Challenges for India in agriculture and the pivotal role of R&D in meeting these

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Abstract

Agriculture globally must meet the challenge of feeding a growing population while minimizing its environmental impacts. For India, there is an additional challenge of making farming profitable for small landholders. I assess the possibility of achieving low-input, high-output agriculture for India; low-input both in terms of natural resources and monetary inputs. Input, output analysis shows that bringing about low-input, high-output agriculture would require curbing the over-exploitation of groundwater resources, soil analysis-based use of fertilizers, conservation agriculture, crop diversification, and doubling of the crop and livestock productivity. Crops need to be protected from pests and pathogens, and abiotic stresses; this will require significantly increased investments in public-funded R&D. Research competency will have to be improved for an effective blending of conventional breeding with the New Plant Breeding Technologies – Marker Assisted Breeding, Genetic Engineering, and Gene Editing. Open-source R&D, collaborations within India and beyond the country with CG institutes and advanced laboratories will improve competency, allow bundling of desirable traits in locally adapted varieties/hybrids, keep the cost of seed low for the small landholders in South Asia and Africa, and overall help in achieving the United Nations SDG 2 of 'Zero Hunger'.

Keywords. Low-input, high-output agriculture; groundwater over-exploitation; conservation agriculture; crop yields; plant breeding; genetic engineering

Introduction

Around 44% of India's population of 1.38 billion are landowners and depend on farming for a living; most of them are small landholders. Besides, many living on the rural side, although not landowners, earn their livelihood from agriculture-related activities. Agriculture, therefore, is not only central to the food and nutritional security of the country but also to poverty alleviation and national prosperity. A viable, resilient, and profitable farm sector is essential for doubling the farmers' income and achieving the ambition of a five trillion dollar economy.

The concept of low-input, high-output agriculture, is akin to the much-discussed idea of sustainable intensification (Godfray et al. 2010; Foley et al. 2011; Godfray et al. 2014; Rockstrom et al. 2017) - more food with less environmental impact, except that in addition, it also seeks to reduce the monetary inputs as the average landholding in India is only around 1.08 hectares (ha) as compared to average farm size of 179.68 ha in the United States and 16.1 ha in the European Union. Landholdings in China and India are similar; therefore, comparisons between the two countries are more pertinent. I examine the data available on the input components listed in Fig 1 and analyse whether the current use of the listed inputs is excessive, optimal, or sub-optimal. The analysis is based either on cross-country comparisons or on meta-analysis studies available in the literature.

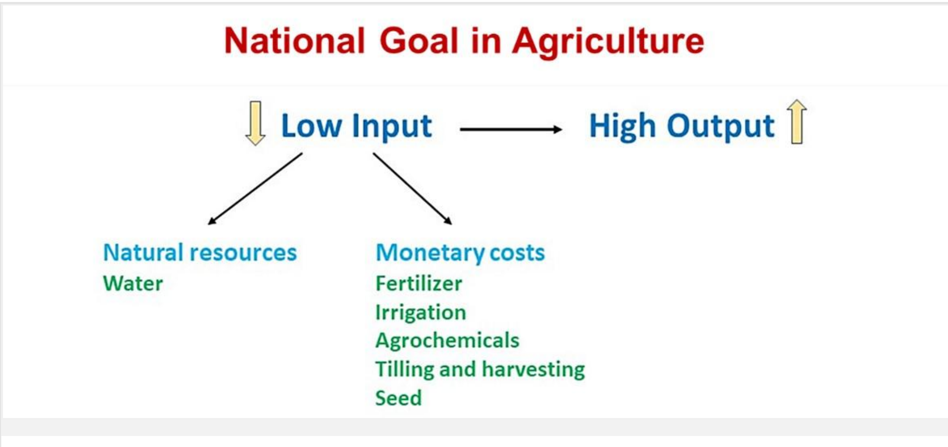

Fig 1 Major inputs that have been analysed in the Perspective

Part 1 of the Perspective deals with some key historical developments in agriculture and an analysis of the inputs and outputs as these exist at present. Part 2 deals with the global status of R&D in agriculture and where India is lagging. Part 3 makes some recommendations on the interventions and reforms required for R&D to contribute towards low-input, high-output agriculture in India.

1 Part 1: Historical developments in agriculture and input, output analyses

1.1 Global population explosion and the role of agriculture

A big shift in human evolution occurred around 12,000 years ago when a sedentary mode of living started around agriculture in the fertile crescent. Several crops and animals were domesticated in the fertile crescent and later in other parts of the world (Doebley et al. 2006). There is strong evidence that warming of the planet and increased moisture availability allowed a shift from a tribal nomadic structure to larger community life. Till 1700 the global population growth rate was around 0.4%. Famines, epidemics, high infant mortality, and wars kept population growth in check. The big population explosion occurred from 1800 onwards, more so in the 20th century – pushing the numbers from 1.96 billion in 1900 to the current level of 7.8 billion (Fig 2).

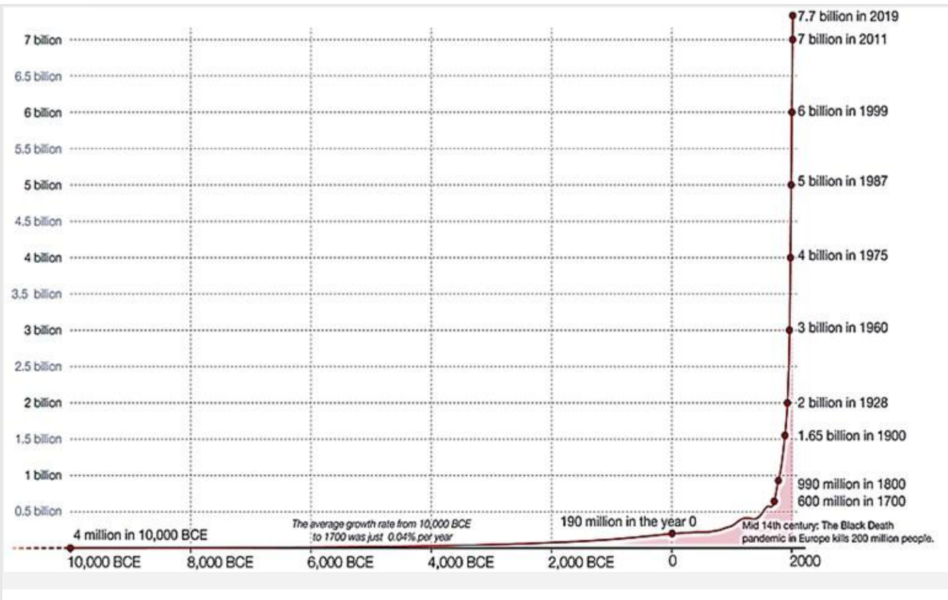

Fig 2 Size of the world population over the last 12,000 year

A United Nations report (World Population Prospects 2019) predicted the global population to peak at 11 billion in 2100. A new forecast (Vollset et al. 2020) predicts the global population to peak around 9.7 billion in 2064. Even with this more comforting prediction – there will be an additional 2 billion people. The population of India will peak at 1.6 billion in 2048.

The global population explosion resulted from better community hygiene through potable water treatment and sewage management, and modern medicine - vaccines, drugs, and diagnostics. Humanity's escape from hunger and premature death since 1900 has been well described by Fogel 2004. Everyone looks forward to technologies that protect human life; however, there is extraordinarily little awareness and appreciation of how the food and nutrition requirements of a current global population of 7.8 billion have been met.

Four post-1900 developments have contributed to feeding the world:

- Nitrogenous fertilizers (Haber-Bosch process)
- Mechanization
- Crop protection chemicals
- Systematic plant breeding

The population increase in the 20^{th} century was hugely supported by the Haber-Bosch process of converting atmospheric nitrogen to ammonia. Estimates suggest that pre-1900 agriculture with all the land currently under cultivation would not have supported more than 3.5 billion people (Smil et al. 2004; Erisman et al. 2008).

1.2 Green Revolution and the importance of plant breeding

Fig 3 explains how the world has defeated hunger and, in many parts, achieved both food and nutritional security by synthetic fertilizers, mechanization, agrochemicals, and some seminal breakthroughs in plant breeding – hybrids in maize (corn), dwarfing genes in wheat and rice (Kingsbury et al. 2009). The introduction of dwarf wheat and rice in Asia in the 1960s brought about the Green Revolution which saved millions of people from starvation. Between 1961 and 2018, the global area under cereal crops increased only by 12%; however, yields per hectare increased by 201% and total production by 238%.

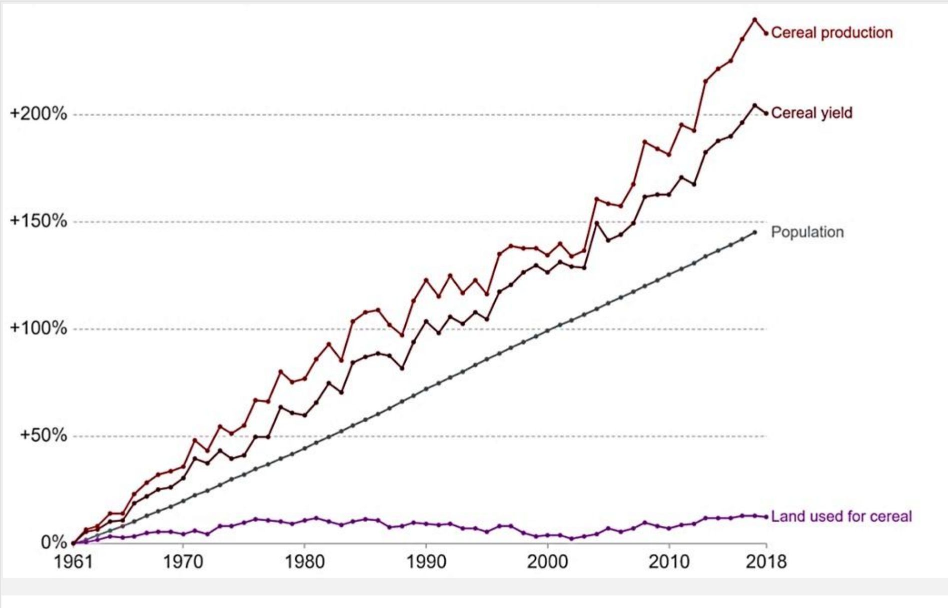

Fig 3 Change in cereal production, yield, and land use since 1961

It is fashionable among ideologues and urban elites to criticize the Green Revolution in Asia for bringing forth high-input agriculture. It is little known that the Green Revolution technologies had already been implemented in the developed countries before they reached the developing world. These technologies helped the developed countries as much as these helped Asia; results looked more dramatic in Asia as a catastrophe of widespread famine and resulting political instability was averted.

Fig 4 illustrates trends in wheat yield in one of the world's dominant economies over the last few centuries – the UK. Till 1930 there was only a limited increase in the yield of wheat, significant increases occurred only after 1960 with the deployment of non-lodging, disease-resistant, higher-yielding varieties.

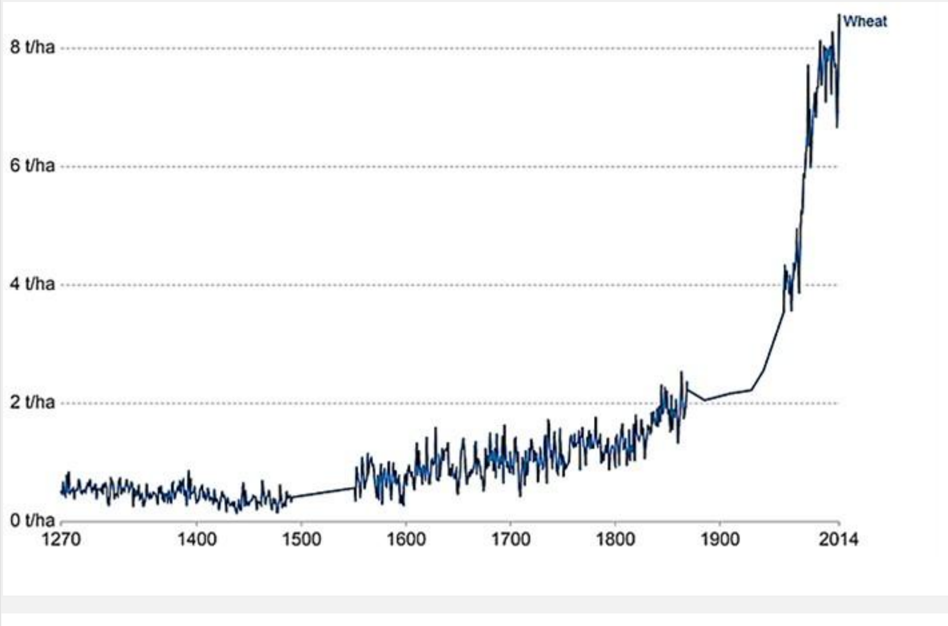

Fig 4 Long term wheat yields in the United Kingdom, 1270 onwards

Fig 5 illustrates the impact of plant breeding on maize (corn) yields in the United States. The significant increase in productivity came from hybrid corn in the 1940s. The average yield in 1940 was 2 t/ha; presently, the average yield has crossed 10 t/ha.

