sequential and/or step-wise depending upon farmers' resources and skills. The adoption of different CSA practices are inter-related. Often, farmers modify the recommendations depending upon their convenience (Aryal *et al.* 2018; Taneja *et al.* 2019; Kharti-Chhetri *et al.* 2017). Adoption levels of CSA practices have varied significantly across the agro-ecoregions and depending upon resource endowments and access to knowledge (Veettil *et al.* 2021). It was found that poorer agro-ecoregions have lower adoption levels compared to the better endowed regions. The important components that are given preference for adoption are laser land levelling, direct seeded rice, zero tillage, stress-tolerant varieties, irrigation scheduling, weather advisory and agricultural insurance (Taneja *et al.* 2019). However, their extent and pace of adoption vary across different agro-ecoregions.

There are multiple opportunities emanating from CSA technologies for minimising the impact of climate change. The concept is relatively new, and there is less expertise among extension personal about different components and practices of CSA (Joshi 2016). However, the KVKs and the National Bank for Agriculture and Rural Development (NABARD) are making efforts to promote climate smart or climate resilient villages in different agro-ecologies to expose their benefits to the farmers. However, the limited resources are constraining their large-scale adoption. More research and extension efforts are needed to further refine the technologies and their extension.

2.6 Biotechnology and Genetic Modified Crops

Application of modern science such as biotechnology and nano-technology in crops provides an opportunity to enhance their genetic potential including agricultural productivity, input requirements and sustainability of agriculture. Agricultural biotechnology is being used as a scientific tool and technique to enhance genetic potential and/or reduce risks due to biotic and abiotic stresses. This includes genetic engineering, molecular markers, molecular diagnostics, vaccines and tissue culture. They help to modify living organisms in plants, animals and microorganisms. Use of biotechnology in breeding has many advantages over the traditional breeding efforts. Tissue culture became very popular in developing and propagating planting material of fruits and vegetables. Tissue culture has created the possibility to generate a whole plant from single cells or tissues, which opened new approaches to plant improvement.[7] It has become an essential technique to produce plants with desired genetic characteristics and productivity. There are basically the following goals of tissue culture: (i) mass propagation of the desired line of the plants, (ii) obtain virus-free plants, (iii) rapid mass production of plants for breeding purposes, (iv) preserve germplasm, and (v) produce haploids for the breeding programme (ibid). In India, the success of tissue culture has been recognised in papaya, banana, grapes, guava, orange and pomegranate.

Of late, the genetically modified (GM) crops are attracting attention in agricultural science. A GM crop is inserting deoxyribonucleic acid (DNA) into genome of an organism through genetic engineering. The aim is to develop resistance against any biotic and/or abiotic stresses, which through conventional methods is either difficult or takes a long time. One of the most successful stories for GM crops is Bt cotton. In 2002, Bt cotton was introduced in India, and thereafter, its area has increased exponentially to occupy close to 90% of the total cotton area in 2011. The Bt cotton has the advantage of increasing yields and reducing the pest infestation, especially the pod borer. The production of cotton increased more than three times from 10 million bales in 2011-12 to 35 million bales in 2011-12. There was a significant increase in exports from 0.05 million bales in 2001-02 to 8.3 million bales in 2009-10. Bt brinjal is the first GM food crop. It is yet to receive the approval by the government for cultivation. The on-farm trials show that Bt brinjal improves productivity by 37%-55% and significantly reduces the use of pesticide (Krishna and Qaim 2008; Kumar *et al.* 2011). The other benefit is higher prices due to absence of infestation from pod borer. The small and marginal farmers are expected to gain more compared to the large farmers, as they allocate proportionately higher acreage to brinjal. The issues related to food safety and biodiversity are yet to be resolved for giving clearance by the government for Bt brinjal and other GM crops in India.

2.7 Biofortification

Biofortification is the process by which the nutrient density of food crops is increased through conventional plant breeding method (Bouis *et al.* 2011). In low- and middle-income countries, economic affordability is a major constraint for the consumption of nutritious food that leads to several health complications, especially among children and women. There are reports that India loses over $12 billion annually in gross domestic product (GDP) due to vitamin and mineral deficiencies.[8] Biofortified varieties can play an important role in improving nutritional security of the poor and undernourished population. The potential of biofortification in reducing the burden of micronutrient deficiencies is a highly cost-effective approach (Meenakshi *et al.* 2010). Global experiences reveal that biofortification is the most cost-effective approach to improve nutritional security of the poor and vulnerable population. The biofortified varieties are rich in important nutrients, such as zinc, iron, calcium and protein, among others. These are 1.5 to 3.0 times more nutritious than the traditional varieties. Besides higher nutrient contents, these varieties provide higher yields and resistance to several biotic and abiotic stresses. For example, high iron pearl millet varieties provide up to 80% of daily iron needs. Its other traits are high yield, mildew resistance, short duration and drought tolerance. Similarly, zinc rich wheat varieties provide up to 50% of the daily zinc needs. It is reported that zinc wheat consumption reduces morbidity in mothers and children (Bouis *et al.* 2011). The varieties are giving higher yields, disease resistance and has adapted to the eastern Indo-Gangetic plain ecoregion. Recently, the Prime Minister launched 17 biofortified varieties of eight crops for cultivation in different parts of the country.

There are several challenges in scaling up of biofortification varieties:

(i) Non-availability of enough seeds of biofortified varieties for larger areas.

(ii) Non-existence of the value chains of the biofortified varieties.

(iii) Lack of awareness about biofortified varieties among the poor and undernourished consumers.

(iv) Disconnect between government's social safety net programmes and production of biofortified varieties.

There is a need to integrate nutrition-dense food commodities with the government social safety net programmes, such as the public distribution system (PDS), mid-day meal scheme and the integrated child development programme. There is a need to develop an effective seed value chain of biofortified varieties to up-scale their cultivation and production by engaging the private and public seed sector.

