REPORT OF THE HIGH-LEVEL COMMITTEE ON DEVELOPING SCIENCE & TECHNOLOGY CLUSTERS IN INDIA

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सत्यमेव जयते

NITI Aayog

TABLE OF CONTENTS

Foreword

The genesis of this report lies in the August 5, 2019 meeting of the High-Level Committee for Developing Science and Technology Clusters, that was constituted by the Prime Minister's Office (PMO). The PMO assigned this committee the task of creating a plan and roadmap for developing science and technology clusters in India which could play a transformative role in India's economic and social journey.

India is favourably positioned, due to its unique strengths and challenges, for a broad-based science centric effort to transform society. Careful and consistent investments since independence have created a large and capable base of skilled human capital and extensive physical resources across universities, government organizations and the private sector. The challenges faced by our people are also vast and diverse in scope and nature, and science and technology can play a catalytic role through the creation of new technologies and products. The Green Revolution of the 1960's took India from being a food-deficient nation to a food surplus nation with improved food security and transformed Indian agriculture. India should aim for similar breakthroughs in other areas where it has the capability and potential, such as biotechnology, nanotechnology and industrial artificial intelligence.

The committee has drawn on inputs from stakeholders across the spectrum: academics, academic administrators, entrepreneurs, industry leaders, scientists and those with prior experience of developing and working with clusters. This has been done to ensure that the analyses shared, and recommendations proposed are grounded, thorough and most importantly, feasible from an implementation perspective.

The committee has tried to offer recommendations instead of a prescriptive template that must necessarily be adopted by participating institutions and stakeholders. We seek to demonstrate the rationale for adopting a cluster-based approach and recommend a framework which combines top-down driven policy decisions with bottom-up organic actions from the participating institutions.

We would like to thank our colleagues at NITI Aayog, the office of the Principal Scientific Advisor, Harvard University and all participating institutions for their contribution, often under demanding timelines. Special thanks are due to the Indian Institute of Science Bangalore, Indian Institute of Technology Delhi, Inter University Centre for Astronomy and Astrophysics Pune and Research and Innovation Circle (RICH) Hyderabad who hosted the townhalls which provided inputs for the report.

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Committee Members

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Executive Summary

The transformative power of science and technology is indisputable. Across the world, scientific and technological developments and innovations have driven economic growth, increased prosperity and impacted virtually all aspects of modern life.

As India looks to continue and accelerate its social and economic transformation, it is critical to harness the full potential of science and technology. This is a multidimensional effort involving government, academia, industry and broader society. Scientific clusters, built around pre-existing pockets of institutional strength, are an important and relatively easy first-step in that direction, a 'low-hanging fruit'. The committee hopes this report will provide a roadmap to develop and scale such clusters in a quick timeframe, and these clusters will then act as a catalyst for broader and more wide-ranging initiatives.

Despite the impressive strides made by India since independence, immense challenges still lie ahead. With an estimated 1 million people entering the work force every month[1] ,there is a need to create ~100 million jobs over the coming decade, while planning for increasing urbanization, climate change and rising inequality. Innovative solutions to these critical issues, implemented at scale, in a sustainable way, are essential.

Science and technology are major drivers of innovation and can be the engines to transform the country. India, with its large base of qualified and skilled human capital, strong scientific infrastructure, diversified and sophisticated industrial sector, and a thriving entrepreneurial culture, is in a position to take advantage of developments in science and technology.

It needs to be emphasized that there is enormous untapped potential in unlocking and harnessing the power of science and technology across the entire developing world. It can help develop innovative and scalable solutions across different areas such as renewable energy, sustainable agriculture and healthcare. India's efforts in this space can become an exemplar for other developing countries to follow and emulate and make the country a global leader.

The report has three sections. **The first section** highlights the role of science and technology in a nation's development. It focuses on the importance of having a strong culture of pure science and how that can yield economic benefits. It also covers the history of science and technology in India, describing the role played by many stalwarts, including scientists such as PC Mahalanobis[a] and Homi Bhabha[b] who returned to India after studying at globally renowned institutions, in building India's scientific establishment and institutions.

The second section dwells upon the reasons why Indian science and technology lags behind that of other countries. As a broad generalization, Indian policy circles appear to have concluded that investments in science and those to meet immediate daily needs (think food, shelter clothing and so on), are substitutes, resulting in the neglect of the former. Further, a resource-constrained mindset fostered a culture where working within constraints became the norm – a culture of 'Jugaad'.While there is room for that approach, the challenge is that the celebratory attitude towards 'fixing-things'seems to have shifted attention away from direct and first-order investments in science, which is an untenable situation.

The importance of public investment is examined, especially in research based on 'pure' science which can act as a feeder for industry and entrepreneurs to develop socially relevant products, technologies and

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[a]PC Mahalanobis (1893-1972) was a renowned statistician who formulated the 'Mahalanobis distance', a statistical measure. He was one of the earliest and most influential members of the Planning Commission and the founder of the Indian Statistical Institute.
[b]Homi J Bhabha (1909-1966) was a nuclear physicist who helped setup the Indian nuclear program.

services. In India, aggregate investment in research in pure science is much lower than in some other countries, and this arena has been dominated by the government. Public investment in science and technology have actually been key to growth in other countries, as they provide the building blocks for industry. The lag in the creation of such public goods has meant that the desired virtuous cycle of public-private collaboration is stillborn and has the pernicious effect of sapping productivity in ways that are difficult to measure.

Other factors covered in this section include the structure of the education system, especially at the higher levels, and the lack of a collaborative culture. While India produces large numbers of professionally qualified graduates, this has led the system to be oriented towards 'training and instructing'. It has been less successful in developing students with skills such as critical thinking and inquiry, which is the foundation for creating research-minded scholars and, indeed, inquisitive professionals of all stripes.

The lack of a collaborative culture within academia has also been a challenge. Numerous co-located facilities, institutions and organizations do not harness the potential benefits of working together and leveraging each other. Administrative and operational features that have become integral to the culture of institutions now present hurdles, albeit inadvertently so. This is further exacerbated by the lack of collaboration with external stakeholders such as large corporations and start-ups. A lack of trust exists on both sides – each regards the other as having a different agenda and diverging interests. This perception, which has not always been inaccurate, needs to be addressed.

The **third and final section** outlines the proposed cluster framework, describes how it can mitigate some of the weaknesses which have held Indian science and technology back so far, help it rise to the levels of which it is capable and play a leading role in India's future. Clusters bring together a diverse set of actors from academia, industry and government in a collaborative ecosystem to harness their diverse strengths.