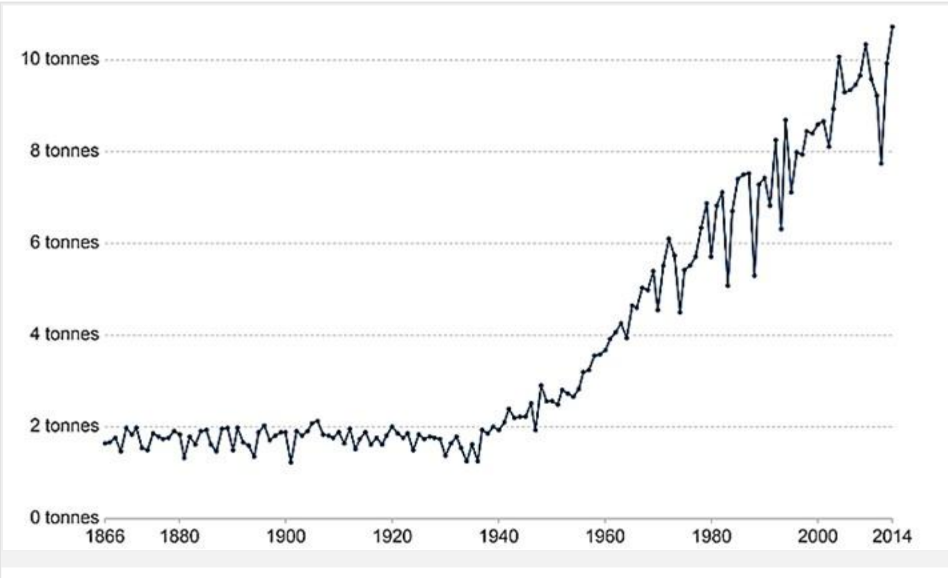

Fig 5 Average maize yields in the United States, 1866 onwards

Currently, the continent where the least yield increase has occurred is Africa. Africa is still struggling with both food and nutritional security. The South Asia region is self-sufficient in cereals but is struggling with nutritional security. In India, a public distribution system (PDS) backed by the National Food Security Act provides subsidized food, mostly cereal grains, to more than 800 million people with low incomes. This meets the calorie requirements but does not fulfil the overall nutritional needs leaving around 196 million people undernourished, which include 26 million children under five that are wasted and around 47 million stunted (Global Hunger Index 2019). The overall cost of PDS in 2021-22 has been estimated to be around Rs 2,42,836 crore (Economic Survey 2020-2021).

India can certainly produce more as I will argue in this Perspective; however, a weak manufacturing sector and underemployment resulting in lack of purchasing power is the real cause of undernutrition. Compared to India, the East Asian countries, with higher economic growth than India have almost achieved both food and nutritional security.

1.3 Natural resource inputs - water in Indian agriculture

India receives annually around 4000 bcm (billion cubic meter) of rainfall, large by any standards. However, a major part of it falls in eastern India. Moreover, most of the rain is received within 100 hours of the torrential downpour, making water storage and irrigation critical for agriculture in the country. In 1890 undivided India had 12 mha of irrigated land compared to the next highest 3 mha in the United States, 2 mha in Egypt, and much less in other parts of the world (Shah 2009). Currently, India has one of the highest water usages for agriculture in the world. The country has made huge investments in large dams and canals (all publicly funded) and wells (mostly private investment). Much of our food security is based on irrigation. Fig 6 provides comparative statistics on water usage in agriculture in three large countries of the world – India, China, and the USA. Both China and the US have either flattened or even reduced their water requirement for agriculture. The demand for water for agriculture in India has steadily increased.

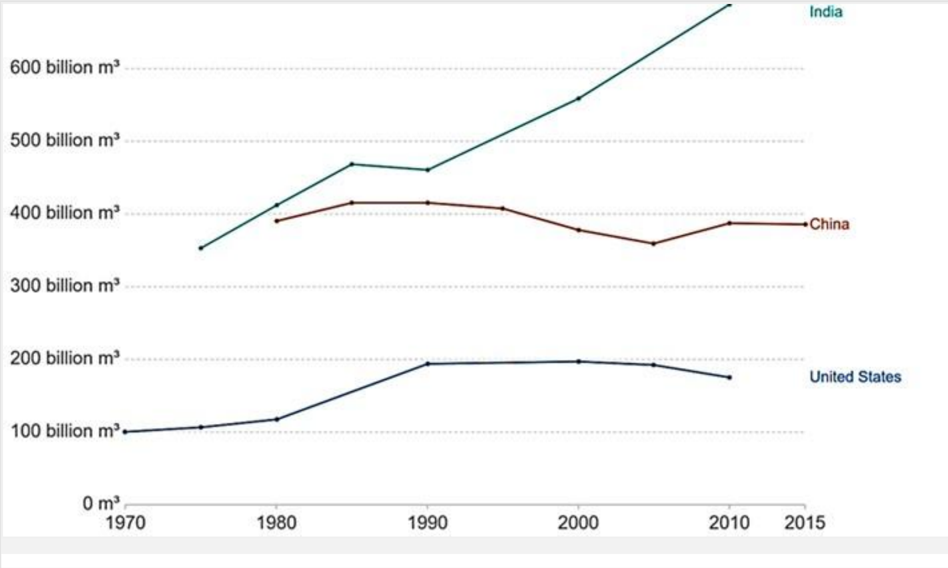

Fig 6 Freshwater usage in agriculture in select countries

Table 1 shows total water withdrawals and the share of three major users of water – agriculture, industry, and municipal services in three large countries. India is overconsuming water for agriculture, leaving the other two sectors short of water.

Table 1 Water withdrawals, sector-wise in three large agricultural countries

Water withdrawals in bcm*	**India**	**China**	**USA**
Agriculture	688 (90.5%)	385.2 (64.4%)	176.2 (39.7%)
Industry	17 (1.2%)	133.2 (22.3%)	209.7 (47.3%)
Municipal usages	56 (7.4%)	79.4 (13.2%)	58.4 (8.1%)
Total water withdrawal	761	598.1	443.3

Note bcm* – billion cubic meters.

The biggest threat to sustainability and long-term prosperity in India emanates from overexploitation of the groundwater resources. The data for over withdrawals of groundwater in India has come from two sources – The GRACE (Gravity Recovery and Climate Experiment) satellite pair that circled the earth at the same altitude about 200 km apart (Rodell et al. 2009) and a survey of lowering of the water levels in deep wells (Central Ground Water Board Annual Report 2018-19). Both types of studies have shown much higher levels of withdrawals against replenishments. Out of the 688 bcm of water used for irrigation, around 230 bcm is pumped groundwater, irrigating about 45 Mha of the gross cropped area. In the year 2019, around 21 million electric, 8.8 million diesel, and 0.13 million solar pumps were operational in the agriculture sector. However, the worrying signs are from the number of deep tube wells; in 1987 the number of deep tube wells was around 0.1 million, by 2014, the number had increased to 2.6 million. Deep well withdrawals increase capital as well as energy costs. In 1965 around 3465 mU (8% of the total generated) of subsidized electricity was provided to the farmers for pumping groundwater. In 2016, this amount was 173,185 mU (17% of the total electricity generated) (Suhag 2016).

The total estimated groundwater depletion in India is in the range of 122-199 bcm as calculated from the observation wells (1996-2016) and GRACE-based data (2002-2016). The depletion of groundwater is the highest in Punjab, Haryana, Rajasthan, and western UP, the regions under very intensive agriculture. The problem of groundwater depletion is becoming more acute due to lesser rainfall in India's north-western parts during the monsoon season (Asoka et al. 2017).

To conclude – India is overexploiting its groundwater resources; this does not augur well for the long-term sustainability of agriculture. A large percentage of available water is being used for agriculture; this will affect the country's overall prosperity as sufficient water may not be available for the other sectors of the economy – particularly, manufacturing.

1.4 Fertilizer inputs and soil health

Fig 7 provides information on fertilizer usage in three large countries globally with a substantial area under agriculture – India, China, USA, and a country with a significant area under agriculture in Europe – Germany. The fertilizer use given in Fig 7 is based on total consumption in a financial year.

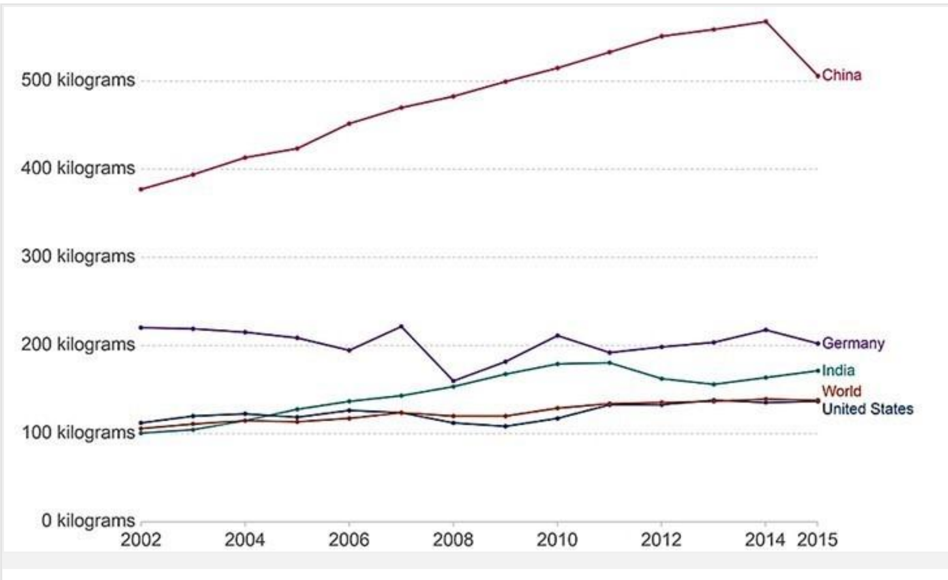

Fig 7 Fertilizer use per hectare of arable land in select countries, 2002-2015

Table 2 provides the data on land under agriculture in the four countries mentioned above, and the average per hectare use of nitrogen, phosphorus, potassium components, and manure based on the total harvested area under crops.

Table 2 Area under agriculture in select countries and fertilizer usage (2017 data)

	China	**India**	**Germany**	**USA**
Agricultural area mha	527.7	179.7	16.7	405.8
Arable land (temporary crops) mha	119.5	156.4	11.7	156.7
Land under permanent crops mha	16.2	13.0	0.2	2.7
Land under permanent pastures mha	392.8	10.3	4.7	245.3
Area harvested, crops (multiple crops + permanent crops) mha	186.7	204.2	8.8	102.5
Cropping intensity	~1.4	~1.2	~0.7	~0.6
Fertilizer usage (mean) cropped area kg/ha				
Nitrogen mostly as urea – N	159.5	88.1	170.2	113.7
Phosphorus as P_2O_5 - P	68.7	33.6	23.7	39.6
Potassium as K_2O - K	57.6	13.7	44.5	46.3
Total NPK kg/ha	283.8	129.4	238.4	199.6
Manure input (estimated by N content) kg/ha	25.6	11.02	85.9	23.9

Germany is almost one crop a year country. Most of the arable land in the US is also under one crop a year. Both China and India have an extensive area with multiple crop sowing. In 2016-17, India's net sown area was around 140 mha, but the gross cropped area, including the area under permanent crops, was around 204.2 mha.

For land under cultivation – the overall quantity of inorganic fertilizers used in India is not excessive. However, there are serious imbalances in the usage. Intensively cultivated irrigated areas under wheat-rice and rice-rice cropping cycles use far more fertilizer than the dryland and high rainfall areas. Further, there is an imbalance in the use of the three major components N, P, and K (Table 2) – N use is disproportionally higher than that of K. To keep the food prices low, the Government of India subsidizes the cost of fertilizers; in the financial year 2019-20, fertilizer subsidies amounted to around Rs 81,124 crore. (Economic Survey 2020-2021). However, N fertilizers (mainly urea) are subsidized by 70% of the market price, P only by 35%; potash is all imported and expensive – leading to an imbalance in the use of the three macro components (Table 2). Indian soils, in general, are deficient in organic matter and micronutrient deficiencies are rampant.

Imbalance in the use of macro elements and microelement deficiencies can be best tackled by more rigorous implementation of the soil health card scheme of the Government of India and rationalisation of subsidies on the fertilizer components. Overall, reduction in usage is not possible, but optimization is.

1.5 Battle against pests - pesticide inputs

In the FAO terminology, crop pests include weeds, insects, rodents, nematodes, and pathogens – fungal, oomycete, bacterial, viral, and mycoplasmas. Total pesticide consumption in agriculture at the global level has increased from around 2.4 mT in 1990 to about 4 mT in 2011; thereafter, the consumption is steady (Fig 8). This flattening of the curve reflects the use of a new generation of chemicals that are effective in lesser quantities (Umetsu et al. 2020) rather than any reduction in the usage.

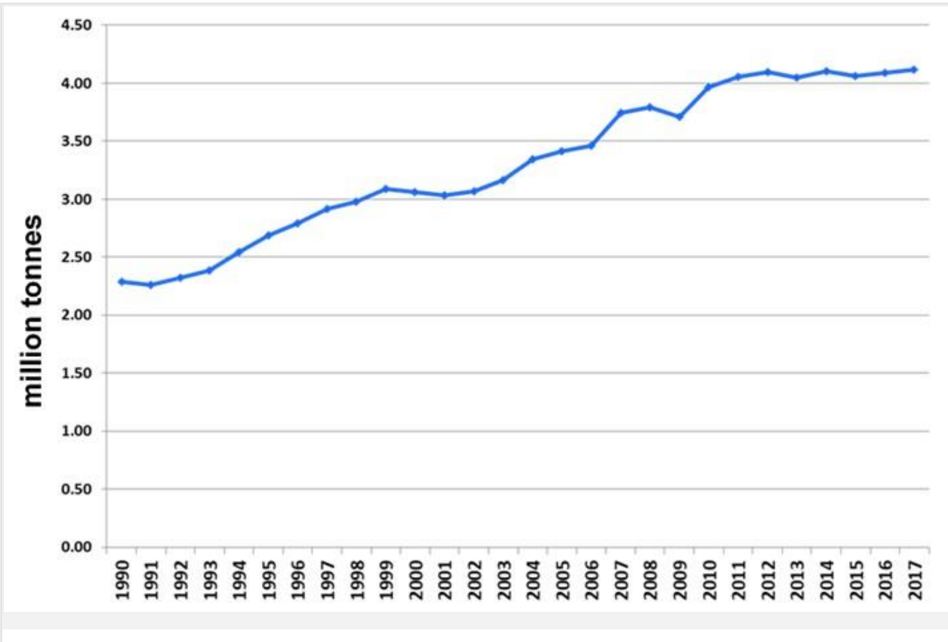

Fig 8 World pesticide usage per year since 1990

India is one of the lowest users of pesticides (Fig 9) – leaving the crops unprotected. Pesticide consumption in India is more akin to that in Africa than to the consumption in the developed countries (Table 3).