2.8 Frontier Technologies

Frontier technologies are known to have positive implications for the agricultural food systems. These include protected agriculture, precision agriculture, vertical farming and hydroponics, among others. Their adoption remains quite low especially in the developing countries. These are popular in east and southeast Asian countries. In these regions, their speedy adoption is reported (Takeshima and Joshi 2019). These are more popular for production of fruits, vegetables and flowers. Specific case studies on protected agriculture report earning of high returns (Rs. 5-10 lakh per year) by cultivating vegetables and flowers (Gondkar *et al.* 2016). The main drivers of adopting protected agriculture are farmers' education level, experience in protected farming and social interaction. The initial fixed cost is the main hindrance in adopting protected agriculture. However, the new research is launching low-cost protected agriculture systems.[9] For instance, inclusion of renewable energy (especially photovoltaic green house) structures in protected agriculture reduces the cost to a large extent. Based on the global review, it can be stated that the success of protected agriculture depends on various technological considerations, such as tunnel height, covering materials, shading structure, climatic control, frame, size of structure and energy sources. Other challenges include: (a) knowledge of the farmers about establishment of the structure, inclusion of crops and supply management, (b) emergence of new pests and diseases associated with a controlled environment, (c) heat management inside the protected agriculture structure, (d) quality and taste issues that are associated with the controlled environment, and (e) postharvest issues related to the dumping of waste materials (Takeshima and Joshi 2019). A study by Sopan (2011) shows that in Pune district of Maharashtra, there is a high concentration of protected agriculture because farmers have insufficient knowledge on supply chain management, cultivation and harvesting.

The second prominent example of a frontier technology is precision agriculture. Precision agriculture is the collecting of timely geospatial information on the requirement of soil, plant and animal, and accordingly, prescribing and applying site-specific treatments to increase agricultural production and protect the environment. It substantially reduces the cost of production and improves the input use efficiency (Shruthi *et al.* 2018). New tools such as remote sensing, Global Positioning System (GPS) and Global Information System (GIS) are applied for taking informed decisions on input use for maximising crop yields. It facilitates precise utilisation of agricultural inputs depending upon the crop, soil and weather requirement to optimize the use of fertilizers, pesticide and irrigation requirements for maximum productivity. The precision agriculture is eco-friendly and cost-effective, thereby, minimises use of water, herbicides, pesticides and fertilizers besides the farm implements. It automates and simplifies the entire management decision making process of the field by allowing application of agricultural inputs at the 'right time' and in the 'right amount', as and when necessary.[10]

Adoption of such technologies is largely limited to the developed countries, and there is an increasing attention for their application in developing countries. In India, the precision agriculture technologies are at a preliminary stage. Precision agriculture is being identified as one of the main thrust areas by the working groups of India and USA partnerships. Several states have taken initiatives to promote precision agriculture. Government of Tamil Nadu started a scheme called Tamil Nadu Precision Farming Project (TNPFP) to be implemented in Dharmapuri and Krishnagiri districts with coverage of 400 hectare of land (Mondal and Basu 2009). The crops proposed under the scheme are hybrid tomatoes, capsicum, babycorn, white onion, cabbage and cauliflower. A collaborative effort of private and public sector has established a new precision farming centre by M S Swaminathan Research Foundation (MSSRF) at Kannivadi in Tamil Nadu with financial support from NABARD. Such collaborative initiatives really holds the key. However, there are several constraints in the adoption of such technologies including small and fragmented farm size, lack of information, absence of agriculture extension, application of GIS and GPS, among others (Soman *et al.* 2013).

Third prominent example for the frontier technology is vertical farming. The vertical farming refers to a system of crop production that maximizes the use of land by having a vertical design (Kalantari *et al.* 2017). Japan is one of the leading countries in vertical farming. Asia accounts for about 20% ($ 0.3 billion) of the market values of vertical farming. One of the important advantages of the vertical farming is the scale of operation, and it requires smaller space as compared to the conventional farming. In terms of economic benefits, it saves land and water, reduces costs, provides higher yield, converts waste into assets, minimises risks due to droughts, floods and other shocks, and creates more jobs and employment opportunities. In India, the concept is at a very nascent stage, but needs to be popularised in view of smallholdings.

Another frontier technology is hydroponics. It is basically a method of cultivation of crops without soil by using mineral nutrient solutions in an aqueous solvent. As compared to conventional method of cultivation, hydroponics saves huge water. The other benefits include saving of land and huge costs, increasing crop yields and improving quality of produce.[11] It is free of chemicals, and the food from hydroponics is safe and healthy. Vegetables (like tomato, lettuce, cucumbers and several leafy vegetables), fruits (like strawberry) and cannabis, flowers and fodder crops are generally cultivated using the technique of hydroponics. There are some start-ups entering in agri-business and following hydroponics in urban areas. The technique needs to be popularised among small and marginal farmers to increase their income.

2.9 Digital Technologies

Adoption and diffusion of digital technologies in agriculture can help in transforming agricultural systems towards sustainability. A growing study on this subject shows that the adoption of technologies such as artificial intelligence, robotics, remote sensing image analysis, optical sensors and equipment design for monitoring have huge potential for sustainable development (UNCTAD 2021; Takeshima and Joshi 2019). According to Shang *et al.* (2021), the key determinants of digital agriculture technologies are the following:

(i) Farm size: it is positively associated with the adoption of such technologies.

(ii) Biophysical conditions: farmers with better quality lands and resources are more likely to adopt these technologies.

(iii) Complementary technologies: farmers who already adopted some digital technologies are more likely to advance it with the adoption of more such technologies.

(iv) Labour availability: farmers with permanent skilled labour are positively related with adoption decisions.

(v) Computer use: farmers with computer skills are positively associated with the adoption of digital technologies.

(vi) Innovative farmers: Innovative and risk-taking farmers are more likely to adopt digital technologies.

(vii) Capacity development: those farmers having received or are receiving training on the use of these technology are likely to follow the digital practices.

(viii) Information channels: an effective communication channel facilitate use of these technologies.

(ix) Technology attributes: higher the compatibility of digital technology with the existing technologies, the adoption is likely to be higher.

(x) Behavioural factors: higher the inclination of user for digital technologies, higher is the adoption.

A recent study by FAO (2019) shows some interesting examples and their impact on the agriculture food systems:

(i) Use of mobile applications to track the past and current prices helps farmers to strategise the production decisions for the future.

(ii) Mobile application designed to provide early warning about the disease among livestock are useful in mitigating the risks involved.

(iii) Agriculture robots on the farmers' field to process the information available, and help farmers to measure and optimise the input use.

(iv) Forecasting tool based geo-mapping, crop planning, individual farm plans, weather, soil, pest and crop data on an almost real-time basis to facilitate farmers in taking and executing optimal decisions on a real time basis.

(v) Artificial intelligence programming in providing real-time solutions to farmers.

The report further highlights the conditions for the success of a digital transformation. These include:

(i) Information technology (IT) infrastructure and networks in rural areas are the minimum conditions for better internet connectivity, its availability and affordability.

(ii) Digital literacy is a primary condition for the success of digital transformation. Effective operations of smart mobile phones, tablets and laptops are the key for the digital literacy.