A hallmark of successful clusters is the high level of organic activity in which stakeholders experiment with different models of collaboration and partnership, with a willingness to try new models and not fear failure. The framework we propose looks to establish the foundation in which such a system can flourish. Bottom-up organic activities are the key drivers, with top down policies acting as light guardrails.

Keeping this imperative in mind, the framework lists a possible structure for the clusters, which includes a central management office and a strategic advisory unit, along with action areas for the management office and some suggested actions in each. These are not meant to be prescriptive and can be modified by each cluster as appropriate. A central S&T cluster apex committee is also proposed to help coordinate central policy actions and act as an assessment center.

The proposed National Research Foundation (NRF) will also play a pivotal role in developing and scaling India's research and innovation ecosystem. Through our framework, we propose mechanisms to foster collaboration between the clusters and the NRF.

The role that science and technology can play in India's future is immense, which goes far beyond economic growth and creating jobs. It has the potential to create transformative new paradigms and inspire a generation to positively impact the world around them. The effort behind creating these clusters is the first critical step in that direction.

"The true wealth of a nation consists not in the stored-up gold but in the intellectual and physical strength of its people"

- Sir CV Raman, Asia's first Nobel Laureate in Physics [2]

"We are convinced that if we are to play a meaningful role nationally, and in the community of nations, we must be second to none in the application of advanced technologies to the real problems of man and society."

- Vikram Sarabhai, founder of India's space program [3]

In 2019, India's Prime Minister, Narendra Modi, announced plans to double India's economy from $2.8 trillion to $5 trillion by 2024. It was estimated that India would need a sustained and significant increase in its real annual GDP growth rate to achieve this goal.[4] Advances in science and technology are critical to realize this economic growth and transform the country's future.

Science & Technology in Economic and Societal Development

Science, defined as the process of generating knowledge based on evidence, is critical to economic and societal development.[5] Widely accepted as the engine of human prosperity, science has improved quality of life, increased wealth, reduced poverty and transformed our understanding of the world around us.[c] Throughout history, scientific breakthroughs and incremental improvements have contributed to advances in nearly all areas of human activity including food production, disease control, telecommunication, energy security and space exploration. Most people around the world now live longer and earn more than their ancestors, can access better healthcare and medicines to prevent diseases, can travel with ease, and enjoy the benefits of a varied diet through contemporary agricultural practices.[6]

This leap forward has been far from uniform. Economist Jeffrey Sachs explained, "A small part of the globe, accounting for some 15% of the earth's population, provides nearly all of the world's technology innovations. A second part, involving perhaps half of the world's population, is able to adopt these technologies in production and consumption. The remaining part, covering around a third of the world's population, is technologically disconnected, neither innovating at home nor adopting foreign technologies."[7]

Linkages between Science & Technology and Economic Growth and Development

Experts argue that scientifically advanced countries enjoy higher levels of wealth and social progress.[8] In the United States, several economists including Robert Solow and Paul Romer have shown the link between economic growth and technological innovation. Solow's growth model predicted that long-term economic growth and prosperity were dependent on technological change. In his seminal work, Solow argued that a residual or unexplained portion of growth in U.S income per capita from 1890 to 1950 stemmed from technological advances while changes in capital and labor made relatively small contributions.[9]

While Solow's model assumes the source of technological change to be exogenous, Paul Romer's work shows how countries can determine their own technology level and make technological investments. His endogenous growth theory and related literature emphasize factors such as population, R&D expenditure

[c] Science includes natural sciences (such as biology, chemistry, mathematics, physics and related disciplines), social sciences (economics, sociology, politics, anthropology and related disciplines) and applied sciences (engineering, medicine and related disciplines).

and spill over effects to explain how technical investments and changes in human capital drive growth. Romer claims that the accumulation of ideas is crucial for long-run economic growth and that a large stock of ideas makes it easier to find new ideas.[10] Even though the pursuit of these ideas is a costly activity, it is nonetheless purposeful.[11]

Other widely cited academic work in this area includes studies by Edward Denison and Edwin Mansfield. Denison looked at additional factors such as changes in labor quality with years of schooling and showed that 20% of U.S.' economic growth from 1969 to 1973 was attributable to research and training.[12] Mansfield, who surveyed US businesses to understand what proportion of their products could not be developed without recent academic research, estimated the social rate of return on R&D investments as 28%.[13,d]

Most of the empirical evidence on the economic benefits of S&T is historical and centred on developed countries. Evidence from developing countries is limited and more tenuous. Researchers generally agree that it is difficult to establish direct causality between scientific and technological investments and economic growth. Compounding the problem is the difficulty in measuring the direct and indirect costs and benefits of science and technology investments. An example of this is the added expense incurred caring for the elderly kept alive by new treatments. Science and technology advocates agree that they need better measurement tools.

There are few studies that demonstrate the impact of investments in science and technology on society. A landmark study by Harvard economist ZviGriliches in 1958,looked at the investments made in the preceding decades across the public and private sector in the development of hybrid strains of corn to improve yield, nutritional value, and drought and disease resistance. Research efforts yielded successful results, with some terming it one of the 'outstanding successes of the century'. Griliches' work attempted to quantify the success through a return on investment framework and found that hybrid corn research yielded a staggering return of over 700% per year.[14]

Given corn's importance as a food staple and its use in other fields (such as corn ethanol), these results were influential in showing the importance of investment in R&D. Subsequent econometric work done by Griliches and Robert Evenson during the 1970s for the World Bank and the Consultative Group on International Agriculture Research (CGIAR) showed a high economic rate of return for both basic and applied scientific research related to agriculture.[15]

A more recent and local example is the development of a new strain of rice in India. This new variety, *samba mahsuri*, developed by introducing a gene from a common plant into an existing strain of rice has higher growth prospects than traditional strains of rice and utilizes less water. Since rice is a water-intensive crop, the introduction of this strain of rice can help conserve groundwater and enable the use of water for other crops, and thus yield high social returns.[16]

Related, but equally important, were the learnings around the importance of public investment in R&D. Griliches' work showed that while the gains of private investment were skewed towards private sub-sections of society, the gains from public investments were spread more equally. In addition, public investments accelerated the development, introduction and scaling of new technologies, while private players were more inclined to build on this existing research. However, there have been instances of end to end development in the private sector, especially in the recent past, such as advanced liquid crystal display technologies. [e]

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[d]This rate was the internal rate of return.