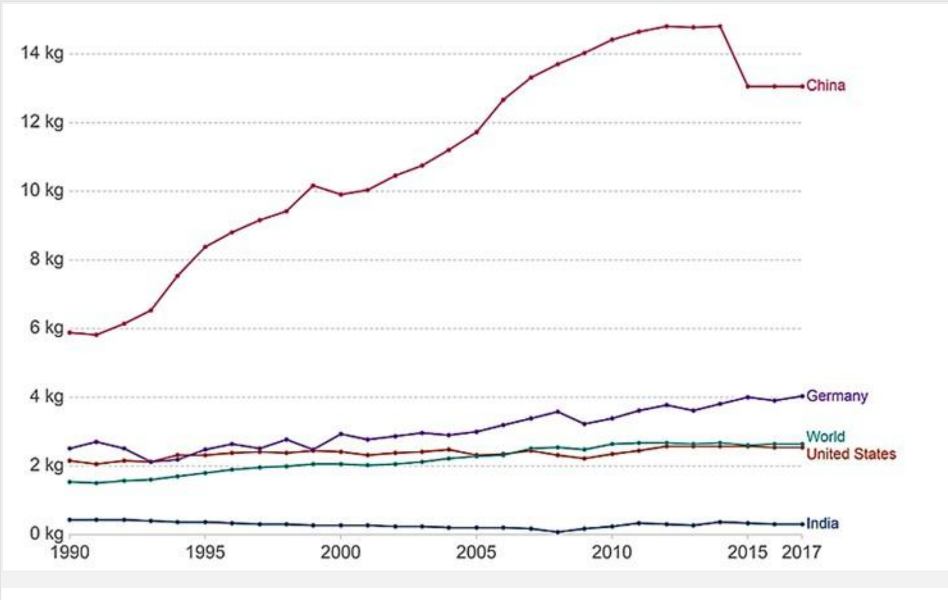

Fig 9 Pesticide use per hectare of cropland, 1990-2017

Table 3 Pesticide usage (kg/ha) in select countries and regions

Country/Region	1990	2014
Africa	0.31	0.30
China	5.87	14.82
EU	3.24	3.09
India	0.44	0.36
Japan	15.22	15.93
US	2.14	2.54

Despite the extensive worldwide use of pesticides, there are massive losses to pests (Oerke 2006). A recent global level study (Savary et al. 2019) on crop losses in the main food security hotspots (including the Indo-Gangetic plains) for five major crops showed significant losses to pests (weeds excluded) that ranged from 10.1-28.1% for wheat, 24.6-40.4% for rice, 19.5-41.1% for maize, 8.1-21% for potato, and 11-32.4% for soybean. These losses are despite the practised control measures. The highest losses were reported in the two food-insecure hotspots – the Indo-Gangetic plains and Sub-Saharan Africa. Losses in the two low-yield areas could be due to either warmer climate and or lack of access to more effective pesticides. It is projected that losses to insect pests and pathogens will increase with global warming (Deutsch et al. 2018; Velasquez et al. 2018).

A survey carried out in 2008 on the major yield-limiting factors in the crops extensively grown in India showed pests and pathogens to be the major constraints on the yield (Fig 10) (Grover and Pental 2003). A study conducted to estimate the yield and economic losses due to weeds between 2003-2014 by the All India Coordinated Research Project on Weed Management has revealed remarkably high losses to weeds in some of the major crops grown in the country (Table 4) (Gharde et al. 2018). Yield losses were recorded from the test plots where a standard practice of one round of manual weed removal was followed. The economic losses calculated for the ten crops are staggeringly high – around Rs 80,000 crore annually.

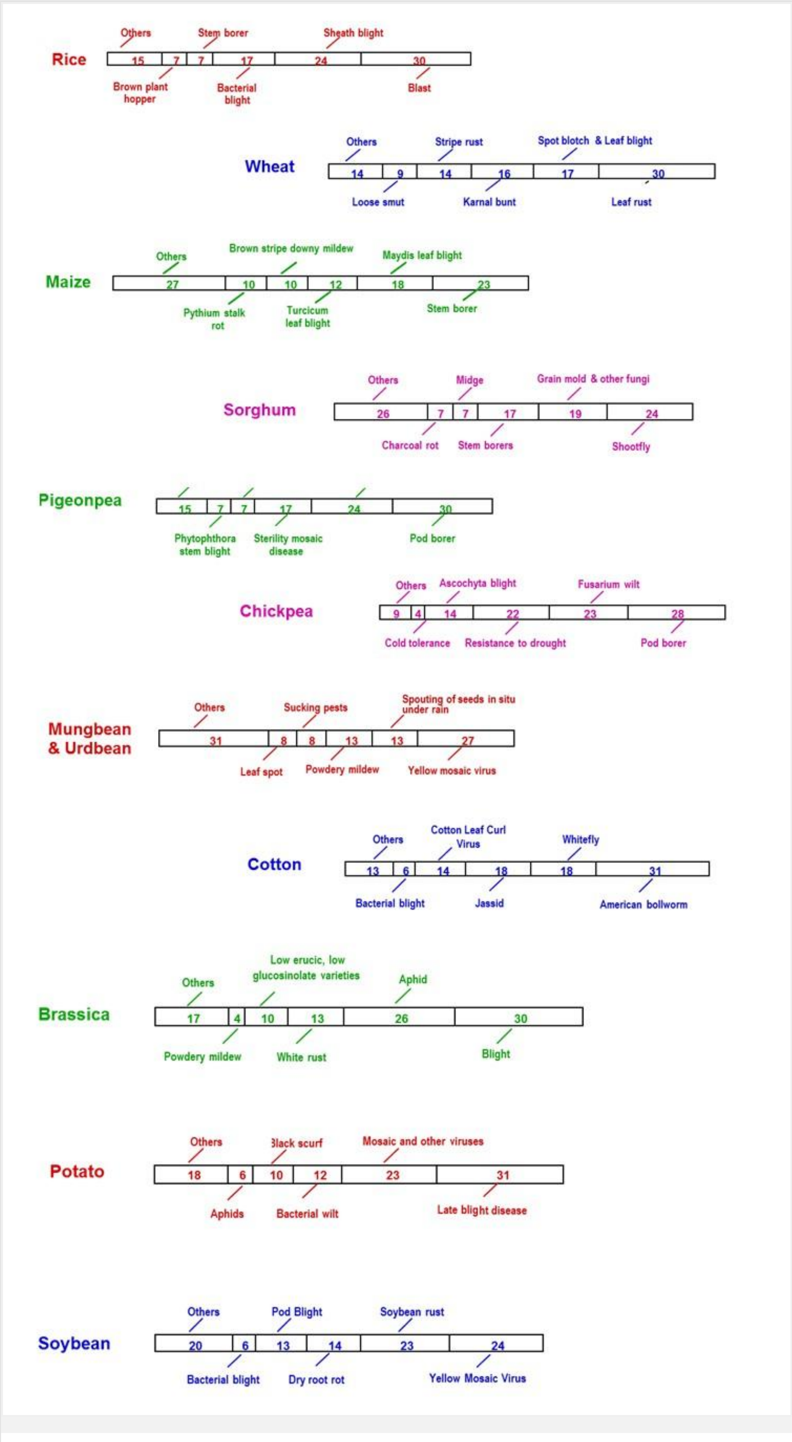

Fig 10 Major breeding objectives in crops grown in India

Table 4 Yield loss estimates due to weeds

Season	Crop	Mean yield loss (%)
Rainy	Transplanted rice	13.8
	Direct-seeded rice	21.4
	Soybean	31.4
	Groundnut	35.8
	Sorghum	25.1
	Pearl millet	27.6
	Green gram	30.8
	Sesame	23.7
Winter	Wheat	18.6
	Maize	25.3
	Mustard	21.4

Weeds can be controlled manually or by chemicals. Herbicides constitute almost 50% of the pesticide usage in the developed countries. Given that only 2-3% of the population in the developed countries is employed in agriculture, herbicides are an essential component of productive agriculture. India will require extensive use of herbicides for higher outputs. Environmentally more benign practices like conservation agriculture and aerobic cultivation of rice will undoubtedly require herbicides.

Pests, other than the weeds, can be controlled by chemical pesticides or by altering the crop's genetics. India currently is neither globally competitive in finding new chemical pesticides nor in finding and implementing gene-based solutions.

1.6 Outputs - crop yields in India

In general, the yields of major crops in India are lower than the global averages. I briefly describe the available information on the yield status of some of the major crops grown in India with some comments.

India has done good work on the breeding of rice, including the basmati types. Some of the released varieties are immensely popular with the farmers in different agro-ecologies. However, average yields in India are lower than the world average (Fig 11). Cultivation of rice in the north-western states of Punjab and Haryana and some of the areas in the southern states is a major threat to groundwater resources. China has increased yields significantly since the 1980s by hybrid breeding, better control of pests while being more frugal with the use of water resources; China uses ~1300 cubic meters of water to produce 1 tonne of rice, while India uses ~2800 cubic meters. In the financial year 2019, India exported rice worth Rs 54,000 crore.

However, this rice export translates into an export of 95 bcm of water – a substantial part of which is groundwater.

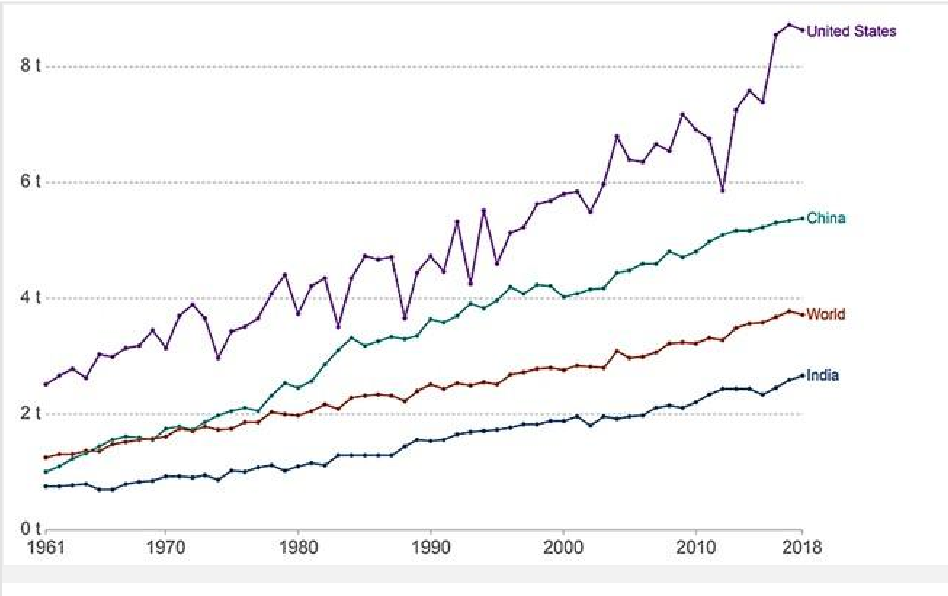

Fig 11 Rice yields (tonnes/hectare), 1961-2018

Wheat yields in India match global averages (Fig 12). However, the yields are significantly higher in China and Mexico, the country where the International breeding Institution on wheat and maize - CIMMYT is located.

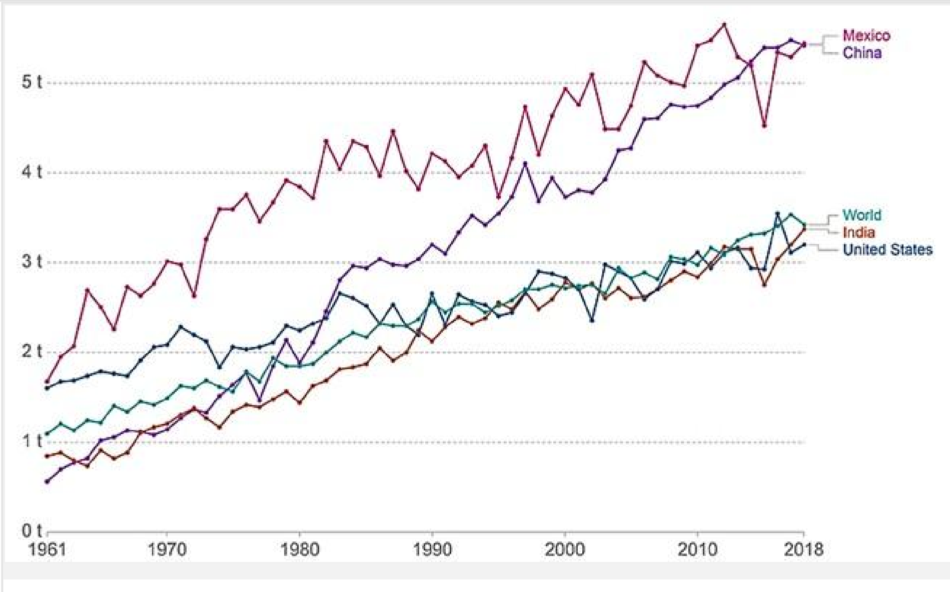

Fig 12 Wheat yields (tonnes/hectare), 1961-2018

Maize is being promoted as an alternative crop to rice. Yields are, however, much lower than the world average – the US being the global leader in yield and production (Fig 13). The best germplasm for maize hybrids is with companies like DuPont-Pioneer and Bayer-Cargill.