(iii) Agripreneurial and innovation culture will promote digital agriculture.

(iv) Need for supportive policies and programmes for digital transformation.

3. Conditions for the Successful Adoption of Agriculture Technologies

In this section, key conditions for the successful adoption and implemen-tation of improved agricultural technologies are presented. The seminal research by Griliches (1957) concludes that the success of adoption of any improved technology relies both on supply and demand side factors. The author characterised the supply side, as origin of the technology, which is driven by its availability and enabling environment for its absorption. The demand side factors, which the author described as the speed of adoption, depends on profitability, availability of supporting inputs, government policies and facilitating institutions and infrastructure. Other studies concludes that if the profit-ability is a sufficient condition, the necessary condition depends on appropriate infrastructure and availability of well-structured organisational network (Joshi and Datta 1990). For a large-scale adoption, there should be a perfect symphony amongst technology traits, enabling policies, effective institutions and appropriate infrastructure. During the Green Revolution period, these were perfectly blended. It is evident that improved technologies were high yielding and giving substantially more profit than the traditional varieties. To support farmers, the government introduced the concept of minimum support prices (MSP) and assured procurement of rice and wheat. The banks were nationalised, and the agriculture sector was included as a priority sector to provide access to credit for the farmers. Each state also started their own seed corporation to ensure affordable seeds of HYVs to the farmers. Agricultural extension system was geared to disseminate components of improved technologies. During the same time, massive investment was made on developing irrigation infrastructure. Such an enabling environment led to the Green Revolution. In case of natural resource management technologies, an additional condition for success is the people's participation, and how institutional arrangements are made for sharing the cost and benefits. In this section, we shall be focusing on demand side factors such as agricultural extension, capital and knowledge. We have also reviewed some recent studies on how the direct cash transfer scheme is contributing to adoption of improved technologies.

3.1 Effective Agricultural Extension Service

Access to effective extension service is one of the most crucial factors for the adoption of agriculture technologies. The agricultural extension system in India started in 1953 as the national extension service to educate farmers about improved agricultural technologies and management practices.[12] Over the period of time, the agricultural extension system in India was reformed to suit the needs of the farming community. A new concept of Training and Visit (T&V) programme was introduced in 1974 with the support of the World Bank (Ameur 1994). Later, under the National Agricultural Technology Project (NATP), the Government of India with the support of the World Bank, established the Agricultural Technology Management Agency (ATMA) in 1998. The ATMA was first introduced in selected districts of seven states and later extended to all the districts and states (Babu *et al.* 2013). In 1974, Krishi Vigyan Kendras (KVKs) was established as a pilot to adapt and refine technology. Over the years, the KVKs were established in every district. Now there is a vast network of 722 KVKs in the country, which are connected with the agricultural technology generation system and the farmers as well as ATMA.

During the period of Green Revolution, the extension system played a key role in providing information about seeds of HYVs and improved management practices to the farmers. A large number of demonstrations were carried out to show farmers the benefits of HYVs and also their management practices. The concept of 'seeing is believing' was very effective in spreading the HYVs, which ushered in the Green Revolution in India. There are evidences that farmers who received the on-site training have had a significant impact compared to those who received only the information from extension agents (Kondylis *et al.* 2017). Varshney *et al.* (2019c) also reveal that the effect of demonstration-based extension system through KVK is stronger than the capacity building programmes. There are a number of studies that highlight the role of social networks in the adoption of agricultural technologies (Munshi 2004; Foster and Rosenzwig 1995; Matuschke and Qaim 2009; Varshney *et al.* 2019c). In particular, the study by Varshney *et al.* (2019c) based on KVKs showed that social interactions can generate information spillovers by 8-10 times. Therefore, social network is crucial, and should be accounted for while designing the agriculture extension programmes.

The effectiveness of agricultural extension depends upon the aspirations of the farmers to connect with the improved technologies (Joshi *et al.* 2016). Citing the example of maize revolution in the most backward district of Bihar, Joshi *et al.* (2016) show that farmers' aspiration to the choice of technology is the key driver for its large-scale adoption. It suggests that policies, while promoting improved technologies, should take into account the farmers awareness level and their aspirations. The available literature suggests measures for further strengthening of agricultural extension system, especially the KVKs. There is a need to connect farmers in a network mode for social-spillover with a targeted approach by taking into account the farmers' aspirations and needs.

3.2 Access to Credit

Both theoretical and empirical literature highlight the significant role of credit facilities for the adoption of modern technologies (Feder *et al.* 1985; Besley and Case 1993; Wossen *et al.* 2017; Fang and Richards 2018; Simtowe *et al.* 2019). Although credit is not a direct agricultural input, it facilitates farmers to meet the expenses needed in adopting improved agricultural technologies. Farmers can access credit either through formal financing institutions like commercial banks, cooperatives and microfinance groups, or through informal moneylenders at higher interest rates. Empirical studies in India reveal that access to credit is an important determinant of the adoption of improved agricultural technologies (Kumar *et al.* 2017; Varshney *et al.* 2019a; Kumar *et al.* 2020). However, there are reports that access to credit for small and marginal farmers is too low, and therefore, they rely more on informal sector despite the exorbitant interest rate.

To enable small and marginal farmers easy access to credit, the government introduced the scheme, known as the Kisan Credit Card (KCC). There are reports that access to KCC is positively associated with the adoption of modern cultivars. According to a study by Varshney *et al.* (2019a), the elasticity of adoption probability was estimated as 0.041, while the elasticity of use intensity as 0.032. The higher elasticity of adoption probability than that of use intensity indicates that access to KCC may be more important for the adoption of improved technologies than for use intensity. A study by Kumar *et al.* (2021) reveals that farmers with access to KCC could earn more than non-KCC farmers. By the end of 2020, there were about 6.5 crore active KCCs taking advantage of the formal credit system. To further expand the use of KCC, the Government of India, under the *Atma Nirbhar Bharat* programme, has issued 1.8 crore KCCs with a credit limit of Rs. 1.68 lakh crore by February 2021. This was expected to benefit 2.5 crore farmers. More efforts are needed to further expand the formal credit to small and marginal holders in backward and marginal environments.

3.3 Human Capital

A rich body of the literature reveals the importance of human capital in adopting improved technologies and attaining higher returns. In particular, the education level along with learning outcomes matter the most for the adoption of improved technologies (Patrinos *et al.* 2020). Education and skill development matter starting from the choice of technology to its appropriate implementation. Varshney *et al.* (2019b) highlight that the innovators and early adopters are those who have attained higher education levels. KVKs are accessible to innovators, but not to the early adopters. Therefore, it is argued that the education level along with training and skill development are necessary for adopting improved technologies and attaining higher returns.