[e]An example quoted by Griliches here is the development of Nylon which was spearheaded in the 1920's and 30's by DuPont corporation. It built on fundamental research carried out at government labs and universities, and it is the author's contention that public involvement could have brought it to the market sooner.

In addition, data from East Asian countries (Japan, Korea and China) shows that policies which improved education in science and technology and increased public and private R&D were linked to rapid economic growth and poverty reduction. Studies also show that a country's ability to "understand, interpret, select, adapt, use, transmit, diffuse, produce and commercialize scientific and technological knowledge in ways appropriate to its culture, aspirations and level of development" positively impacts economic growth and national wealth.[17]

Contributions of science and technology also extend to the social, organizational and cultural realms of society. S&T triggers social inclusion. It creates systems for exploring, imagining and innovating. S&T has provided solutions and helped communities cope with natural disasters, environmental change and energy and water shortages. Science directly led to the mobile telephony revolution, impacting billions of lives. Research from the Rand Corporation also argues that "building S&T capacity in developing countries may help them define and choose development options, acquire indigenous capacity to create human capital and appropriate institutions and infrastructure for development, and to have a more equitable voice in international affairs."[18]

A strong scientific base is a necessary but not sufficient condition for economic growth. Studies undertaken by the World Bank and other agencies show that countries had to make complementary investments in other areas in order to realize the full potential of scientific and technological progress. This included investments in human resource development, setting up knowledge and research-based institutions, ensuring a competitive market for private firms and designing public policies to instil scientific temper and disseminate knowledge and information. The studies argued that such capabilities and investments were needed to maximize returns and translate a strong scientific base into the development of technology clusters and the resultant knowledge transfer between higher education and industry.[19]

A Brief History of Scientific Knowledge in India

Most analyses of the history of science in India, that link to what we must do for the future start with early periods of British colonial influences. While pointing to these, it is important to recognize the many strong trends of original thinking from India that influenced, and in some cases, helped transform the rest of the world. These cover subjects as diverse as mathematics, chemistry, metallurgy, astronomy and so on, There are also well documented centers of learning such as Nalanda and Takshashila. Further, examples of scientific schools, from abstract mathematics to implementation, through technology and practice can be found across the subcontinent. As but one example, the history of Astronomy in India is magnificent and deep. Aryabhata (476-550 CE) knew that only the Sun (Surya) gives light, and all other bodies like the planets (Shukra, Mangala, Budha, Shani) and the Moon (Chandra) are bright because they reflect the light of the Sun. When there is reflection of light, there must also be shadows. He also advocated that the Earth spins on its own axis, and accurately measured the size of the Earth from the size of shadows at various locations. In his "Kalakriya", he gives a pioneering explanation for the eclipse of the Sun and the Moon, both from a philosophical and mathematical perspective. In his mathematical treatise "Gola", towards the end, he says how the lunar eclipse happens when the Moon enters the shadow of the Sun (this happens on some days of Purnima), and a solar eclipse happen when the Earth passes through the shadow of the Moon (on some days of Amavasya). He showed mathematically how to calculate the size of the Earth's shadow, in the following verses, and thus how to calculate the duration of an eclipse, and how much of the Sun will be eclipsed. Later on, among his disciples, Bhaskara I (600-680 CE, not Bhaskaracharya), who was also a poet, did much to popularize the view of Aryabhata by writing beautiful verses (Aryabhatiya-bhasya) describing how the eclipse happens, how the calculations are done and about the natural beauty of such phenomena. Many other followers of this view, including and Haridatta (around 680, in his Graha-cara-nibandhana) and Govindaswamin (around 800 AD) developed these theories. Later, in Kerala, Madhava of Sangamagrama (1340-1425 CE), who invented an early form of calculus and used it to calculate the positions of celestial objects, very accurately calculated the position of the Moon at any time with the mathematics that he invented. This could be used to predict eclipses to much greater accuracy than before.

Our modern tradition in astronomy is pathbreaking, we have the Giant Metre Wave Telescope near Pune, and telescopes in Kodaikanal, Udhagamandalam, Gurushikhar, Nainital and Hanle-Ladakh. ISRO also has an astronomical satellite called AstroSat orbiting the Earth, and is about to launch another called Aditya, to research the Sun. India is a leading astronomy researcher in the World. Of course, our modern tradition is proximally derived from Western scholarship and discoveries. But this traditionmust be aware and connected to older schools[f].

In colonial India in 1784, The Asiatic Society of Bengal, modeled after the Royal Society of London, was set up in Calcutta to explore the "History and Antiquities, the Natural Production, Arts, Sciences and Literature of Asia".[20] It is known to have supported some of the earliest surveys – trigonometrical (1818), geological (1840), meteorological (1875), zoological (1911) and botanical (1912) – in the region.[21] During this time, Calcutta also gained recognition as a city of scientific activity and enquiry.[22] This recognition grew further when, nearly a century later in 1876, the Indian Association for the Cultivation of Science was set up. To maintain complete independence from British authorities, this institution was established entirely using funds from Indians, including philanthropist and medical practitioner Mahendra Lal Sircar.[23] It was successful in supporting greater Indian involvement in basic sciences and soon became home to several eminent Indian scientists including Sir C.V. Raman, Asia's first Nobel Laureate in Physics. There was simultaneous growth in scientific instruction in the sub-continent with the establishment of institutions such as the Medical College of Bengal, St. Xavier's and Presidency College. In 1914, a College of Science was established in the University of Calcutta, becoming the first in India to offer postgraduate degrees in mathematics and science.[24] The University of Calcutta was also home to M. N. Saha, an eminent scientist whose major contribution – the Saha equation - remains fundamental to modern astrophysics.[25]

The Indian Institute of Science was established in 1909 with support from Jamsetji Tata of the Tata Group and the Maharaja of the Kingdom of Mysore in the city of Bangalore. In 1933, the first Indian director Sir CV Raman started the physics department at the institute. IISC ranks as India's leading research institute today in global and national rankings.[26]In 1931, another renowned scientist, P. C. Mahalanobis, who made key contributions to statistics theory with the formulation of the 'Mahalanobis distance,' founded the Indian Statistical Institute in Calcutta. The establishment of the Planning Commission in 1938, and the inclusion of science-based industrialization as a key objective for economic restoration of the country, helped drive research across fields.[27]Mahalanobis also played a key role as one of the earliest Indian leaders of the Planning Commission and his statistical models formed the basis of key policies of the second five - year plan.[28]

The 1940s saw tremendous scientific and technological advancement, and India's early approachtowards development was heavily dependent on state-funded science and technology.[29]The Council of Scientific and Industrial Research (CSIR) was established in 1942 to promote scientific knowledge and allow for a greater contribution of science to nation-building.[30] CSIR employed thousands of scientists, researchers and staff in its network of laboratories across India, covering nearly all aspects of various sciences, and eventually became one of the largest publicly funded R&D organizations in the world. In 1945,Homi Bhabha, founded the Tata Institute of Fundamental Research (TIFR). He, eventually served as the chairman of the Atomic Energy Commission of India (AEC) (established in 1948) and the first Secretary of the government's Department of Atomic Energy.[31,32]In 1947, Vikram Sarabhai founded the Physical Research Laboratory, which went on to become the 'cradle of space sciences' in the country. Two years later, M. N. Saha founded the Institute of Nuclear Physics (INP).