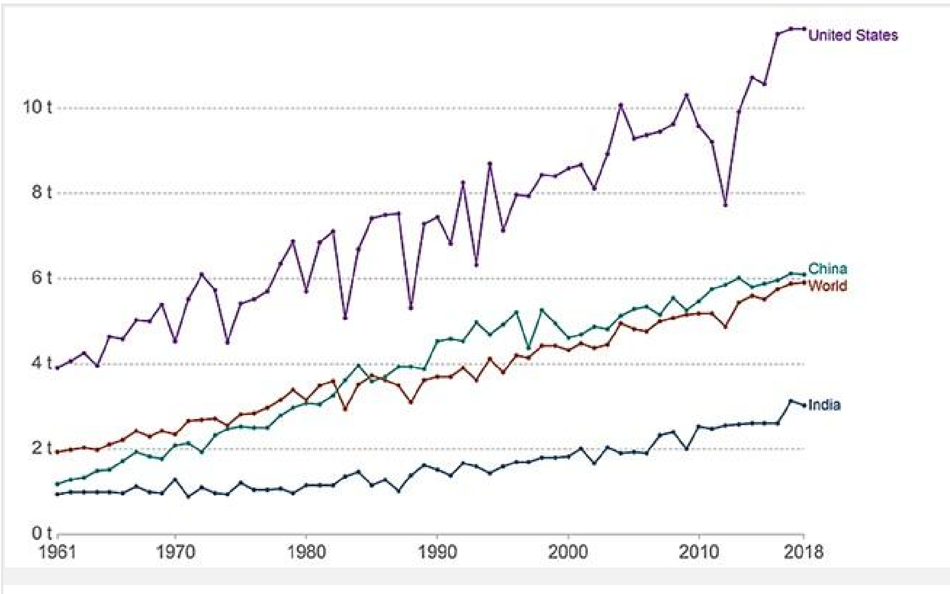

Fig 13 Maize yields (tonnes/hectare), 1961-2018

Sorghum and millets are projected as alternatives to wheat and rice for crop diversification and reducing water consumption. However, sorghum yields are stuck at 1 t/ha (Fig 14); pearl millet is a little better at around 1.5 t/ha (Fig 15). These crops are not viable alternatives for the irrigated areas - as yields despite the advantage of saving water are too low due to several biotic stresses (Fig 10).

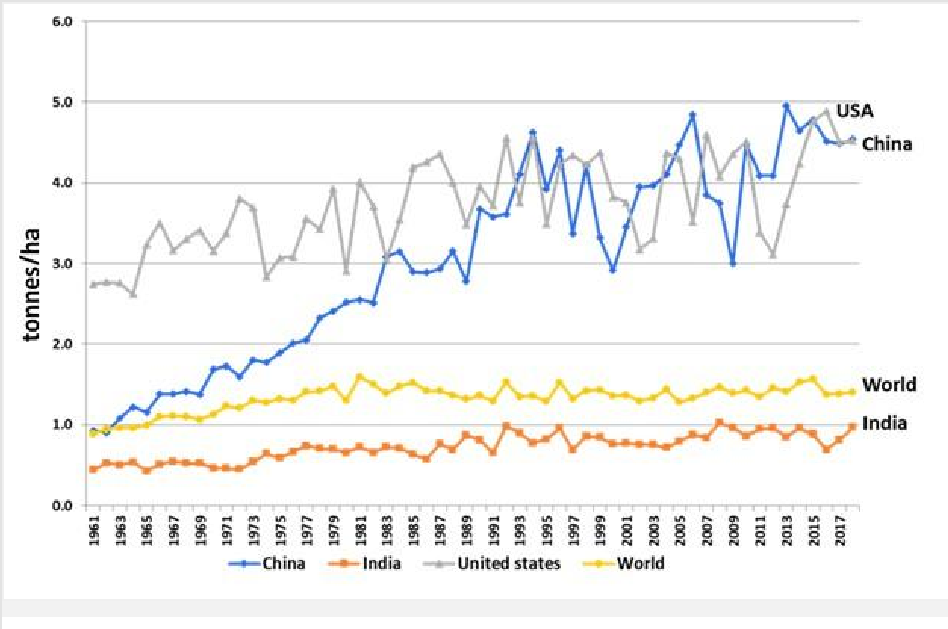

Fig 14 Sorghum yields (tonnes/hectare), 1961-2018

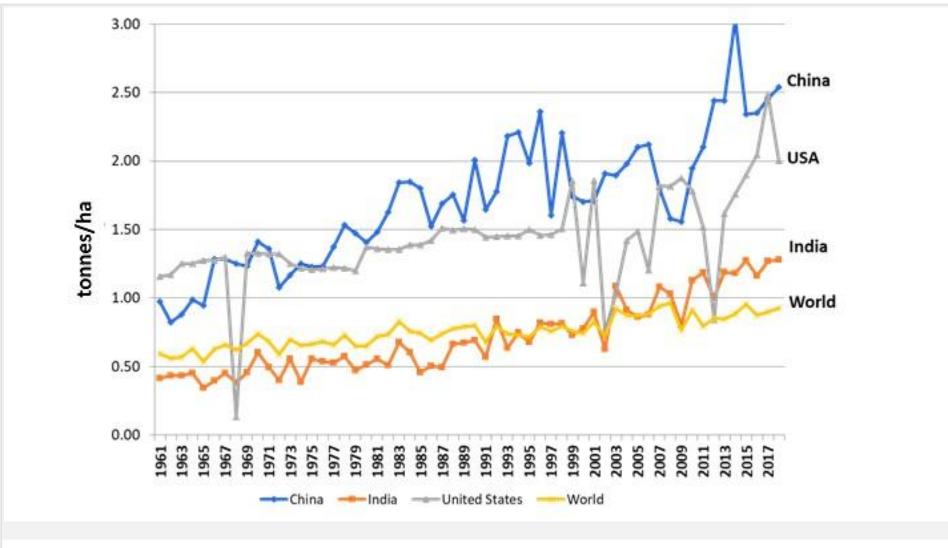

Fig 15 Millet yields (tonnes/hectare), 1961-2018

India's cotton yields are among the lowest in the world, despite some boost from Bt cotton since 2003 (Fig 16). The crop generates massive downstream employment – low yields should be a major concern.

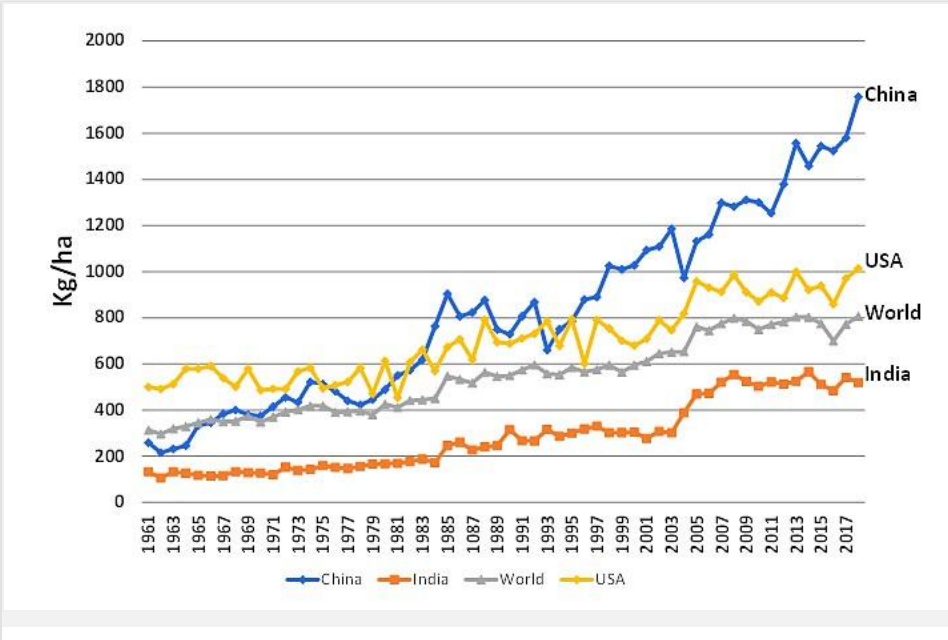

Fig 16 Cotton lint yields (kg/hectare), 1961-2018

Oilseed crops – groundnut, soybean, and rapeseed/mustard are potential crops for expansion to meet a huge edible oil deficit in India. In the financial year 2017-18, India imported around Rs 76,000 crore worth of edible oils (Fig 17). Yield data shows India has globally the lowest yields in the three oilseed crops (Fig 18, Fig 19, Fig 20). Globally hybrids in rapeseed have pushed up the yields. The worst performance is in soybean – a crop that can help improve both the edible oil production and meet the protein requirements of a large vegetarian population of the country. Improving the yield of oilseed crops should be a major thrust area.

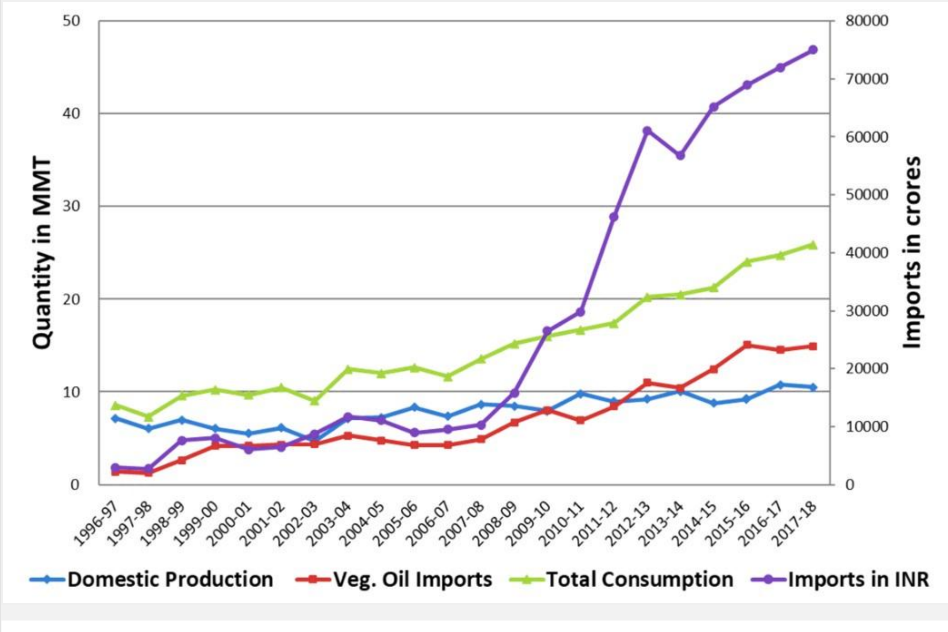

Fig 17 Domestic production and imports of vegetable oils: quantity in million metric tonnes, value in Indian rupee