3.4 Direct Benefit Transfer

Growing evidence suggests that cash transfer schemes raise the likelihood of adoption of improved technologies. Recently, the government has introduced the cash transfer scheme, known as PM-KISAN, with the aim to provide income support to farmers for easing their liquidity needs and to facilitate timely access of inputs. The scheme has significantly helped in purchase of seeds, fertilizers and other inputs. The farmers need not rely on informal moneylenders to buy key inputs (Varshney *et al.* 2020). It was noted that the time of the cash transfer is very important for incurring expenses for agricultural inputs. Interestingly, the impact of the scheme in adopting improved technologies would be higher if the farmers are connected with the KVKs. It suggests that the cash transfer (through PM-KISAN) complements the knowledge (through KVK) for higher impact. Further study shows that the fungibility of funds received under the government transfer package was significant in alleviating credit constraints and increasing expenses on agricultural inputs (Varshney *et al.* 2021). The beneficiary farmers of PM-KISAN scheme spent significantly more on the procurement of improved seeds, fertilizers and pesticides compared to the non-beneficiaries. Such social safety nets can play an instrumental role in providing assistance to marginal and small farmers, whose accessibility to credit schemes is low. Therefore, the cash transfer scheme such as PM-KISAN could increase the productive investment capacity of farmers to achieve the long-term goals of farmers' welfare.

4. Agriculture Research and Development: Investment and Returns

Investment in agriculture, both by the public and private sectors, is the key for its growth and prosperity. The rationale for the public investment in the agriculture sector is driven by (a) economic inefficiencies because of market failures, (b) inequalities in the distribution of goods and services, and (c) its potential to trigger private investment (Mogues *et al.* 2015). The inefficiency in markets arises from public good, risks, externalities, information asymmetries and so on. The equity issue stems from the fact that the majority of the poor in developing countries depends on the agriculture sector for their livelihoods. Hence, the argument is that the government expenditure is important in those components which boost agriculture sector, especially agriculture research, extension and infrastructure (roads, irrigation, markets, etc).

Often questions are raised on the impact of investment on agriculture, especially agricultural research and technology dissemination. Studies based in Asia, Africa and Latin America show that the investment in agricultural research and development (R&D) is highly productive and significant in improving efficiency and equity objectives (Rosegrant *et al.* 1998; Thirtle *et al.* 2003; Fan *et al.* 2008; Mogues *et al.* 2015; Perez and Rosegrant 2015). A cross region study reveals that the impact of agriculture research led technological change is more pronounced in Africa and Asia compared to Latin America (Thirtle *et al.* 2003; Mogues *et al.* 2015). It also shows that the financial allocation to agricultural research has been accompanied by a rise in physical and monetary value of agricultural output. Perez and Rosegrant (2015) simulated the impact of altering the TFP from the current 1.6% to 2% by 2030, on agricultural productivity, cultivated area and food prices. It clearly reveals that technological change (higher TFP) is expected to increase crop area and agricultural productivity by 2.4% and 8.5%, respectively. As a result of higher production, the cereal prices may come down by about 15%. Hence, investment in agriculture research and development not only benefits farmers directly through improved incomes, but can benefit the poor through reduced prices to address the food security concerns.

Is India investing enough in agriculture sector and agricultural R&D systems? We explore this issue by comparing the spending in agriculture and agricultural research in selected countries including Bangladesh, Pakistan, Brazil, China, Russia, South Africa and India. Figure 10 presents the share of agricultural expenditure as percentage of the agricultural GVA. In India, there is an increasing trend in the agriculture spending over the time. However, India's spending in agriculture is lower than in China. In 2017, India spends 6% of the agricultural GVA compared to 30% in China.

Earlier studies in India have shown that the public investment on sectors such as roads, irrigation, education, energy and R&D play significant role in improving agricultural productivity and reducing poverty. The returns to investment in agricultural R&D on enhancing agricultural productivity have a larger impact compared to other sectors. The marginal returns from additional investment on irrigation systems, roads and agricultural R&D during the 1960s to 1990s were positive, and the contribution of agricultural subsidies was decelerating during same period (Fan *et al.* 1999; Fan *et al.* 2008). A study by Bathla *et al.* (2017), covering the period 1990 to 2010, reveals that

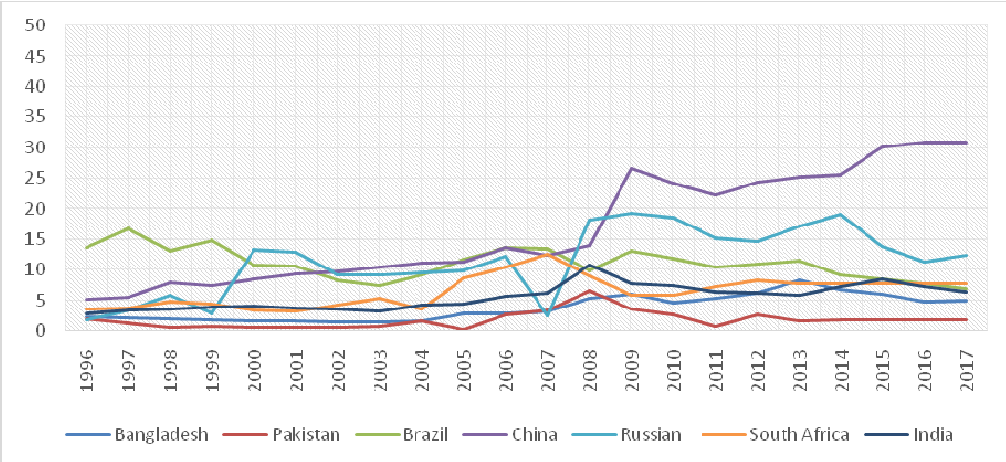
Table 4: Rate of Return to Agricultural Research and Extension in India