Many of the leading scientists of this era, such as Bhabha, Mahalanobis and Sarabhai, had all studied and done research in leading academic institutions overseas[g]and were aware of the importance of investing in

[f] The details on the history of science in India have been shared by Professor Somak Roychaudhary, Director, Inter-University centre for Astronomy and Astrophysics.
[g]Bhabha, Mahalanobis and Sarabhai completed their graduate studies at Cambridge University in the United Kingdom.

and developing a robust scientific infrastructure. They also incorporated best practices from their alma maters abroad into their work in India. Homi Bhabha while at Cambridge worked with many leading scientists of the day such as Niels Bohr and Enrico Fermi, who were part of the UK-US efforts to develop atomic energy programs[33]. He also witnessed the benefits of having an environment like Cambridge's in which leading minds worked together and pure science and applied research flourished. [34]

These leaders and scientists of the soon-to-be independent India also recognized the need to improve the quality of education. They believed this would encourage young individuals to take up a career in science and technology, and eventually lead to a higher quality of scientific research. Towards the end of the 1940s, a government committee recommended the establishment of four institutes of higher technical education across the country.[h] The aim was to ensure that graduates from these institutes were at par with the best institutions of higher education in advanced countries.

As a result, in 1950, the first Indian Institute of Technology (IIT) was established in Kharagpur (east India).[35] Over the next few years, four more IITs were set up.[36] Many more such institutes were introduced in the decades that followed, and IIT came to be globally reputed for high quality academic and research facilities. A parallel effort was launched in medical sciences with the establishment of the All India Institute of Medical Sciences in New Delhi in 1956 under the All India Institute of Medical Sciences Act, to promote public education in the field of medical science.

To build on its strong legacy of science research, the Indian parliament passed the first Science Policy Resolution in 1958. According to the resolution, the goal of India's science policy was "to encourage individual initiative for the acquisition and dissemination of knowledge, and for the discovery of new knowledge in an environment of academic freedom; and in general; to secure for the people of the country all the benefits that can accrue from the acquisition of knowledge."[37]

While India built up its scientific capabilities and infrastructure, the world's first artificial satellite, Sputnik I was launched in 1957. This marked the beginning of a new phase of intensive space science research by many countries including India. The Indian government introduced numerous initiatives to improve research in space technology.[38]In 1969, the Indian Space Research Organization (ISRO) was established by Sarabhai. With ISRO, the government aimed to harness space technology for national development.[39]In 1975, India's first unmanned Earth satellite, Aryabhatta was launched.

The Indian Agricultural Research Institute (IARI), played a significant role in bringing Green Revolution to India, in the 1970s. The institute was established as early as 1905, with the goal to conduct agricultural research and education in India. The Green Revolution is an outstanding example of how convergence of science and technology with appropriate budgetary and policy support has transformed life on earth for the better. The application and integration of science and technology enabled the transition of India from ship to mouth existence to a net exporter of food grains[40]. And today, India has become world's second largest producer of both wheat and rice and the largest exporter of rice.

There were several developments in nuclear science research during the 1970s and 1980s, and in May 1974, India successfully tested its first nuclear explosive device.[41] Scientists who worked on this were celebrated as national heroes.[42] However, the test was met with negative reactions from many countries including the US and Canada, despite the device being dubbed a Peaceful Nuclear Explosive.[43]Further development of nuclear science in India was with little if any international interaction. The 1990s, and post-'Pokhran-II' period also witnessed a 'technology denial regime' during which India was unable to access select technologies from other countries which hindered growth in key areas. However, this led to the scientific community developing technologies indigenously, especially in the space program. An example was the

[h] The institutes were possibly modelled along the lines of MIT in the US.

development of cryogenic rocket technology by 2013, which significantly enhanced India's satellite and rocket launching capabilities and helped develop expertise across disciplines.[44]

During the 1980s, India benefitted from advancements in biotechnology. The success of the National Biotechnology Board created in 1982 and subsequently the Department of Biotechnology in 1986 led to many advances such as enhanced crop productivity and quality.[45]This was a tremendous benefit for scientists working in avenues such as agricultural practices, food security and plant biotechnology. This period was also marked by the rise of the generic drugs and vaccines industry in India, development of a strong industrial base and firms which eventually became globally prominent.

Despite many successes, scientific research in India struggled and research output was stagnant compared to advanced countries. India was also 'losing a generation of scientists' to other countries.[46] This was especially apparent in the lack of scientists that not only excelled in their field but also had the ability to develop and lead research institutions.

Acknowledging this, at the turn of the century, the government attempted to improve the situation. In addition to increased funding, numerous schemes were designed to expand research output and quality, such as providing generous scholarships to young people to pursue science as a career, and attractive fellowship programs to reduce the number of people seeking opportunities abroad. These initiatives had limited successes given the overall disparities in opportunities and the weaknesses still prevalent in the system. However, they indicated a growing recognition within India's policy making leadership of the importance of having a strong science and technology focus.