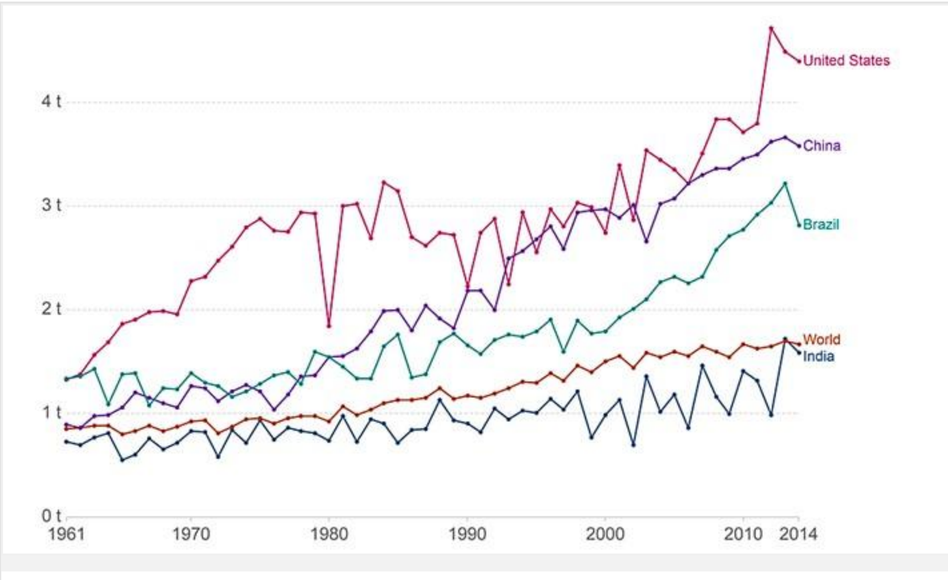

Fig 18 Groundnut yields (tonnes/hectare), 1961-2014

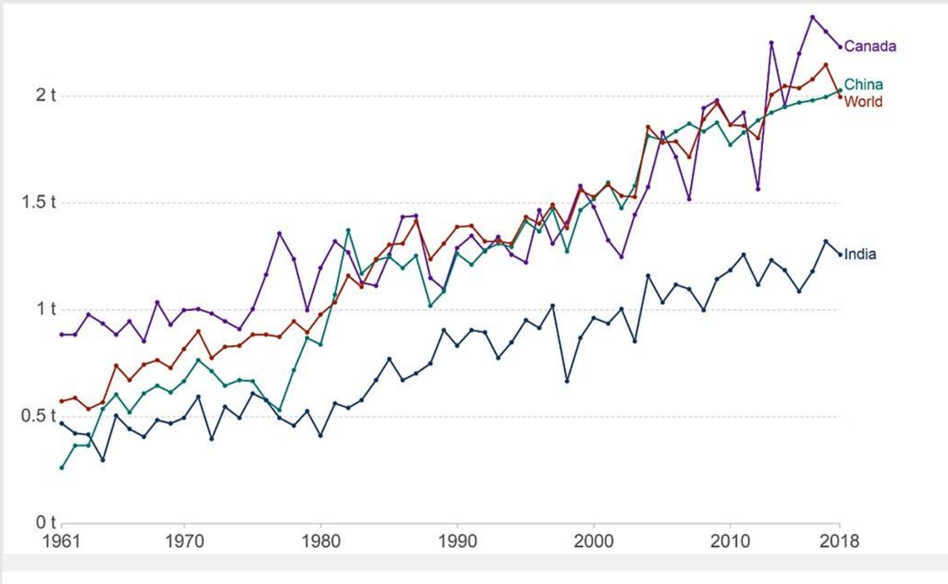

Fig 19 Rapeseed/mustard yields (tonnes/hectare), 1961-2018

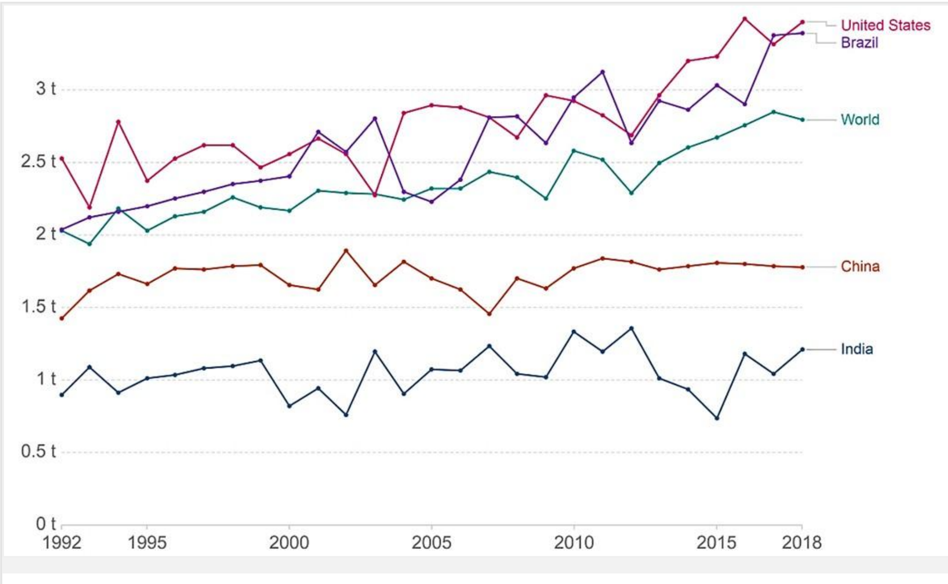

Fig 20 Soybean yields (tonnes/hectare), 1961-2018

1.7 Some conclusions from the input and output analysis

There are glaring imbalances in the inputs that are going into agriculture in India. Out of the total water consumption of 688 bcm, around 87% (more recent figure) is going into agriculture, leaving extraordinarily little water for the industrial sector and human needs. There is over-exploitation of groundwater reserves leading to a dramatic lowering of the water table, increasing investments into deep well boring, and higher energy costs of water pumping. Better utilization of water in agriculture would require the cultivation of less water requiring crops, conservation agriculture, aerobic cultivation of rice in the heavily irrigated areas, better methods of irrigation, and watershed development in the dryland areas to provide some level of protective irrigation to realize the yield potential of otherwise adapted crops.

Fertilizer usage in India is not excessive; however, there are imbalances in the use of the three major fertilizer components N, P, and K, and micronutrient deficiencies. There should be better utilization of manure, more extensive cultivation of legume crops as these fix their nitrogen and using fertilizer components based on proper testing of the soils.

The most significant agricultural output losses are from pests – weeds, insects, nematodes, fungi, bacteria, and viruses. The inputs of agrochemicals and plant breeding-based genetic enhancement in India are grossly inadequate to meet the challenge of pests, not only in the grain crops but also in the vegetable and fruit crops. R&D has a major role to play in crop protection.

Abiotic stresses reduce yields in a substantial way. The challenge posed by abiotic stresses is only going to exacerbate with climate change, particularly in the tropics and subtropics. While for the limited area crops, favourable agro-ecologies can be found in a large country like India, major crops will certainly require R&D-based solutions. India needs rice that can grow aerobically, wheat that is not affected by terminal heat stress, maize that can withstand waterlogging due to heavy downpours, meeting such challenges would require intensification of R&D efforts.

2 Part 2: Global status of R&D in agriculture and India's position

I analyse how the two areas - genetic enhancement through plant breeding and optimal use of agrochemicals are essential for achieving low-input, high-output agriculture. I describe the major global trends in R&D related to plant breeding and pesticides and what are the lessons for India from this analysis.

2.1 Agricultural R&D: Major global breakthroughs

The green revolution technologies were based on the effective use of germplasm and strong phenotypic selections. Astounding developments in molecular biology in the early second half of the 20^{th} century and their translation into recombinant DNA technologies since the 1970s have brought forth unprecedented new opportunities for genetic improvement of crops. In 2000, the genome sequence of the first flowering plant – A*rabidopsis thaliana*, a model plant species with a relatively small genome, was published (Arabidopsis genome initiative 2000). Since then, genomes of all the important crops - grain, vegetable, fruit, and forage have been sequenced. Earlier genome assemblies were carried out with shotgun Sanger sequencing, followed by short-read next-generation sequencing (NGS) technologies. The earlier assemblies have been improved in the last five years using long-read sequencing and more efficient scaffolding technologies (together called the third-generation technologies) to produce highly contiguous genome assemblies (Giani et al. 2020). More recently, germplasm in the primary gene pool and the wild relatives of some of the major crops have also been sequenced (Khan et al. 2020). The big challenge now is to make effective utilization of the enormous sequence data that is available. The new genomics assisted technologies of plant breeding, also called NPBTs (New Plant Breeding Technologies) can be grouped as follows:

- Molecular markers and marker-assisted breeding (MAB)
- Genetic engineering (GE)
- Gene editing (GEd)

Marker-assisted breeding is already proving to be useful in bringing precision and reproducibility into classical plant breeding (Moose and Mumm 2008; Bevan et al. 2017; Varshney et al. 2020). Tagging important traits with DNA markers takes time and effort but allows rapid diversification of the tagged traits into locally adapted varieties. All the developed countries and large seed companies have incorporated marker-assisted breeding as a routine activity in their crop and livestock breeding programs.

Genetic Engineering (GE) technologies, an offshoot of the recombinant DNA revolution, are exceptionally powerful technologies for improving crops. Any gene from any biological species can be cloned and introduced into a crop plant. A large amount of pioneering scientific work has gone into the development of GE technologies (Sussex 2008). A good illustration of GE technologies is BT cotton, where an insecticidal bacterial gene was introduced into the cotton plant to confer resistance to some important lepidopteran pests of the crop. Another example is golden rice, where genes from different species have been introduced into rice to improve the crop's β carotene content. Despite ideological opposition to GE technologies, the area under GE crops has increased from 1.7 mh in 1996 to around 191.7 mh in 2018 (Fig 21) (ISAAA 2019). The GE crops in the field have significantly contributed to the well-being of the small landholders and sustainability (Qaim 2020). The crop events currently in the field are just a glimpse of what can be achieved with the GE technology. There are huge untapped possibilities like breeding for more efficient nitrogen uptake and improving photosynthetic efficiency (Bailey-Serres et al. 2019). The use of GE technologies can contribute immensely to breeding for resistance to pests and pathogens (Pixley et al. 2019).

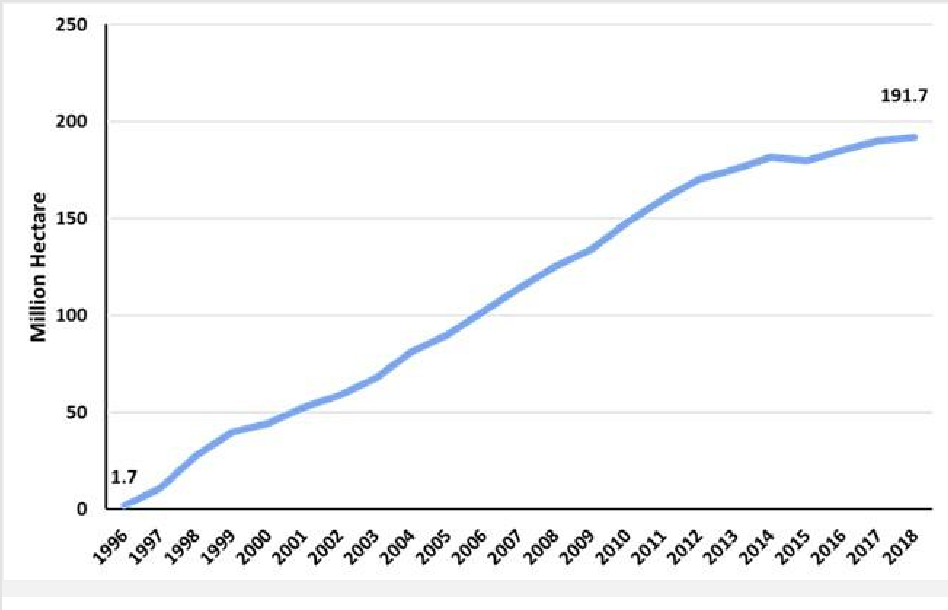

Fig 21 Growth in the area under GE crops

Gene editing (GEd) technologies, the latest addition to GE repertoire, allow precise mutagenesis. The CRISPR/Cas9 technology and its variants have immense implications for crop breeding. Earlier mutation breeding using chemical and radiation mutagens caused random mutations – many of these deleterious. As a result, despite so much activity in the 1950s and 60s, conventional mutagenesis contributed truly little to crop improvement. The new technologies allow targeted mutagenesis and are already proving to be of significant value in plant breeding (Chen et al. 2019; Wada et al. 2020).

India's efforts in breeding with all the three NPBTs – MAB, GE, GEd are half-hearted and below the thresholds required for meeting some of the challenging breeding objectives. There is currently virtual paralysis on the use of genetic engineering (GE) and gene editing (GEd) technologies.

The Green Revolution was based on conventional breeding methodologies, and there was remarkable openness in terms of the exchange of germplasm and the availability of advanced breeding lines. The new plant breeding methodologies based on the recombinant DNA revolution are mostly under strict IPR. The Bayh-Dole Act in the US in 1980 allowed the federally funded research in the universities/institutions to be patented and passed on to companies on an exclusive basis through commercial agreements. Thus, in most of the developed world, science and technology developments are mostly funded with public money, and R&D for product development and marketing is with the private companies.

The two commercialisation models, one being followed by the developed world and the other by India, are compared in Fig 22.

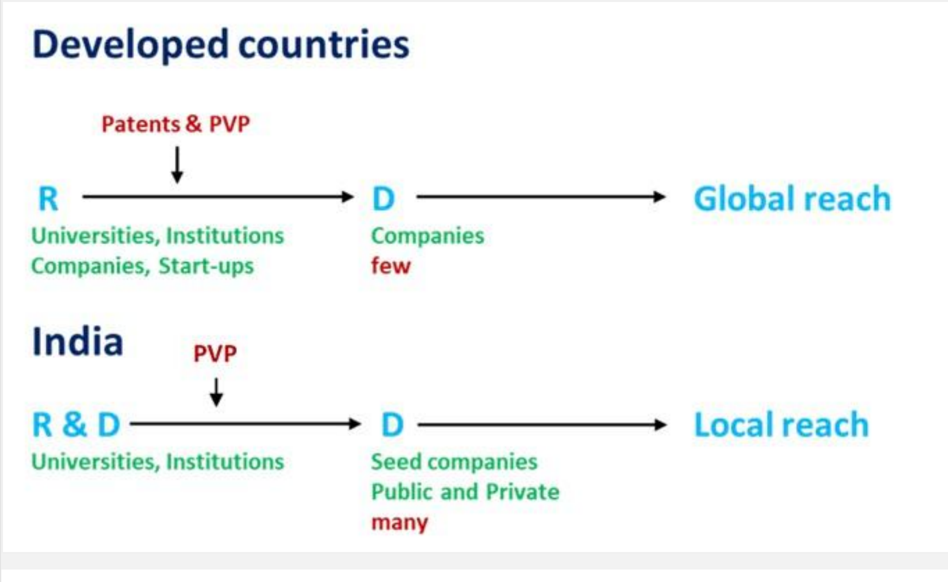

Fig 22 Agricultural R&D commercialisation pathways

2.2 Threats – monopolization of agrochemical and seed technologies

Besides overzealous patenting, a worrying global development is the extraordinary consolidation of the seed and agrochemical industry, leading to a concentration of the new technologies with four big transnational companies (Bonny 2017; Deconinck 2020). Out of the big four – Bayer-Monsanto and BASF are based in Germany, Dow-DuPont (Corteva) is US-based, and ChemChina-Syngenta is a China-based company. Therefore, North America, the EU, and China have not only taken care of their agricultural R&D interests but also have achieved a global reach for their products. Sales by the big companies in pesticides and seeds are given in Fig 23.

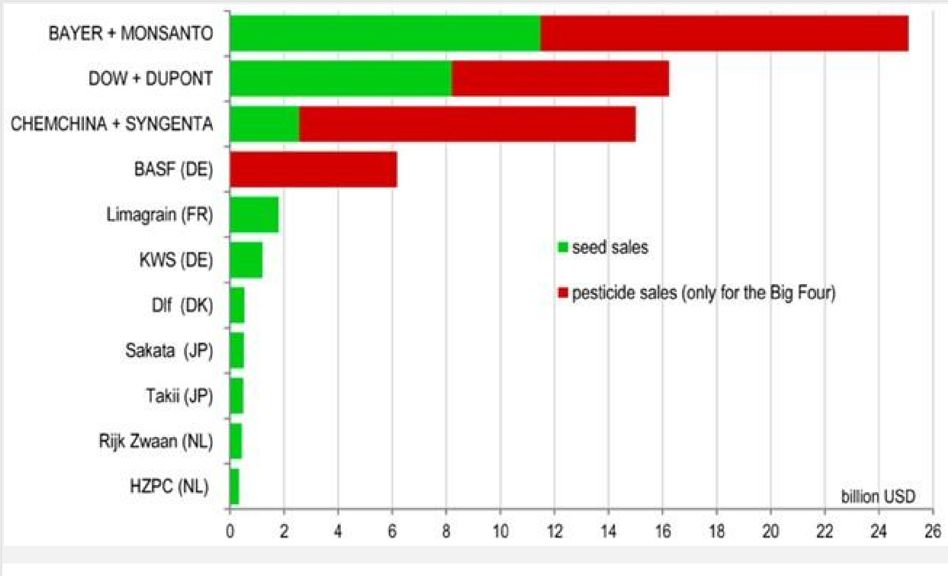

Fig 23 Sales in billion US dollars of the 12 leading companies in the seed and pesticide sector

India neither has any large seed company (Bonny 2017) nor any big agrochemical company (Nishimoto 2019) except UPL, which mostly deals with generic pesticides (Fig 24).