Sector	Metric	Year	Impact	Authors
Agriculture Extension	Marginal internal rate of return	1956-87	45%	Evenson *et al.* (1998)
Agriculture R&D (public)	Marginal Internal Rate of Return	1956-87	55%-58%	Evenson *et al.* (1998)
Agriculture R&D (private)	Marginal Internal Rate of Return	1956-87	35%	Evenson *et al.* (1998)
Agriculture R&D	Simulation	1970-1993	Investment of Rs. 100 billion in Agriculture R&D would increase productivity growth by 7%	Fan *et al.* (1999)
Agriculture R&D	Returns in Agriculture GVA of Rs. 1 investment	1960s	Rs. 3.12	Fan *et al.* (2008)
Agriculture R&D	Returns in Agriculture GVA of Rs. 1 investment	1970s	Rs. 5.9	Fan *et al.* (2008)
Agriculture R&D	Returns in Agriculture GVA of Rs. 1 investment	1980s	Rs. 6.95	Fan *et al.* (2008)
Agriculture R&D	Returns in Agriculture GVA of Rs. 1 investment	1990s	Rs. 6.93	Fan *et al.* (2008)
Agriculture R&D	Internal Rate of Return	1990-2007	42%	Chand *et al.* (2012)
Agriculture Extension	Returns in Agriculture GVA of Rs. 1 investment	1981-2014	Rs. 2.64	Bathla *et al.* (2017)
Agriculture R&D	Returns in Agriculture GVA of Rs. 1 investment	1981-2014	Rs. 2.32	Bathla *et al.* (2017)
Agriculture Extension (KVK)	Benefit to Cost Ratio	2003-13	8-12	Kumar *et al.* (2019)
Agriculture Extension (KVK)	Spillover impact	2018-19	8-10 times	Varshney *et al.* (2019c)

Notes: R&D refers to research and development; KVK refers to Krishi Vigyan Kendra; GVA refers to gross value added.

Source: Compiled by the authors.

Figure 10: Agriculture Expenditure in Select Countries (% of Agriculture GVA)



Source: FAOSTAT

the marginal returns for agricultural R&D, education, health and energy were higher compared with other services including subsidies, roads and surface irrigation.

The rate of return from investment in agricultural research and extension are very high as shown in Table 4 (Evenson *et al.* 1998; Fan *et al.* 1999; Fan *et al.* 2008; Chand *et al.* 2012; Bathla *et al.* 2017; Kumar *et al.* 2019; Varshney *et al.* 2019c). During 1956-87, the marginal internal rate of return of agricultural extension was about 45%, and that of agricultural research was between 55% and 58%. However, it decelerated to 42% during 1990-2007. The corresponding rate of return were 35% for investment in agriculture research by the private sector. A simulation exercise for a period 1970-97 by Fan *et al.* (1999) reveals that an investment of Rs. 100 billion in agriculture research and extension would increase agricultural productivity growth by 7%. In terms of returns to the agricultural GVA, the study reveals that investment of Rs. 1 on agriculture research and extension would contribute to Rs. 3.12 in agricultural GVA in the 1960s. For the 1970s, 1980s and 1990s, the estimates were Rs. 5.9, Rs. 6.95 and Rs. 6.93, respectively. This suggests that returns to research and extension on agricultural GVA are consistent over time. However, during 1981-2014, the returns on agricultural GVA decelerated to Rs. 2.32. Bathla *et al.* (2018) showed that the marginal returns to public investments in agricultural R&D, roads, energy and irrigation are generally higher in the low-income agriculture-dominant states, suggesting for a location-specific investment strategy.

The returns to investment in frontline extension system (like KVKs) reveals a very high benefit-cost ratio of 8 to 12 under different scenarios (Kumar *et al.* 2019). Consistent with this study, Varshney *et al.* (2019c) indicate that one rupee investment in agricultural extension system through KVKs is paying 8 to 10 times through the diffusion of improved technologies. A more granular analysis by Chand *et al.* (2012) reveal that one-fourth of growth in the output of wheat and cotton, one-fifth in case of pearl millet and around one-eighth in paddy and maize have been achieved due to investment on agricultural research. Overall, the agriculture spending in India is lower compared to the neighbouring and competing nations. The cross-country evidence highlights that the investment in the agriculture R&D have a huge potential in achieving higher marginal returns. In the context of India, the empirical evidence for the recent period suggests that the returns to agriculture extension is relatively higher compared to agriculture R&D.

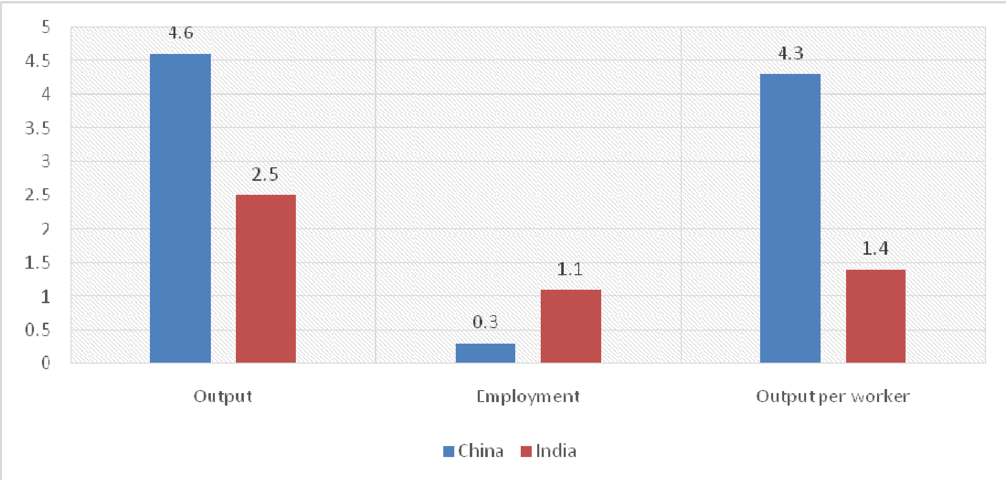
5. Learning from International Experiences

A comparison is being made between India and China to learn lessons to further improve the performance of the agriculture sector. Bosworth and Collins (2008) examine the sources of economic growth for India and China for the period 1980-2005. During the period, the per capita GDP has almost doubled in India, but increased seven times in China. The study analysed the sources of growth by decomposing it into agriculture, industry and services.

The agriculture sector has grown by 4.6% per annum in China compared to 2.5% per annum for India from 1978 to 2004. Figure 11 presents the rate of growth (annual rate of change) of output, employment and output per worker for the agriculture sector. It shows that the employment growth in the agriculture sector is 0.3% in China compared to 1.1% for India. In terms of output per worker, the annual growth in China was 4.3% compared to 1.4% for India.