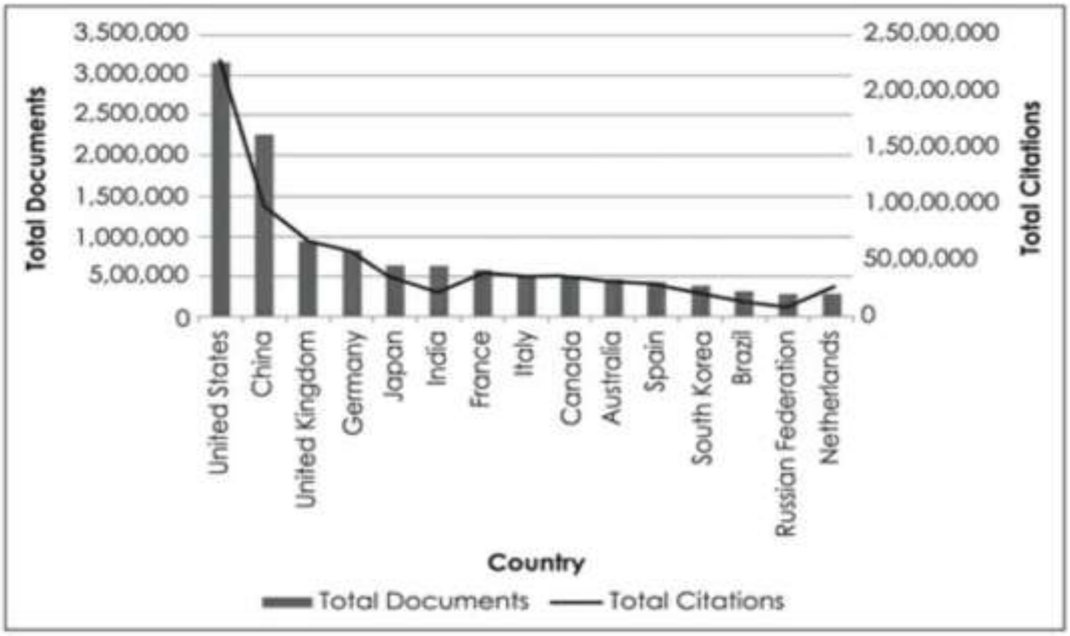
Why Science and Technology Lags in India

In recent years, India has had several notable achievements in science and technology, such as the Mangalyaan mission (to Mars). In addition, India has a strong legacy of frugal innovation with developments of several products like the low-cost refrigerator and infant warmers. However, India lags countries such as the U.S and China in science research and technological development.

This is demonstrated by several indicators. As of 2018, India had 156 researchers per million citizens, which was far lower than the global average of 1,500, and much lower than China and the U.S, who boasted of 1,096 and 4,217 researchers per million people.[47, i] The output of India's research personnel can be measured by the number of research papers published and citations received. India ranked sixth in the number of papers published, producing one fourth the number of research papers produced by China and one fifth of those produced by the U.S. for the period between2012 and2016, as illustrated in exhibit 1. In the same period, India stood twelfth in number of citations received.[48] In addition, a survey of highly cited papers by country, revealed that India lagged China by a factor of six, as illustrated in table 1.

[i] The Department of Science & Technology reports the number of researchers per million as 218 in 2015.

Exhibit 1: Number of Research Papers and Citations by Country 2012-2016



Source: Varun Aggarwal, *Leading Science and Technology: India Next?*, New Delhi, Sage Publications, 2018, page 43.

Table 1 Number of Highly Cited Papers from 2012 to 2016

Country / Number of Citations	>= 100	>=250	>=500	>=750	>=1000
USA	15,000*	4,013	976	437	234
Australia	3,041	616	173	80	41
China	7, 213	952	194	84	50
South Korea	1,505	330	100	56	34
India	989	169	39	21	17
Japan	2,307	429	110	63	39
Germany	6,573	1,069	272	130	69
UK	7,358	1,395	375	175	94

Source: Varun Aggarwal, *Leading Science and Technology: India Next?*, New Delhi, Sage Publications, 2018, page 52.

Patent filings is another metric often adopted to measure a country's technological progress. India's patent office ranked sixth by total number of patent applications received, with 46,582 applications. In contrast, China's patent office received 1.38 million patent filing applications and the U.S office received 606,956.[49, j] Filing patent applications abroad typically represents a desire to commercialize technology in foreign markets. India lags on this metric too, as can be gauged by the number of applications under the Patent

[j] The total number of patent applications includes applications by residents and non-residents. While the bulk of applications received by China were from residents (9.8% applications by non-residents), U.S and India received a high-share of non-resident applications (51.9% and 67.9% non-resident applications, respectively).

Cooperation Treaty (PCT).[k]Although India's patent applications under the PCT grew by one of the highest rates at 27% from 2017 to 2018, it filed just 2013 PCT applications, compared to 53,345 for China and 56,142 for U.S, the top countries.[50]

These measures indicate that there is a gap between India and other major economies in research and technological development. This is rooted in India's post-independence economic history. After independence, building the country's basic infrastructure and providing for the people's basic necessities were a priority. This led to a slowdown in the area of science and technology compared to the pre-independence period.

Moreover, as a developing nation with a large number of poor people, the focus was on having people build job-ready skills, a sentiment that was reflected in the country's educational system. The era was one of chronic shortages in basic areas such as food, housing and essential needs such as medicines and the government was forced to prioritize those needs. This created a resource- constrained mindset among India's central planners. The bureaucratic systems and processes that emerged were oriented in this direction.

The slow economic progress of the country from the 1960's through the 1980's also played a part. During this period, the average real annual economic growth rate was between 3% to 3.5%, barely keeping pace with population growth, resulting in an annual real per capita income growth between 1% and 1.5%.[51] This was in stark contrast to other Asian economies such as South Korea that had similar income levels to India in the 1950's but had moved far ahead by the early 1990's.[52]

These factors combined to slow the growth and development of Indian science and technology despite its proud past and strong roots, which are covered in detail in the following sections.

Under-investment in science and technology

India has chronically under-invested in science and technology. In 1959, India invested 0.12% of GDP in research and development, compared to 1.28% of GDP by the U.S.[53] Although India's investment in research increased over time, the gap in total amount invested between U.S and India widened. By 2002, India was investing only 0.49% of GDP in research and development, compared to the U.S. investment of 0.89% of GDP.[54] By 2018, Indian investment in research and development stood at 0.8% of GDP as compared to 2.7% for the U.S and 2% for China. This amounted to US$ 48.0 billion (adjusted PPP$), with the corresponding figures for the US, China and Germany being $476 billion, $370 billion and $109 billion.[55]

As discussed, this underinvestment has historical roots. After achieving independence, India focused on becoming self-sufficient and catering to the basic needs of its citizens. The initial focus was on agricultural self-sufficiency, food security and building capabilities in defense. A huge success in the 1960s was the Green revolution which saw India adopt globally advanced agricultural practices such as the large-scale use off arming implements, high yielding varieties of seeds and modern irrigation techniques. As a result, India's food grain production doubled from 80 million tons in 1961 to 177 million tons by 1990-91with a significant reduction of imports and improvement in food security.[56]With time, the focus was expanded to include other sectors such as education, healthcare, industry, and infrastructure, but remained hobbled due to headwinds caused by slow economic growth, outflow of skilled human capital to other countries, and weak international linkages.[l]

[k] The Patent Cooperation Treaty (PCT) is an international patent law treaty, concluded in 1970. It provides a unified procedure for filing patent applications to protect inventions in each of its contracting states.