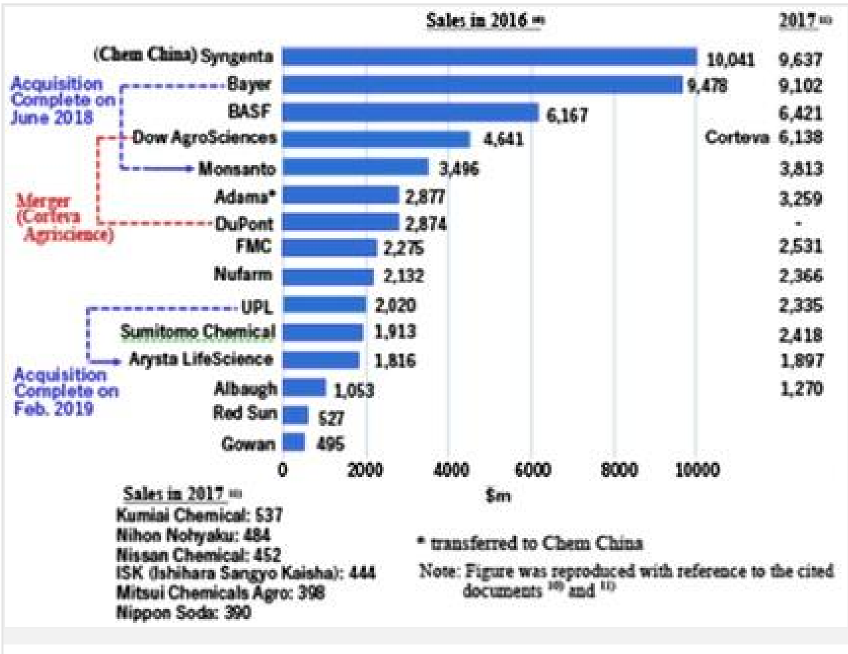

Fig 24 Sales (in million US dollars) of leading global pesticide companies in 2016-2017

2.3 Threats - ideological oppositions to new genetic technologies

The use of GE and GEd technologies has been made difficult by ideological opposition to these technologies (Borlaug 2000; Roberts 2018; Pental 2019). Some ideologues are wary of transnationals, some derive inspiration from global NGOs like Greenpeace. Others want to go back to agriculture as it existed before 1900 – free of synthetic fertilizers and agrochemicals. The solutions these ideologues offer, like organic agriculture, zero budget agriculture, are based on wishful thinking (NAAS 2019). Numerous studies have shown that organic yields will be lower than conventional agriculture by 20-30% (de Ponti et al. 2012; Seufert et al. 2012). Moreover, there is not enough organic manure available to sustain the whole agriculture system.

As the data for 2017 shows (Table 5), despite all the clamour for organic agriculture, only 1.3% (20.9 mh) of the global cropland area of around 1590 mh is under certified organic cultivation (Willer and Lernoud 2019).

Table 5 Global cropland area – total andcertified organic

Categories	Area in mh
Total global agricultural land (A+B)	4870.0
A. Pastures and grazing land	3280.0
B. Crop land (permanent + arable crops)	1590.0
Total land under certified organic cultivation (C+D)	69.6
C. Pastures and grazing - organic	48.7
D. Crop Land (permanent + arable crops) - organic	20.9
Permanent crops – 4.9 mh	
Arable land crops – 12.1 mh	
Area under organic (details unknown) – 3.9 mh	

Unfortunately, the ideologues only see the issues in binaries – like organic vs. conventional, GE vs. non-GE. The pragmatic approach will be to replace conventional agricultural inputs with organic inputs to the extent possible. Scientific studies have shown that manure improves the soil. However, despite a large livestock population, the use of manure is low in India (Table 2). Aggregation of livestock excreta is the major limiting step. Currently, conservation agriculture – low or no-till, along with returning previous crop residues to the soil is the best available option to improve soil fertility and to reduce water requirement (Knapp and van der Heijden 2018; Shyamsunder et al. 2019; Jat et al. 2020). Conservation agriculture needs to be implemented wherever possible.

2.4 Agricultural R&D in India – the impediments

There are some significant impediments in creating an ecosystem for high achievements in agricultural R&D in India - these are:

- Low investments in agricultural R&D
- Structural issues - lack of trained human resource, outdated approaches to breeding, intra-institutional and inter-sectoral competition rather than cooperation, lack of policy clarity on the commercialization of the developed technologies
- Succumbing to wishful thinking, ideological obscurantism on the GE and GEd technologies

Before an analysis of India's efforts in agricultural R&D is undertaken, a look at the country's overall spending on R&D will be revealing. Over the last twenty years, India has been spending between 0.7 to 0.8% of its GDP on R&D, way below the percentage of GDP spent by the developed countries and east Asia's rapidly growing economies (Fig 25).

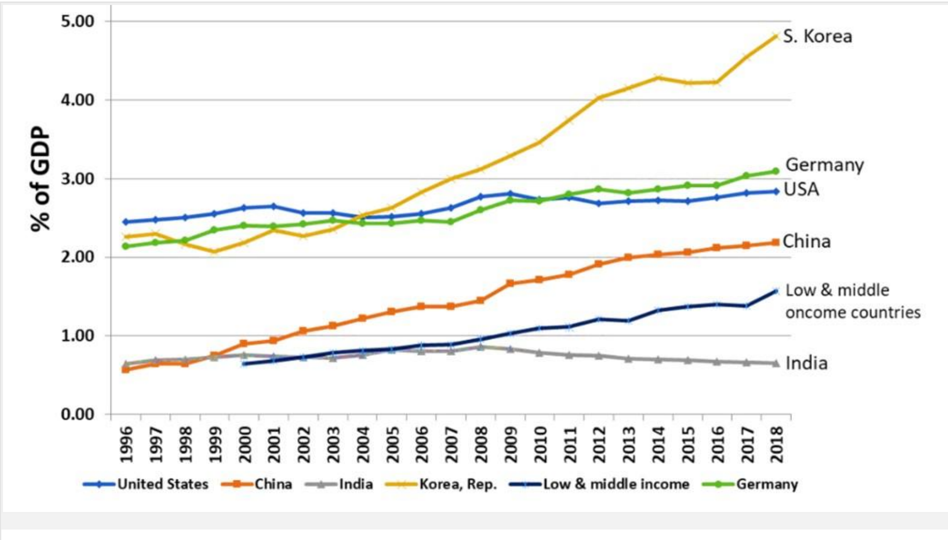

Fig 25 R&D expenditure in some countries

While the successive central governments, cutting across the party lines, have supported R&D in the strategic sectors like space and nuclear energy, and these investments have served the country well, R&D has never been seen as pivotal to economic growth and central to nation-building (Sukumar 2019). India's failure in electronics, both in R&D and manufacturing, is a glaring example of political reticence on R&D and manufacturing of goods of everyday use and open economic systems for rapid growth. A stagnant expenditure of 0.7% of the GDP on R&D

clearly shows that the political class and elite that runs the country, and the scientific community in general, are comfortable with the status quo.

An accepted method of evaluating a country's agricultural R&D investment and cross-country comparisons has been to use an indicator known as the research intensity ratio (IR) – which is calculated as agricultural research spending of a country to its agricultural gross domestic product (AgGDP). IR for India is stagnating at 0.3 since 2000, is around 0.6 for China (ASTI Agricultural R&D Indicators Factsheet 2016), and more than 3 for high-income countries (Fig 26). India is spending much lower than UN recommended IR of 1 to meet the United Nations Sustainable Development Goal 2 of 'Zero Hunger.'

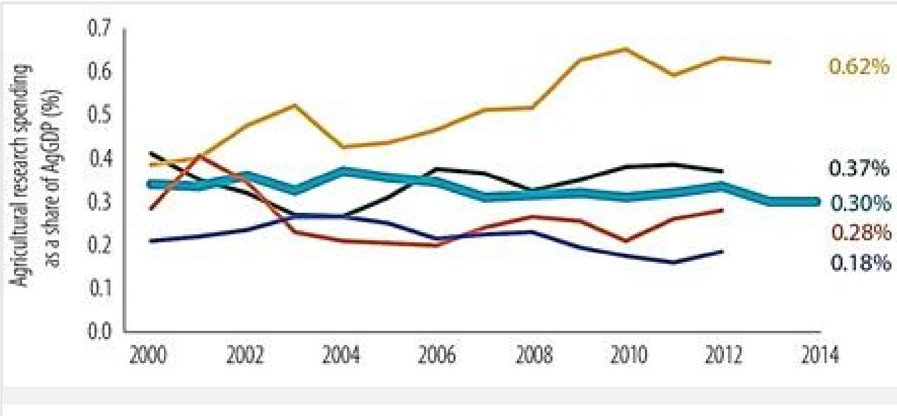

Fig 26 Agricultural Research Intensity in South Asian countries and China, 2000-2014

Besides inadequate funding, India has a shortage of trained human resources in some key areas, and in the emerging science and technology fields including in agricultural R&D. In the 19th century, Japan trained many scientists and technologists in the scientifically advanced countries. After the Korean war, South Korea and later China trained thousands of students by supporting them for doctoral and postdoctoral work in Western laboratories. In India, there have been some attempts by the Ministry of Science and Technology departments to attract some of the scientists trained abroad by providing them fellowships. However, this effort has been grossly inadequate.

In the context of agricultural research, India has inadequate competency in the areas of genomics, gene discovery, plant-pathogen interaction, genetic engineering, genome editing, livestock genetics, and genomic selection in crops and livestock. As an example, India participated in the international rice genome sequencing project but did not follow it up by participating in the rice pangenome sequencing project. Even in the non-GE technologies like precision breeding through markers, India is way behind the developed countries and China.

For employment in the ICAR institutions, scientists are recruited through ASRB (Agricultural Scientist Recruitment Board). Most of the recruited scientists have been good students, but their training, except those who get an opportunity to work in a small number of competent laboratories, is inadequate. There is no worthwhile postdoctoral experience for the recruited scientists.

ICAR has 106 institutions, additionally, there are three Central Agricultural Universities, four Deemed Universities, and 63 State Agricultural Universities. Several institutions were opened out of political expediency of leaving a legacy. Many institutions have a very narrow mandate with below threshold R&D support. The number of doctoral degrees in agriculture increased from 586 in 2010-11 to 4748 in 2017-18 (Research and Development Statistics 2019-20), a substantive increase. However, there has been no concomitant increase in the competency of the developed human resource. A look at the publications and areas of research covered would show that it is mostly 'more of the same'.

Out of the three NPBTs - MAB, GE, and GEd, there is a virtual logjam on the use of GE technologies as very few new events are being released, worldwide. In India, no new GE crop event has been released after Bt cotton and no guidelines have been finalised for the release of more widely accepted GEd technologies. Missing out on GE and now on the GEd technologies is a historical blunder for a country that has so many challenges in agriculture. Meanwhile, other countries have moved on. For example, China, a country comparable to India in area and population, has invested heavily in the genomics of crop plants and GEd technologies. ChemChina, a generic pesticide manufacturing company in China in 2016 bought Syngenta - one of the biggest agrochemical and GEd technology companies for the US $ 43 billion, making China strong in crop breeding through both conventional and new technologies (Cohen J 2019a; Cohen 2019b). Many countries, including the US and Japan, have dropped the requirement of any biosafety analysis for some of the GEd interventions (El-Mounadi 2020).

Much of the seed for planting is supplied by private companies in India. Unlike at the global level where over-consolidation is an issue, India has too many seed companies, most being too small with no effective R&D. There is a release of too many varieties by both the public and the private system. An ICAR report (Outcome Review Report ICAR 2012-13 to 2019-20) shows a release of 1534 crop varieties in a span of eight years. Most of the released varieties are devoid of any significant genetic gains.

Besides 106 institutions, ICAR has 60 All India Coordinated Research Programmes (AICRPs). AICRPs were created to coordinate research between various ICAR institutions and the State Agricultural Universities. All the AICRPs on crops have the additional responsibility of conducting multisite trials of the varieties and hybrids developed by the public-funded R&D and recommend their release. Many private companies also enter their varieties/hybrids in the AICRP trials. The AICRP system played a key role in generating competition between different laboratories for breeding superior varieties. The model was appropriate until the 1990s when a phenotypic selection was the sole breeding methodology. Currently, the AICRP system suffers from two significant flaws. The new approaches of MAB require collaboration rather than competition – the spirit behind establishing the AICRPs must be recaptured. Secondly, the AICRP trial coordinators are active plant breeders who have their materials in the trials, they surely have a conflict of interest. Testing for the release of the varieties and hybrids needs to be separated from the mandate of coordinated development of new materials.

There is no worthwhile research in India on pesticide discovery – either in the public sector or in the private sector. The country, therefore, is dependent upon the transnationals for the new generation of pesticides. As new molecule discovery and its deregulation require significantly high investments (Nishimoto 2019), the use of the new generation pesticides developed by the transnationals would increase the input costs for the small landholders.

3 Part 3: R&D objectives, deficits, and reforms

In this section, I define some major objectives for agriculture, suggest measures to achieve low-input, high-output agriculture, and argue for some policy decisions that would be essential for securing the future of the country in the agricultural sector.

3.1 Overall objectives for agriculture and the pivotal role of R&D

Crop diversification, crop rotation, conservation agriculture, and doubling the productivity of crops (field, horticultural, and forage) and livestock should be the overall national goal in agriculture. Analysis carried out in Part l clearly shows that water usage in agriculture needs to be optimized, and extraction of the groundwater must be reduced in the northwestern regions, which are facing a rapid decline in the water table. Frugal systems of irrigation, crop diversification, and conservation agriculture hold the key to reducing the quantity of water required for irrigation.

The support on fertilizers needs to continue but cover all the components equally for a balanced application. However, the provision of subsidized or free electricity must be withdrawn as these are inducing over-exploitation of the groundwater resources. A switch to solar energy will reduce the carbon footprint but will not help in curbing the overexploitation of groundwater resources. Current groundwater use is an explicit example of Hardin's 'tragedy of the commons' when a common and free resource is overexploited with tragic consequences. (Hardin 1968).