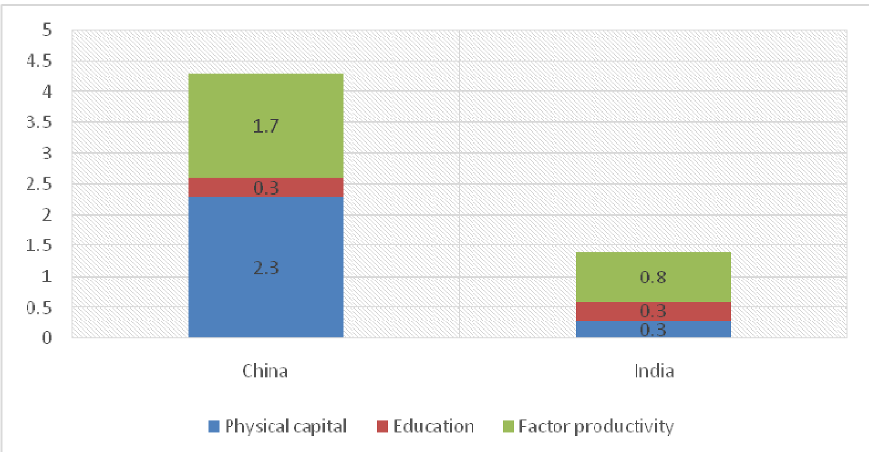
Figure 12 presents the contribution of physical capital, education and TFP to the output per worker. The physical capital contributes 2.3% annually in China compared to 0.3% in India. This suggests that the investment in the physical capital drives a large part of the agricultural growth. The contribution of education is almost same for both China and India. The contribution of TFP is 1.7% for China and 0.8% for India. This suggests that technological intervention is the second important

Figure 11: Growth Rate of Output and Employment, 1978-2004 (annual rate of change)



Source: Bosworth and Collins (2008)

Figure 12: Contribution to Output/Worker, 1978-2004 (annual percentage change)



Source: Bosworth and Collins (2008)

factor for driving China's growth. India needs to learn from the Chinese experiences by allocating more resources in agriculture and agricultural research for continuous flow of improved technologies. It is clear that the future agriculture research and extension would need more resources for developing new technologies to address multiple challenges.

We have also tried to examine the institutional and policy reforms that explains China's progress through by agriculture research and agriculture extension systems. One of the major institutional reforms in China was that of the household responsibility system (HRS) or contract responsibility system, which was implemented between 1978 and 1984. In HRS, farmers as a relatively independent economic entity contract for the collective land. Several studies show the HRS accounted for 30% - 50% of the total rise in agricultural output during the period 1978-84 (Fan 1991; Lin 1992; Huang and Rozelle 1996). McMillan *et al.* (1989) demonstrate that the HRS accounted for 90% of the rise in TFP between 1978 and 1984. Empirical evidence suggests that the reform not only result in increasing agricultural productivity, but also helps in shifting farmers from cereals towards high value crops and livestock. Another major reform was initiated in 2000s to facilitate land consolidation (Huang and Ding 2016). Additional notable innovation in land institutions was the introduction of three separate land rights, namely, village collective landowner rights, individual household land contract rights and land operation rights.

China has also initiated a number of reforms in agriculture research and extension system since the 1980s. These reforms have been classified in four stages as follows:

1. In the first stage (1979-1985), the number of agricultural research institutes has increased from 597 to 1,428. At the same time, the total agricultural research staff increased from 22,000 to 1,02,000.

2. In the second stage (1986-1998), the Chinese government emphasised on the commercialisation of agriculture R&D activities. The government changed the budget allocation system from planned base to competitive base (Jin and Jou 2005). However, it resulted in reducing the number of researchers from 1,02,000 to 65,000.

3. In the third stage (1999-2006), the Chinese government focused on the transformation of the agriculture R&D towards enterprise-based research and development. To do so, the country has classified agriculture R&D institutes into three functional types, namely, public R&D institutes which were fully funded by the government, science and technology service institutes partially funded by the government, and technology development institutions led by the private sector in a phase-wise manner.

4. In the fourth stage (2007-), a significant expansion of funds for the agricultural research were allocated. The technology innovation system, with 50 subsystems for agricultural commodities, has been established. As a result, the number of public sector agricultural researchers in China had reached 96,300 by 2010 itself (Hu *et al.* 2012).

Babu *et al.* (2015) compared the agriculture research and extension system of China and India with a focus on their goals, institutional structure, investment and human capital. Mandate of National Agricultural Research System (NARS) system in both China and India is to push agriculture production to meet the national food security. In China, NARS is publicly dominated and highly decentralised in terms of management and funding. India follows the agricultural research council model, centred on the Indian Council of Agriculture Research (ICAR). China's NARS is largely funded by the public investment and through competitive funding. While India's funding moves through block grants from the central government to ICAR and State Agricultural Universities (SAUs) as determined by five-year plans (till 2014). In China, there are 1,215 agricultural research institutes and 67 agricultural universities with 55,061 fulltime staff in 2012. In contrast, India has 100 ICAR research institutes and 70 agricultural universities with 9,328 fulltime staff. This clearly indicates that China has larger infrastructure, more human resources and higher funding for agricultural research, extension and education. Therefore, funding for agricultural research, extension and education needs to be expanded strategically in India.

6. Conclusions and the Way Forward

In this study, an attempt has been made to examine the adoption of improved agricultural technologies related to the genetic enhancement, natural resources management, fertilizers, farm machineries, conservation agriculture and climate smart technologies. Further attempt has also been made to assess the scope of genetically modified crops, frontier technologies and digital agriculture. The main objectives of this review were to investigate: (a) What are the adoption levels of improved technologies and their impact on farmers' income, agricultural production, natural resources and environment? (b) What are the constraints in up-scaling improved technologies and to analyse conditions for success of their adoption? (c) What is the rate of return of agriculture research and extension system? and (d) What can be learnt from the global perspective on agriculture research and extension services?

The review shows that the adoption of improved technologies varied across commodities and geography. Adoption of improved technologies have shown a positive impact on agricultural productivity and agricultural production. More specifically, these have an impact on increasing farmers' income, conserving natural resources, improving input use efficiencies, generating employment opportunities and promoting diversification. However, defective policies and incentives have led to degradation of natural resources, especially a fall in water table and deterioration of soil health. Improved technologies also generated employment opportunities in the non-farm sector through strong linkages between farm and non-farm sectors. Demand and supply side factors, such as extension, credit, human capital, technology traits, institutional barriers and enabling environment, play a crucial role in the adoption of improved technologies. Small and fragmented size of land holdings, education level of the farmers, access to knowledge systems and availability of irrigation also determine adoption of improved technologies. Therefore, land consolidation through institutional reforms, connecting farmers with technology delivery systems and markets, and strengthening agricultural credit system are to be addressed for faster and wider adoption of improved technologies.