[l] The nuclear tests of 1974, while conducted for peaceful purposes, drew a negative reaction from major diplomatic partners which partly impacted exchanges and cooperation in the field of science and technology.

India's GDP has grown 10 times since 1991, and today its nominal GDP per capita is $ 2,000 ($7,000 in adjusted PPP terms), which is indicative of moderate prosperity.[57] However, India's growth masks vast income disparities and inequalities across the country. India's top 10 cities account for a third of its GDP, and the GDP per capita of 110 million urban citizens is 4times that of the remaining 1.2 billion.[58] Even wealthier urban regions face development-related issues on basic necessities such as sanitation and housing. Given this, there is enormous pressure to focus on basic amenities.

This may result in a sense that investing in research is a luxury that India cannot afford. While India has invested in Space, atomic-energy and defense research; substantial investments towards widening a research culture in our undergraduate and higher- education system has been wanting. In its absence, a culture of working within constraints and optimizing available resources has arisen. This culture of 'Jugaad' is often celebrated as a mark of a creative and solution-oriented mindset.

For India to harness its potential in science and technology, there must be a clear focus on developing a robust science culture where fundamental research in science is coupled with development of cutting-edge technologies to fuel innovation and growth.

Across the world, the private sector and public sector have complemented each other's efforts in research and development, with the private sector often building on the results of publicly funded research. In the U.S., scientist and inventor Vannevar Bush[m] was one of the first to highlight the government's responsibility for "promoting the flow of new scientific knowledge and the development of scientific talent". In his seminal 1945 report titled 'Science – The Endless Frontier', he noted "New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science!"[59]The National Science Foundation was set up at his behest.

Since then, public R&D has contributed to immense scientific progress in many areas. A prominent example is the role played by National Institutes of Health (NIH), the primary biomedical and public health research agency of the United States, which took the lead in the Human Genome Project[n], which evolved into a worldwide collaboration. The NIH with its 27 facilities, 1,200 principal investigators and 4,000 fellows is one of the largest medical facilities in the world, and has numerous accomplishments such as the invention of fluoride which fights tooth decay and the development of vaccines for diseases such as HPV and hepatitis.[60] In 2019, it was ranked number 2 in the world for its contributions to biomedical sciences.[61] Similarly, the technology underpinning the Internet was developed at public institutions such as the National Science Foundation and Department of Defense in the U.S. and CERN in Europe.[62] This spread through strong networks to partnering universities and was one of the driving forces behind the rise of Silicon Valley as a hub of innovation. Many of the world's leading technological firms such as Microsoft, Amazon, Apple, Google (Alphabet) and Facebook have strong roots in Silicon Valley.

A more recent example, from the 1980's onwards, is that of nanotechnology which was emerging as a popular field of research in many countries including the U.S. and Europe.[63] Towards the late '90s, the EU and American governments increased spending on research for nanotechnology. The U.S. government established the National Nanotechnology Initiative (NNI) which works with 20 different departments and independent agencies across the country.[64] This initiative led the way for nanotechnology initiatives worldwide.[65]The private sector soon began pumping more investment into this industry; and by 2012, the

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[m] Vannevar Bush (1890-1974) was vice-president and dean of the School of Engineering at the Massachusetts Institute of Technology and then head of the Office of Scientific Research and Development..

[n] The Human Genome Project was an international scientific research project with the goal of determining the sequence of nucleotide base pairs that make up human DNA, and of identifying and mapping all of the genes of the human genome. It remains the world's largest collaborative biological project to date.

U.S. contributed $4.1 billion and Japan, $2.9 billion, leading global corporate spending on nanotechnology.[66]

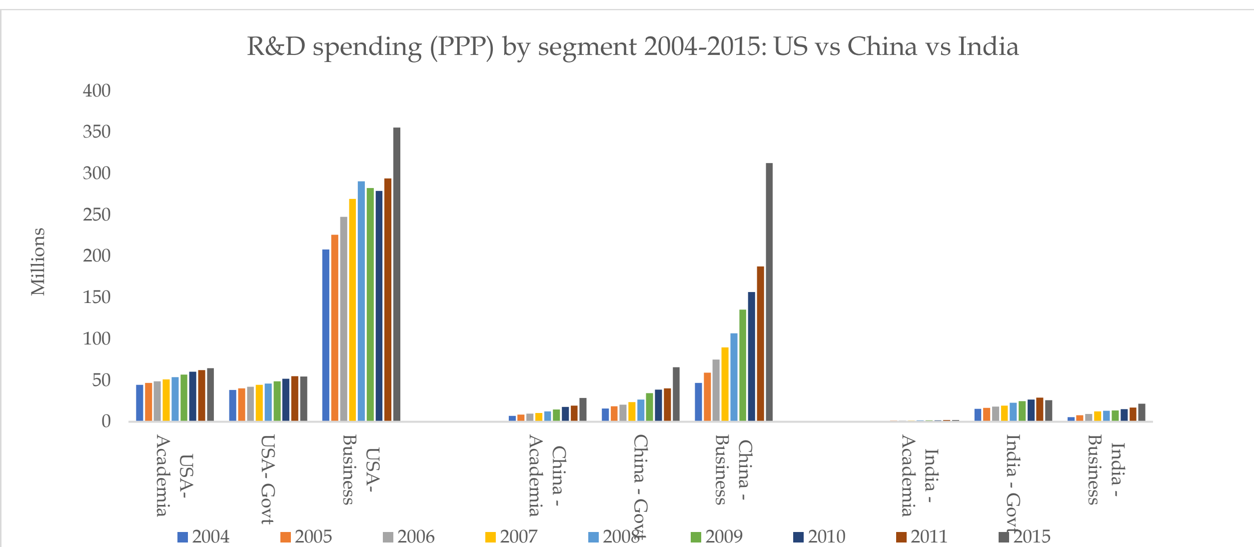
In many scientifically advanced nations, such as the U.S., publicly funded research is spurred by enquiry, builds a strong knowledge base and has a long-term horizon for discoveries or successes and private sector firms have ready access to this knowledge. Firms and entrepreneurs willing to take on the risk of combining this nascent knowledge with capital and other resources to build products and services useful to consumers have the potential to reap immense rewards. In the U.S., this was facilitated by the BayhDole Act of 1980 which created a uniform patent policy for publicly funded research and allowed private firms the right to retain ownership of patents.[67,o]An evidence of this is the large number of patents awarded to private firms in the U.S. In 2016, 85%of the 151,000 patents awarded by the United States Patent and Trademark Office (USPTO), were to the private sector, led by firms such as IBM, Qualcomm and Google.[68]

Table 2 R &D Spending by Sector for India, China and U.S. in 2017 (in PPP $MN)

	Business	Government	Universities	Private non-profit
India	17,044	29,066.8	1,952.3	NA
China	286,465	58,566.5	25,573.7	NA
U.S.	340,728	54,106	62,346	19,272

Source: UNESCO Institute for Statistics, "How much does your country Invest in R&D?" http://uis.unesco.org/apps/visualisations/research-and-development-spending/, accessed September 2019.