Conservation agriculture with emphasis on returning crop residues to the soil and low-till, soil analysis-based inputs of synthetic fertilizers and micronutrients, the addition of properly prepared manure, and rotation with legume crops are well-established methods to improve both the soil profile and its water retention capacity. Conservation agriculture and crop diversification are viable solutions to the problem of crop residue burning in the wheat-rice cultivation in the northwestern parts of India leading to massive air pollution at the beginning of the winter season.

For implementing crop diversification, around 15 million hectares of land sown with high water-consuming crops like wheat, rice, and sugarcane causing serious depletion of the groundwater resources needs to be put under oilseed, grain legume, and perennial fruit and nut crops. India is currently importing around Rs 75,000 crore worth of edible oils and Rs 10,000 crore worth of fruits and nuts. Thus, there is plenty of scope for crop diversification in the wheat-rice cropping pattern in the north and rice-rice cycle in the south and east. Crop diversification and rotation are not happening because the suggested alternative crops do not yield enough.

Part 1 of the Perspective clearly shows that despite overstretching of the water resources for agriculture and a reasonable input of synthetic fertilizers, yields per hectare of all the major crops in India, except wheat, are below the world average. If wheat and rice are to be replaced with another crop, the replacement crop must provide a similar net income to the farmer. Thus, tripling the yield of coarse grains (now referred to as nutri-cereals in India) and doubling the yield of legume, oilseed, fruit, and vegetable crops should receive high priority.

A major deficit in Indian agriculture is inadequate protection of the crops from the pests – weeds, insects, nematodes, and pathogens – fungi, oomycetes, bacteria, viruses, and mycoplasmas. The 'arms race' between the pests and the hosts is real; this should be clear to everyone after the Covid-19 pandemic. Pests can be dealt with either by pesticides or by genetic means by mobilizing resistance-conferring genes from the landraces or the wild relatives of the crop by crossing and in case of more distantly related species by GE technologies. GEd technologies have a high potential for pest control by knocking off susceptibility genes present in the host plants. GEd technologies could also eliminate or suppress pests by molecular drives.

The other constraint on the yield has been breeding from a very narrow genetic base except to some extent in wheat and rice where pre-breeding materials available from the CGIAR institutions were incorporated in the local breeding programs. India needs some big dimension projects in developing climate-resilient crops. To cite a few areas, there is a need to breed rice for aerobic cultivation, wheat for terminal heat stress, and maize and soybean for flooding tolerance. Large breeding programs are also required to increase the yield potential using divergent germplasm.

As a recent report shows (Gharde et al. 2018), weeds are causing significant losses. Weeds can be tackled either manually or with herbicides. Unfortunately, labour is either not available at the right time or is too expensive. Rainy season crops are especially vulnerable to weeds. Conservation agriculture requires weed control as under low till the weed pressure increases. In rice cultivation, the choice is between suppressing weeds by flooding – wasting enormous amounts of water or growing the crop under water-saving regimes of wet and dry cycles – a practice that would save significant quantities of water but will require herbicides.

The world over the trend in protection from pests other than weeds is through breeding for resistance to reduce the use of agrochemicals (Corvalho 2017). In the year 2016, the top six seed and pesticide companies (now after mergers – four) spent around US$ 25 million on agrochemical R&D and close to the US $ 38 million on seed and trait R&D. Genetic mapping and genome sequencing have provided novel insights into genetic loci and genes present in the germplasm and the wild relatives of crops for resistance breeding. The new technologies provide the scope (Hickey et al. 2019). The country needs to improve the competency of the students and younger scientists in using the vast genomic data for mapping, marker-assisted breeding, gene discovery, genetic engineering, and gene-editing.

3.2 What needs to be done – in general for R&D

Once India gets out of the present economic downturn and reasonable growth rates return, the country must commit 1.5% of the GDP to R&D and increase it to 2.5% (combined public and industrial R&D expenditure) of the GDP in the next five to ten years to unleash the power of science and technology in achieving economic prosperity.

The new National Education Policy 2020 has recommended the establishment of the National Research Foundation, a body like the NSF in the US for better handling of the funding of the R&D projects. However, it is not clear how will it be different from the present funding arrangements. What needs to be implemented are good practices – time-bound peer reviews and decisions, comprehensive funding of the projects, and empowering of the Principal Investigator and the coordinators of large multi-institutional projects to spend the grant as per the established financial norms. Such practices will save time, cut down on interference from the authority, and provide active faculty members the capability to manage any larger administrative responsibilities in the future. All the Science and Technology departments – DST-SERB, DBT, CSIR, ICAR, and others can implement globally well-established practices without waiting for a new body.

Thousands of talented students from India have gone abroad for doctoral degrees by their personal efforts and never returned. Training the brightest in the best laboratories outside India to strengthen the areas in which the country wants to develop competency should receive the highest priority. Postdoctoral work within the country and abroad needs to be encouraged with better fellowships. A new cadre of National Professors and Researchers should be created to keep outstanding scientists/technologists engaged with R&D work and stop their drift into administrative posts to achieve recognition. National Professors/Researchers should receive the same salaries as Directors and Vice-Chancellors.

3.3 Action Plan for meeting the R&D deficit in agriculture

Based on some of the findings of this Perspective – the following recommendations are being made to achieve low-input, high-output agriculture in India. Some of these recommendations seek better implementation of the ongoing programs, some require changes in the way R&D projects are run, others require major policy interventions.

Effective utilization of the available knowledge

Extensive knowledge is already available on germplasm, mapping populations, mapped loci, and useful genes for almost all the major grain, fiber, vegetable, and fruit crops that are grown worldwide. This knowledge needs to be exploited for improving our extensively grown mega varieties of each crop. It must be understood that in agricultural research the lag between investments in R&D and economic returns is considerably long (Fig 27). Therefore, utilizing technology spillovers is critical.

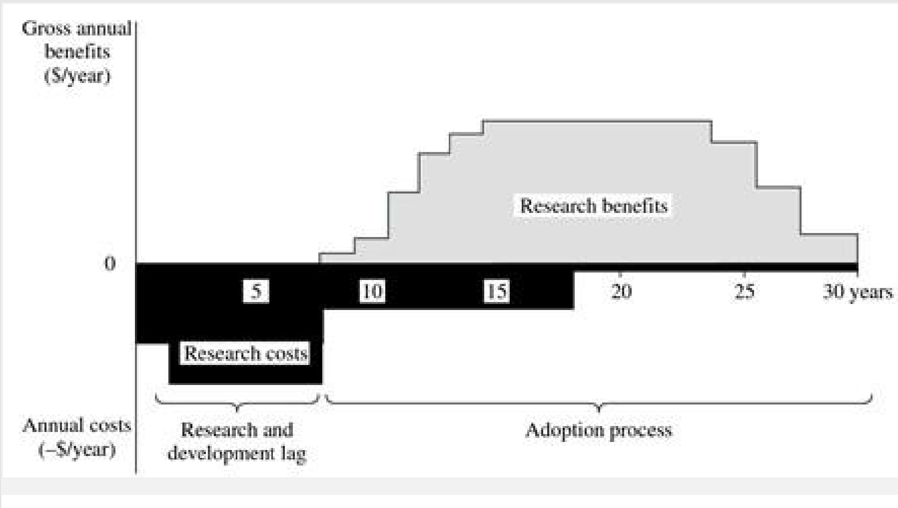

Fig 27 Flows of resources, benefits, and costs in agricultural R&D, a model by Alston et al, 2000

Each crop-specific ICAR institute should take the lead in preparing a report that contains the following information on their mandate crop(s):

- Major breeding objectives in the crop.
- Information and knowledge currently available on key germplasm, molecular markers, genes, GE, and GEd protocols in India and globally to meet the identified breeding objectives.
- Status of genome assembly, sequence information on – key germplasm, pangenome, supra-pangenome.
- Mega varieties of the mandate crop that could be improved for biotic and abiotic stresses with the available knowledge.
- Laboratories/institutions that are actively working on the crop at the global level.
- The sources and availability of the germplasm and genes; any patent protection on the genes/germplasm.
- Available facilities and required facilities for marker-assisted breeding, genetic engineering, gene editing, and rapid generation advance.
- Capability and competence of the staff to handle MAB, GE, and GEd work.
- Institutes within India and outside that can provide help with materials and methodologies.
- Region-wise desirable agronomic practices for low-input, high-output cultivation of the crop, and reasons for the non or under-implementation of the best practices.

- Breeding objectives for which new knowledge is required.

Once the reports are ready, technology development shall be the focus of the specialized institutions. Besides generating new variability, utilization of the available knowledge for maintenance breeding should receive the highest priority.

Creating new knowledge through multi-institutional projects

A significant recent development in agricultural R&D has been the launching of some major multi-institutional projects by DBT/ICAR on screening the germplasm available with the National Bureau of Plant Genetic Resources (NBPGR-ICAR) for agronomic traits and resistance to biotic stresses. An earlier effort supported by ICAR on the screening of wheat germplasm has been useful in finding lines that are resistant to diseases like spot bloch and rusts. An analysis of this pioneering effort shows some lacunae. The characterization of 22,416 wheat accessions for multiple traits including resistance to diseases and thermotolerance was initiated in 2011-12 and completed by 2014-15, a formidable accomplishment indeed. However, a comprehensive paper on the results was published after a lag of five years (Phogat et al. 2021). A paper on the identification of the accessions resistant to rust and spot bloch disease was published earlier (Kumar et al. 2016). However, no group has followed up on these important leads to take up the mapping of the resistance-conferring loci, what to speak of the fine mapping and identification of the candidate genes/alleles. This is both due to complacency in publishing and a dearth of competent scientists to take the work forward. Both the deficits need to be addressed in the currently funded projects.

Building scientific capacity

ASRB should recruit talented students from diverse backgrounds rather than confining the intake only to students from agricultural universities and institutes. In the next five years, around 200 students with MSc/MTech degrees should be selected at the national level and sent to the best laboratories abroad for doctoral degrees to develop competency in the areas of big data handling, statistical genomics, bioinformatics, genomic selection, livestock breeding, pest-pathogen interaction, and protein engineering. A similar number of scientists selected through ASRB should be trained in the best global laboratories for 2-3 years of postdoctoral work to upgrade their skills and competency. A reasonable number of scientific positions in the ICAR institutions (not less than 30%) should be filled with lateral entries to broaden the scope of research being carried out currently.

A new mechanism for varietal/hybrid trials

Multisite trials on the comparative performance of varieties, hybrids, and planting materials developed by the public and private organizations should be handled by scientists who have no conflict of interest. AICRPs cannot and should not handle both research and release. ARS scientists can be specifically trained for the trials for release recommendations. Private companies should be encouraged to test their varieties/hybrids in nationwide trials. Multi-site trials should be monitored by a Board consisting of senior scientists, industry representatives, and legal experts. All the information should be put in the public domain so that farmers can make informed choices on the planting material. Information on the most optimal agronomic practices for each crop can be best delivered through short documentaries on TV channels like DD Kisan and personal devices.

Building India's seed industry and marketing of seed/planting stocks

Private companies have a major role to play in the multiplication of seed and planting materials. India eventually must have a dozen medium-sized world-class seed companies. To keep the input costs of quality seed low for the farmers, technologies like disease or pest resistance developed through public funding should be provided to multiple seed companies including the transnationals for use within the country. Mechanisms need to be in place for the rapid dissemination of varieties/hybrids developed by ICAR institutions through exclusive arrangements between the institute and the seed companies. The process of technology transfer of public-funded research to seed companies needs to be made less cumbersome. Companies should be allowed to release their varieties/hybrids, as is the current practice, as truthfully labeled seeds. However, the submission of DNA fingerprints to PVPFRA and the state agricultural departments, and the display of resistance/susceptibility profile to the crop pests on the seed packet should be made mandatory.

Initiatives in pesticide R&D

Despite the worldwide emphasis on biological solutions to control pests, the use of chemical pesticides cannot be eliminated. Herbicides will be essential for reducing huge losses to weeds and for the successful implementation of conservation agriculture. Compared to other agriculturally productive regions of the world, we have hardly any research on new pesticides. A study needs to be carried out on identifying pesticide molecules on which patents have expired and that have low toxicity. CSIR should be approached for the greening of the out-of-patent agrochemicals. Local manufacturing of the upgraded and scrutinized older generation molecules within the country should be encouraged. Farmers should be educated on the safe and timely use of pesticides through TV and personal devices. A national-level strategy is required to make the new-generation pesticides developed by transnationals available to the farmers at a reasonable cost.

Need for GE and GEd technologies

The GE and GEd technologies are critical for many breeding objectives like breeding for resistance with genes from the wild relatives of crops, knocking out disease susceptibility genes, insect and herbicide resistance, and nutritional enhancement. Biosafety guidelines for different types of GE interventions need to be revised taking into consideration the experience of the past twenty years. GE crops that have been grown in millions of hectares of land and have been in the food chain for more than 10 years should be deployed in the country without any extensive biosafety analysis. GEd technology regulations should be finalized and implemented. Some of the GEd interventions do not require any biosafety oversights, only reporting at the institutional level should suffice (NAAS 2020).

Open R&D platforms and collaborations

A big issue with crop breeding – particularly when GE and GEd technologies are used pertains to overzealous patenting. This significant issue has taken a back seat as onslaughts on the safety of the technologies have grabbed the headlines. Each crop has multiple breeding objectives (Fig 10). Dealing with each trait may require multiple components – each one protected by IPR. Stacking several traits in the seed not only will require time and effort but would also require negotiations with many IPR holders. This can kick in what Heller 2008 has described as 'the tragedy of anti-commons' - wasteful underuse due to fragmented ownership.

Low-input, high-output agriculture would require a return to the spirit with which the world dealt with the global food production in the 1960s – free exchange of germplasm, philanthropy, strengthening of national agricultural systems, public investments, and support for the CGIAR institutions. India should commit to higher investments in agricultural R&D, open R&D platforms, collaboration with CG institutions and philanthropic organizations for implementing low-input, high-output agriculture not only in India but also in South Asia and Africa to help meet the United Nations Sustainable Development Goal of 'Zero Hunger' by 2030.