Social networking is important for faster adoption of improved technologies, but was almost ignored in the past. It is suggested that the social networking should be a part of the strategy for promoting improved technologies. The study also noted that a perfect symphony is needed amongst technology traits, policies, institutions and infrastructure for the accelerated adoption of improved technologies.

Investment in agricultural research and extension significantly contribute to increasing productivity and agricultural growth in India. But the spending in agricultural research and extension in India is lower compared to China. This largely explains the slow agricultural growth in the country compared to China. The cross-country evidence highlights that the investment in the agriculture R&D have a huge potential in gaining the marginal returns. Therefore, there is a need to strategise the investment in agriculture research and extension to generate and disseminate improved technologies to different agro-climatic regions.

New challenges, such as climate change, degradation of natural resources and undernourishment, need a different approach and larger research resources. It appears that future agricultural research would be more capital intensive, and this would require modern tools, infrastructure and upgraded skills. Next-generation technologies, such as climate smart agriculture, frontier technologies and digital agriculture, require a different approach in technology generation and their dissemination. There is a need to reform agricultural research and extension system by allocating more financial resources, improving capacity of human resources, creating an enabling management structure, promoting multi-disciplinary and multi-institutional research, strengthening public-private partnership, and developing appropriate research infrastructure.

Notes

1. Other elements of the Green Revolution include adoption of modern inputs, scientific methods of farming,

2. The IR-8 was short, stiff strawed and yield between 5 and 1 0 ton per hectare. It is developed by the International Rice Research Institute (IRRI).

3. Available at: https://www.pib.gov.in/PressReleasePage.aspx?PRID= 1746942.

4. The study distinguished between new (released after 2004) and old cultivars (2004 or before) based on the release year.

5. Soil Health Card (website: www.dac.gov.in).

6. Joshi *et al.* (2019) examined the willingness to pay (WTP) for a labour-saving technology (known as direct-seeded rice). The study shows that women value more WTP for this technology compared to the men, as they account for a large family labour in the paddy cultivation.

7. Available at: https://www.plantcelltechnology.com/blog/tissue-cultures-application-for-horticultural-crops/

8. Available at: https://www.harvestplus.org/where-we-work/india

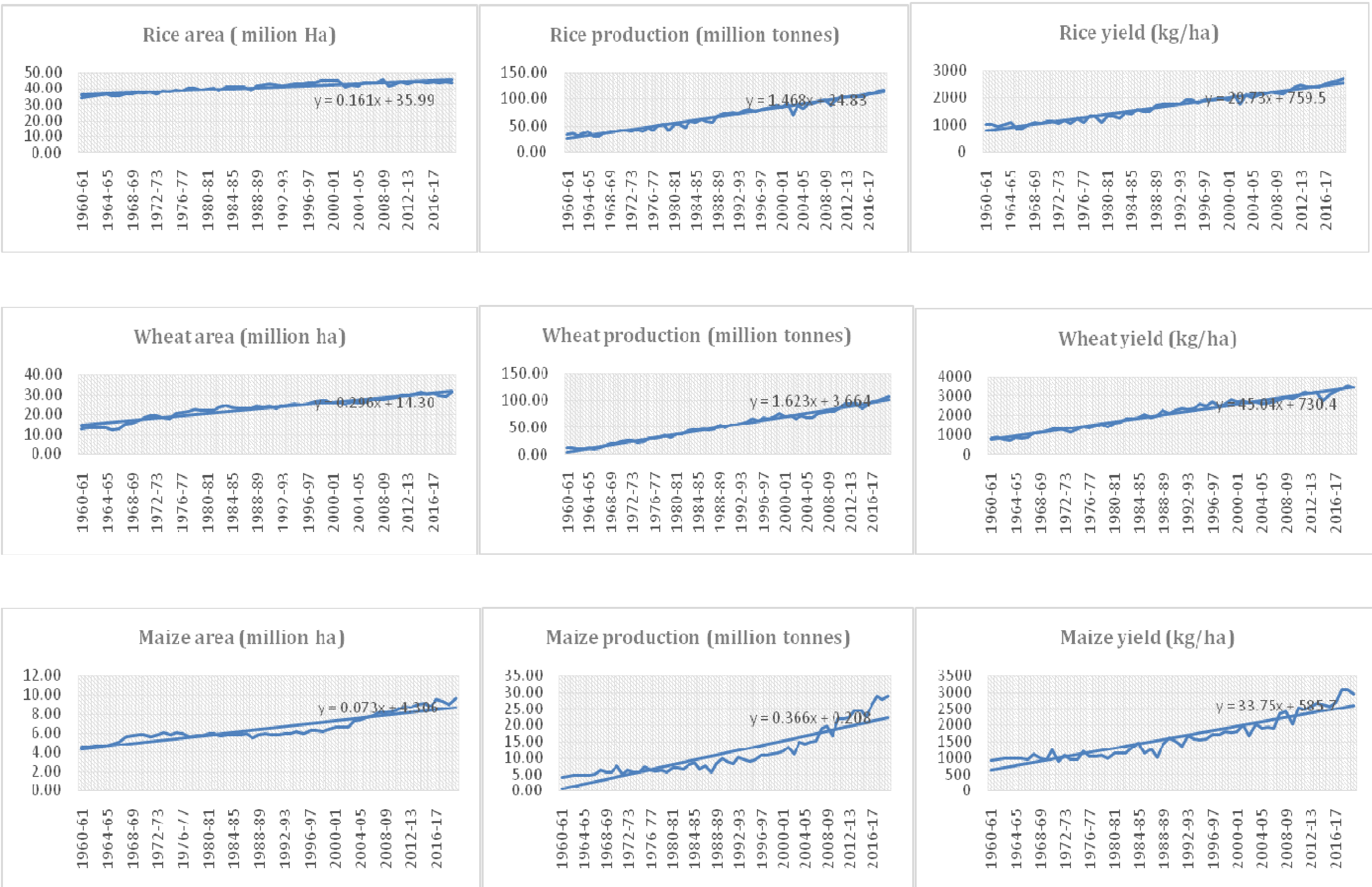
9. In China, the agriculture research focuses on the adoption of Photovoltaic (PV) greenhouses structures which have reduced the costs.

10. Available at: https://www.precisionag.com/in-field-technologies/precision -agriculture-in-india-new-technologies-are-here-but-wide-scale-adoption-is-far-off/

11. Available at: https://www.freshwatersystems.com/blogs/blog/what-are-hydroponic-systems

12. Intensive Agricultural District Programme (1960), Intensive Agriculture Area Programme (1964) and High Yielding Varieties Programme (1966). For more details, see Gulati *et al.* (2018).