Exhibit 2: R&D spending by segment by country (PPP $)



Source: UNESCO Institute for Statistics, "How much does your country Invest in R&D?" http://uis.unesco.org/apps/visualisations/research-and-development-spending/, accessed September 2019.

o The Bayh-Dole act, or the Patents and Trademark Law Amendments Act, permitted non-profit organizations and small business firm contractors to retain ownership of inventions developed through public funding. It also authorized federal agencies the right to grant exclusive licenses for inventions owned by the federal government to others. This helped create a uniform patent policy which enabled private players such as universities, non-profits and companies to retain ownership of publicly funded innovations and commercialize them.

In contrast, while India's overall investment in research and development is dominated by the public sector, the private sector finds it difficult to access this research, as illustrated in table 2 with details. This is borne out by the fact that although the private sector's contribution is increasing, up from 25% in 1991 to 40% in 2018, is still lags behind other countries such as the U.S and Germany, where the corresponding numbers are 71% and 67%.[69]As exhibit 2 illustrates, growth in private sectors pending have been accompanied by increases in public spending in other countries such as the US and China, which has not happened in India.

There is significant scope in India to increase publicly funded and driven research in basic, pure science. Public funding has always outstripped private spending in India, with the latter only gaining significance in recent years. Within public funding, major allocations have been towards defense, space and atomic energy. The focus of this spending is on basic research as well but also on applications which can be utilized in industry, agriculture and medicine. The charter of the Department of Atomic Energy is to 'empower India through technology' and its goals include 'making India energy independent' and 'providing better health care through deployment of nuclear and radiation technologies and their applications'.[70]

This is commendable and should be continued, but investments in basic science which lead to findings and discoveries which can be taken forward by entrepreneurs and industry also need to be increased. Private firms and entrepreneurs can effectively bear the risks involved in translating basic science into commercially viable and socially useful products, services and technologies. In turn, these private firms would benefit from the rewards that accrue. This has been successfully done in India in life sciences, in the area of generic drugs and vaccines.

In conjunction, there is scope for India's private sector to increase its investment in research that can build on publicly funded research. Unfortunately, private sector investment is often hindered by government regulations. For example, private firms cannot not bid on projects if they have been a part of the initial advisory team. Further, bidding on government projects requires private sector entities to have a proven track record. Ideally, the private entity should have completed similar projects that cost a certain percentage of the project they are bidding for.[71]

Recent policy initiatives by the government to include research and development expenditure as part of the mandatory corporate social responsibility spending are expected to have a positive impact on driving private sector investment in research and development .[72]This has been a growing area over the past few years, with leading Indian institutions reporting an increase in sponsored research. For instance, IIT-Madras' sponsored research funding has seen steady growth of 10-15%. Its sponsored research funding increased from Rs108 crores in 2014-15 to Rs 536 crores in 2018-19.[73]

India's Education System: Promoting Research and Inquiry?

India has the world's largest primary school system and a robust higher education system. It has the world's largest number of universities at 3,944, far ahead of 2,208 for China and 3,257 for the United States.[74] There are about 34 million students in higher education, with about 8-9 million graduates per year.[75] This includes ~50,000 medical professionals and over one million engineers, both of which are amongst the highest in the world.[76]In addition, there are over 2 million science and technology graduates.

Since only a small fraction of this graduate population proceeds further to pursue doctoral and post-doctoral studies, India lags other countries in terms of number of such students. Typically, India has half the number of graduating doctoral students compared to China and the U.S.[77] Only a small proportion of these students come from India's best institutes of higher learning—11% of Ph.D students come from the Indian Institutes of Technology and Indian Institute of Science and another 19% graduate from the top 50 educational institutions in India.[78] This is because of several reasons: a low awareness of research as a career path, insufficient recognition of research achievements, low level of personal and professional rewards, and often a poorly defined career path for those that want to pursue research.

In a 2016 survey of 241 undergraduate students, 86 Ph. D students in India and 46 Indian Ph.D. Students in the U.S., revealed that less than 20% of undergraduate students wanted to pursue a Ph.D. in India.[79]Students inclined towards pursuing a career in industry, cited low interest in research, long duration of Ph.D. programs and lack of a career path as the top reasons for preferring careers in industry. Lack of awareness was another major factor for students who were enrolled in institutions outside the top bracket of nationally renowned universities and programs, with 25% citing that as a reason for not considering a career in research.[80]

The Indian educational system also values building industry and job-ready skills over building critical thinking and inquiry. There is lesser focus on producing theoretical, inquiry-driven scientists and scholars, with most students in public universities having little to no exposure to research methods and activities. The National Research Foundation, announced in the June 2019 budget and to be implemented shortly, hopes to address many of these issues.

Collaboration

Another reason for the limited amount of cutting-edge research in India, is the low-level of collaboration at all levels—across disciplines, institutions and with global partners. Collaboration is crucial for scientific research. As researchers today develop specialized domains of expertise, working alone might limit the acquisition of broad knowledge and expertise that working together may facilitate. Further, innovative solutions to large-scale global problems require cross-disciplinary thinking and collaboration. For example, in recent years, American geneticist David Reich worked closely with the Center for Cellular and Molecular Biology (CCMB) in Hyderabad, building on the research of two researchers from CCMB. The researchers brought a part of the vast collection of DNA samples at CCMB to Reich's home institution, Harvard Medical School in Boston, since technology to analyze such DNA was not available in India. This led to several findings, such as the discovery that South Asians are more prone to rare genetic population specific diseases.[81] This is just one example of how expertise and resources, clubbed together through collaborative efforts can yield significant impactful insights.