Epilogue

No country has become prosperous without engaging strongly with R&D. There are several compelling reasons for increasing investments in agricultural R&D in India. Huge capital expenditure has been incurred on irrigation – public investments in dams and canals and private investments in pump sets and agricultural machinery. In addition, huge subsidies are provided to the agriculture sector. In the year 2017-18 subsidies on fertilizers, electricity, insurance, and loan waivers amounted to around Rs 3,81,500 crore. However, the productivity of crops and livestock remains below global averages.

I have identified many areas in which R&D efforts need to be increased including the area of meeting the present and future threats from pests, pathogens, and weeds. Low yields of the frugal water requirement nutri-cereal, oilseed, and grain legume crops make these unattractive replacements for wheat, rice, and sugarcane. Yields of such replacement crops must increase for securing food and nutritional security as well as sustainability.

Achieving low-input, high-output agriculture would require the use of new plant breeding technologies. However, successive governments have been dithering on the use of genetic engineering (GE) and now on gene editing (GEd) technologies. Policy paralysis on the use of the new breeding technologies has led to a loss of expertise and no new gains in expertise. It seems the forces wedded to stasis are winning. Success in R&D and downstream innovations would require a dynamic outlook.

The stasis is not limited to agricultural R&D but is a general malaise afflicting the R&D ecosystem in the country. Investments in R&D are stuck at 0.7% of the GDP for more than a decade. The science and technology departments, regulatory bodies, universities, institutes - most of them seem to have made peace with the prevailing stasis.

I have suggested many reforms, some specific to agricultural R&D, and a few for creating an overall dynamic ecosystem for R&D in the country. These suggestions have been flagged in many reports and discussions but have not been implemented. This Perspective hopefully will reinforce the need for significantly increased budgetary allocations for R&D, dismantling of stifling bureaucratic oversights, and enhancing the competencies of the new generation of scientists by exposing them to the leading laboratories worldwide at the doctoral and post-doctoral levels.

The science and technology academies are best placed to persuade the government and citizens on the centrality of R&D and institutional reforms in bringing about national prosperity and meeting big challenges like low-input, high-output agriculture, effective control of infectious diseases, competitiveness in manufacturing, and securing strategic needs to name a few.

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References

1. Godfray H. C. J., Beddington J. R., Crute I. R., Haddad L., Lawrence D., Muir J. F. and Pretty S. et al. 2010 Food security, the challenge of feeding 9 billion people. Science 327, 812-818.
2. Foley J. A., Ramankutty N., Brauman K. A., Cassidy E. S., Gerber J. S., Johnston M. et al. 2011 Solutions for a cultivated planet. Nature 478, 337-342.
3. Godfray H. C. J. and Garnett T. 2014 Food security and sustainable intensification. Philos. Trans. R. Soc. B: Biol. Sci. 369, 2012.0273.
4. Rockstrom J., Williams J., Baily G., Noble A., Matthews N., Gordon L. et al. 2017 Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46, 4-17.
5. Doebley J. F., Gaut B. S. and Smith B. D. 2006 The molecular genetics of crop domestication. Cell

127, 1309-1321.

6. World Population Prospects 2019. United Nations Department of Economic and Social Affairs, Population Division. Available at population.un.org/wpp/
7. Vollset S. E., Goren E., Yuan C-W., Cao J., Smith A. E., Hsiao T. et al. 2020 Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017-2100: A forecasting analysis for the Global Burden of Disease Study. Lancet 396, 1285-1306.
8. Fogel R. W. 2004 The Escape from Hunger and Premature Death 1700-2100: Europe, America, and the Third World. Cambridge University Press, Cambridge, UK.
9. Smil V. 2004 Enriching the Earth: Fritz Haber, Carl Bosch and the Transformation of World Food Production. MIT Press, Boston, USA.
10. Erisman J. W., Sutton M. A., Galloway J., Klimont Z. and Winiwarter W. 2008 How a century of ammonia synthesis changed the world. Nature Geoscience 1, 636–639.
11. Kingsbury N. 2009 Hybrid: The History & Science of Plant Breeding. University of Chicago Press, Chicago, USA.
12. Global Hunger Index 2019. Available at www.globalhungerindex.org
13. Economic Survey 2020-2021 – Statistical Appendix. Ministry of Finance, Government of India. Available at www.indiabudget.gov.in/economicsurvey/
14. Shah T. 2009 Climate change and groundwater: India's opportunities for mitigation and adaptation. Environ. Res. Lett. 4, 035005.
15. Rodell M., Velicogna I. and Famiglietti J. S. 2009 Satellite based estimates of ground water depletion in India. Nature 460, 999-1002.
16. Central Ground Water Board Annual Report 2018-19. Ground Water Authority of India, Ministry of Jal Shakti, Government of India. Available at http://cgwb.gov.in/Ann-Reports.html
17. Suhag R. 2016 Overview of Groundwater in India. PRS Legislative Research, New Delhi, India.
18. Asoka A., Gleeson T., Wada Y. and Mishra V. 2017 Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. Nature Geosciences 10, 109–117.
19. Umetsu N. and Shirai Y. 2020 Development of novel pesticides in the 21st century. J. Pesticide Sci. 45, 54-74.
20. Oerke E. C. 2006 Crop losses to pests. J. Agri. Sci. 144, 31-43.
21. Savary S., Willocquet L., Pethybridge S. J., Esker P., McRoberts N. and Nelson A. 2019 The global burden of pathogens and pests on major food crops. Nature Ecol. Evo. 3, 430-439.
22. Deutsch C. A., Tewksbury J. T., Tigchelaar M., Battisti D. S., Merrill S.C., Huey R. B. and Naylor R. I. 2018 Increase in crop losses to insect pests in a warming climate. Science 361, 916-919.

23. Velasquez A. G., Castroverde C. D. M. and He S. Y. 2018 Plant - pathogen warfare under changing climate conditions. Curr. Biol. 28, 619-634.
24. Grover A. and Pental D. 2003 Breeding objectives and requirements for producing transgenics for major field crops of India. Curr. Sci. 84, 310-320.
25. Gharde Y., Singh P. K., Dubey R. P. and Gupta P. K. 2018 Assessment of yield and economic losses in agriculture due to weeds in India. Crop Protection 107, 12-18.
26. Arabidopsis genome initiative. 2000 Analysis of the genome sequence of the flowering plant Arabidopsis thaliana. Nature 408, 796-815.
27. Giani A. M., Gallo G.R., Gianfranceschi L. and Formenti G. 2020 Long walk to genomics: History and current approaches to genome sequencing and assembly. Comput. Struct. Biotech. J. 18, 9-19.
28. Khan A.W., Garg V., Roorkiwal M., Golicz A. A., Edwards D. and Varshney R. K. 2020 Super-pangenome by integrating the wild side of a species for accelerated crop improvement. Trends in Plant Sci. 25, 148-158.
29. Moose S. P. and Mumm R. H. 2008 Molecular plant breeding as the foundation for 21st century crop improvement. Plant Physiol. 147, 969-977.
30. Bevan M. W., Uauy C., Wulff B. B. H., Zhou J., Krasileva K. and Clark M. D. 2017 Genomic innovation for crop improvement. Nature 543, 346-354.
31. Varshney R. K., Sinha P., Singh V. K., Kumar A., Zhang Q. and Bennetzen J. L. 2020 5Gs for crop improvement. Curr. Opin. Plant Biol. 56, 190-196.
32. Sussex I. 2008 The scientific roots of modern plant biotechnology. Plant Cell 20, 1189-1198.
33. ISAAA (International Service for the Acquisition of Agri-biotech Applications). 2019 Accomplishment Report. Available at www.isaaa.org
34. Qaim M. 2020 Role of new plant breeding technologies for food securities and sustainable agricultural development. App. Eco. Perspectives and Policy 42,129-150.
35. Bailey-Serres J., Parker J., Ainsworth E. A., Oldroyd G. E. D. and Schroeder J. I. 2019 Genetic strategies for improving crop yields. Nature 575, 109-118.
36. Pixley K. V., Falck-Zepeda J. B., Giller K., Glenna L. L., Gould F., Mallory-Smith C. A. et al. 2019 Genome editing, gene drives, and synthetic biology: Will they contribute to disease-resistant crops, and who will benefit? Ann. Rev. Phytopathology 57, 165-188.
37. Chen K., Wang Y., Zhang R., Zhang H. and Gao C. 2019 CRISPR/Cas genome editing and precision plant breeding in agriculture. Ann. Rev. Plant Biol. 70, 667-697.
38. Wada N., Ueta R., Osakabe Y., Osakabe K. 2020 Precision Genome editing in plants: State-of-the-art in CRISPR/Cas 9-basedgenome sequencing. BMC Plant Biol. 20, 334.

39. Bonny S. 2017 Corporate concentration and technological change in the global seed industry. Sustainability 9, 1632.
40. Deconinck K. 2020 Concentration in seed and biotech markets: Extent, causes, and impacts. Ann. Rev. Resource Econ. 12, 124-147.
41. Nishimoto R. 2019 Global trends in crop protection industry. J. Pesticide Sci. 44, 141-147.
42. Borlaug N. E. 2000 Ending world hunger: The promise of biotechnology and the threat of anti-science zealotry. Plant Physiol. 124, 487-494.
43. Roberts R. J. 2018 The Noble Laureates' campaign supporting GMOs. J. Innovation and Knowledge 3, 61-65.
44. Pental D. 2019 When scientists turn against science: Exceptionally flawed analysis of plant breeding technologies. Curr. Sci. 117, 932-939.
45. NAAS (The National Academy of Agricultural Sciences). 2019 Zero Budget Natural Farming - A Myth or Reality? Policy paper no. 90. Available at http://naasindia.org
46. de Ponti T., Rizk B. and van Ittersum M. K. 2012 The crop yield gap between organic and conventional agriculture. Agricultural Systems 108, 1-9.
47. Seufert V., Ramankutty N. and Foley J. A. 2012 Comparing the yields of organic and conventional agriculture. Nature 485, 229-234.
48. Willer H. and Lernoud J. 2019 The World of Organic Agriculture Statistics and Emerging Trends. 2019. FIBL and IFOAM. Available at www.organic-world.net/yearbook/yearbook-2019.html
49. Knapp S. and van der Heijden M. G. A. 2018 A global meta-analysis of yield stability in organic and conventional agriculture. Nature Comm. 9, 3632.
50. Shyamsunder P., Springer N. P., Tallis H., Polasky S., Jat M. L., Sidhu H. S., et al. 2019 Fields on fire: Alternatives to crop residue burning in India. Science 365, 536-538.
51. Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A. and Gerard B. 2020 Conservation agriculture for sustainable intensification in South Asia. Nature Sustainability 3, 336-343.
52. Sukumar A. M. 2019 Midnight's Machines: A Political History of Technology in India Penguin/ Viking, Gurgaon, India.
53. ASTI Agricultural R&D Indicators Factsheet, India 2016. ASTI-IFPRI, Washington DC, USA. Available at https://www.asti.cgiar.org
54. Research and Development Statistics 2019–20, Department of Science & Technology, Government of India. Available at www.nstmis-dst.org
55. Cohen J. 2019a China's CRISPR revolution. Science 365, 420-421.

56. Cohen J. 2019b Fields of dream: China bets big on genome editing of crops. Science 365, 423-425.
57. El-Mounadi K., Morales-Floriano M. L. and Garcia-Ruiz H. 2020 Principles, applications, and biosafety of plant genome editing using CRISPR-Cas9. Front. Plant Sci. 11, 56. doi:10.3389/fpls.2020.00056
58. Hardin G. 1968 "The tragedy of the commons". Science 162, 1243-1248.
59. Corvalho F. P. 2017 Pesticides, environment, and food safety. Food and Energy Security 6, 48-60.
60. Hickey L. T., Hafeez A. N., Robinson H., Jackson S. A., Leal Bertioli S. G. M., Tester M. et al. 2019 Breeding crops to feed 10 billion. Nature Biotech. 37, 744-754.
61. National Education Policy 2020, Ministry of Education, Government of India. Available at https://www.education.gov.in/en
62. Alston J. M., Chan-Kang C., Marra M. C., Pardey P. G. and Wyatt T. J. 2000 A meta-analysis of rates of return to agricultural R&D: ex pede herculem? International Food Policy Research Institute (IFPRI), Washington DC, USA.
63. Phogat B. S., Kumar S., Kumari J., Kumar N., Pandey A. C., Singh T. P. et al. 2021 Chracterization of wheat germplasm conserved in the Indian National Genebank and establishment of a composite core collection. Crop Science 61, 604-611.
64. Kumar S., Archak S., Tyagi R. K., Kumari J., Vikas V. K., JacobS. R. et al. 2016 Evaluation of 19,460 wheat accessions conserved in the IndianNational Genebank to identify new sources of resistance to rust and spot blotchdiseases. PLoS ONE11, e01167702. https://doi.org/10.1371/journal.pone.0175610
65. NAAS (The National Academy of Agricultural Sciences). 2020 Regulatory Framework for Genome Edited Plants: Accelerating the Pace and Precision of Plant Breeding. Policy brief no. 7. Available at http://naasindia.org
66. Heller M. A. 2008 The Gridlock Economy: How Too Much Ownership Wrecks Markets, Stops Innovation, and Costs Lives. Basic Books, New York, USA.

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16. Fig 13: https://ourworldindata.org
17. Fig 14: FAOSTAT
18. Fig 15: FAOSTAT
19. Fig 16: International Cotton Advisory Committee (ICAC), Washington DC
20. Fig 17: Dept. of Agriculture and Dept. of Commerce
21. Fig 18: https://ourworldindata.org
22. Fig 19: https://ourworldindata.org
23. Fig 20: https://ourworldindata.org
24. Fig 21: www.isaaa.org
25. Fig 23: Bonny 2017
26. Fig 24: Umetsu and Shirai 2020
27. Table 5: Willer and Lernoud 2019, J. FIBL and IFOAM.
28. Fig 25: https://data.worldbank.org
29. Fig 26: https://www.asti.cgiar.org