Appendix Figure A1: Trends in Area, Production and Yields of Major Crops, Fruits and Vegetables, 1960-2020

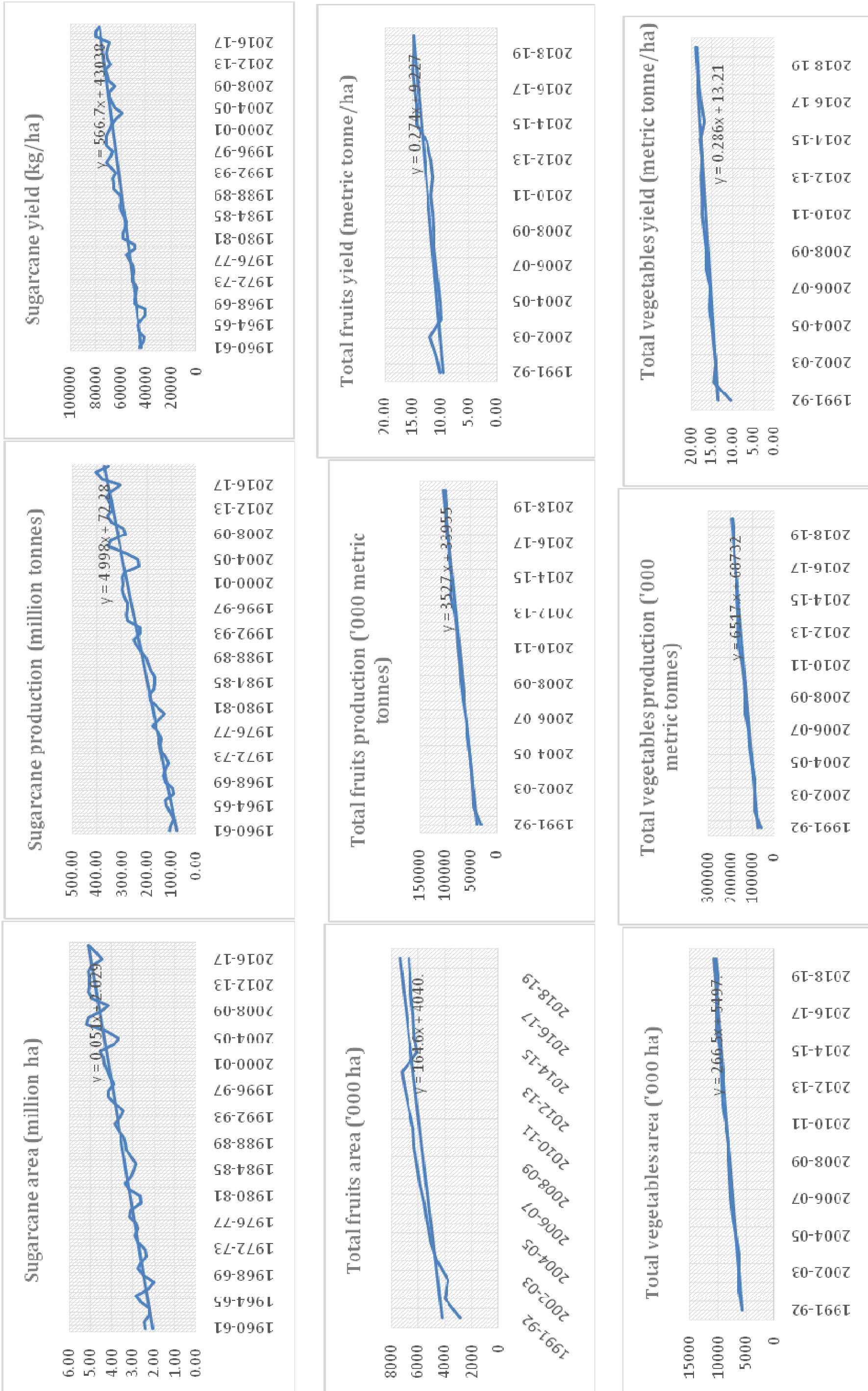


(Contd....)

Appendix Figure A1: Trends in Area, Production and Yields of Major Crops, Fruits and Vegetables, 1960-2020 *(Contd...)*

(Contd....)

Appendix Figure A1: Trends in Area, Production and Yields of Major Crops, Fruits and Vegetables, 1960-2020 *(Concluded)*



Source: Ministry of Agriculture and Farmers Welfare, *Agriculture Statistics At Glance, 2020*, Government of India, New Delhi. Ministry of Agriculture and Farmers Welfare, *Horticulture Statistics At A Glance 2018*, Government of India, New Delhi.

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About The Authors

Dr. P. K. Joshi superannuated as Director-South Asia, International Food Policy Research Institute (IFPRI), Washington D.C. Prior to this, he was holding the positions of Director, ICAR-National Academy of Agricultural Research Management and Director of the ICAR-National Centre of Agricultural Economics and Policy Research.

Dr. Joshi has received Dr M S Randhawa Memorial Award of the NAAS, Dr R C Agarwal Life Time Achievement Award of the Indian Society of Agricultural Economics, Life Time Achievement Award of the Pantnagar Alumni Almamater Advancement Association and Global Leadership Award by the Indian Chambers of Food and Agriculture. He is presently President of the Agricultural Economics Research Association and Secretary of the NAAS. Dr. Joshi has served as Chairman of the SAARC Agricultural Centre's governing board in Dhaka, Bangladesh, Chairman of the UN-CAPSA governing board in Bogor, member of the BRICS-Agriculture group, and member of the intergovernmental panel on the International Assessment of Agricultural Science and Technology for Development.

Dr. Joshi has extensively worked towards transforming agriculture and integration of commodity markets in India, and many south and southeast Asian countries. He has published more than ten books and several journal articles in national and international journals of repute.

Dr. Deepak Varshney is Assistant Professor at the Development Planning Centre, Institute of Economic Growth, New Delhi. He worked as a consultant to various international organisations including the IFPRI, the World Bank, and the International Water Management Institute. His research mainly focuses on agriculture technology, public policy, impact assessment, agriculture and labour markets, which were published in the national and international journals of repute. His recent work on the impact of India's social assistance package amid COVID-19 on the agriculture sector appeared in the top agricultural economics journals including *Applied Economics and Perspective Policy* and *Agriculture Systems*.

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Department of Economic Analysis and Research
NATIONAL BANK FOR AGRICULTURE AND RURAL DEVELOPMENT
Plot No. C-24, 'G' Block, BKC, Bandra (E), Mumbai - 400 051