A 2018 report on the future of education by the Organization for Economic Cooperation and Development, visualized that the future of scientific knowledge would come from collaboration: "Innovation springs not from individuals thinking and working alone, but through cooperation and collaboration with others to draw on existing knowledge to create new knowledge."[82]

Modern science, across fields, has been marked by two related developments. An explosive growth in the cumulative amount of knowledge has led to increased specialization as each individual can master only a small sliver of knowledge. For example, biology as a discipline now has numerous sub-disciplines such as biotechnology, marine biology and biophysics. Thus, solving large complex challenges now requires the coming together of a wide array of specialists in a collaborative environment.[83]

Collaborations within Research

A few Indian research institutions such as the Indian Institute of Science Education and Research (IISER) were set up with multi-disciplinary research as a core area of focus. This has enabled them to undertake research that leverages development across several fields in science. For example, the researchers at IISER Pune are collaborating on fuel transportation technologies, including water-based fission technologies. This effort requires the coming together of physicists, chemists, biologists and material scientists. This is possible because the institute houses several different labs and provides resources as well as conditions for collaboration. This example illustrates the immense scope for Indian science research institutes to undertake more multidisciplinary research.

India's track record for global collaboration is weak. Although India's scientific research output increased by 68% between 2009 and 2013,only 16% of India's research output came from international collaboration in 2014.[84] This is indicative of India's low participation in global research projects. Since collaboration drives further engagement, increasing collaboration is a significant way for India to participate in future globally significant research projects.

There are several reasons for limited collaborations. The governance culture at research institutions is inward looking, with leaders focusing on optimizing resources within their individual institutions. With a few individual exceptions, there is limited focus on building partnerships, which could fuel collaboration and innovation. Further, governance mechanisms are not always formal or transparent. For instance, in the recent past, the heads of many institutions were selected by a group of eminent scientists, without such positions being advertised or opened up to candidates at large.[85]

The structural setup of institutions also acts as an impediment to collaboration. Most government funded institutions have individual governing boards that report to related ministries and government departments that have the final authority on administrative decisions. Decisions related to staffing and resource deployment require a chain of approvals which increases turnaround times on decisions. The limited autonomy has an impact all the way down to individual researchers, with administrative restrictions on how funds can be used. Sufficient overall budgets notwithstanding, researchers often lack discretionary funds to attend conferences or participate in research meetings or procure equipment.

In fact, one of the largest impediments to institutional and international collaboration is the lack of travel budget for researchers. Being able to travel to conferences, present papers and meet the larger community is the foremost enabler of collaboration. However, budgets at research institutions very rarely allow for travel at the undergraduate level and are severely limited for Ph. D students and even faculty. Moreover, to access the limited resources that are available, a researcher must go through a bureaucratic approval system.[p]

Further, these governance systems have also resulted in silos within institutions. Recently, an individual who had graduated from an IIT with an undergraduate degree in electrical engineering, and a Ph. D in statistics from a leading U.S. university was refused permission to teach at an IIT, because the focus of his graduate program was different from the focus of his doctoral program. The engineering department required a Ph. D in engineering and the statistics department required a graduate degree in statistics. There was limited appreciation of the fact that a strong statistics background would be helpful in pursuing engineering research and that this sort of multi-disciplinary background is an asset. This refusal, at a time when 31% teaching posts at IITs are vacant, reflect the mindset that is a hurdle to collaboration.[86]

Together, these factors have resulted in a culture where individuals, and departments are focused on their own goals, with limited incentive to collaborate with others.

Collaboration with Industry

Across the world, collaboration between industry and academia have been the criticalfuel for innovation and technological process. Regions which have been able to structure collaboration into networks, such as

[p] There is no support for international travel at 'non-autonomous' institutions but a streamlined process is being developed for autonomous institutions (more details to be added).

California's Silicon Valley and Cambridge's Bio Cluster have seen sustained long-term success. In recent years, several mini clusters have been very successful such as those in Nice (France) and Barcelona (Spain). Industry represents the best option to translate the gains in scientific knowledge into practical applications in the form of products and services. Annalee Saxenian, Dean of the Information School at the University of California-Berkeley, has studied the long-term performance of Silicon Valley and the Boston technology corridor, known as Route 128, which were both were home to a number of high-performing large technology firms in the 1980s. Silicon Valley went from strength to strength to become home to some of the world's largest firms while the Route 128 area declined, with its key firms losing relevance.

Saxenian's work demonstrates that it was the higher level of informal and formal networks between firms as well as with academic and other organizations that were instrumental in Silicon Valley's success.

Indian academic institutions have seen some successful collaboration with industry. The solar power and electric mobility focused start-up ecosystem promoted by IIT-Madras (IIT-M) has seen good traction. For example, Cyngi Energy Private Ltd. is using solar technology developed at IIT-M to light up remote areas in states like Meghalaya, Assam, and Manipur.[87] The Indo-US Science and Technology Forum (ISSSTF), funded by both countries' governments, promotes scientific research and exchange between academic organizations and industry across both countries. IUSSTF's science and technology endowment provides aid to commercialize science and technology-based innovations. Over 2013 to 2018, the endowment supported 27 projects and aided the launch of 12 products that had been collaboratively developed by Indian and American entrepreneurs.[88]

Another example of strong collaboration is that of Pune based National Chemical Laboratory(NCL) under the leadership of Dr. Raghunath Mashelkar in the early 1990's. NCL, one of CSIR's 42 labs across the country, collaborated extensively with leading firms such as General Electric to develop and patent polymers. Dr. Mashelkar believed that research organizations should focus on patent creation as 'patents are wealth creators' instead of relying on government support. His focus on 'patent, publish and prosper' resulted in NCL owning 88% of all foreign patents granted in 1994 across all of CSIR's labs . Upon taking over as director-general of CSIR, Dr. Mashelkar endeavoured to inculcate this mindset across all labs.[89]

Such examples of collaboration remain the exception, rather than the norm. The broader picture is one of a major gap between industry and academia, especially public and state-run institutions, which comprise the bulk of Indian academia. As per a survey of leading executives done by the World Economic Forum, India ranked number 26 on university-industry collaboration in research and development, compared to the U.S. at number 2. India was ahead of China which ranked number 28.[90,q,91]

This gap in academia-industry collaboration stems from a divergence in how both sets of stakeholders view their own and each other's roles. Researchers view their role as building foundational knowledge in their fields and using public infrastructure for further deployment. The private sector is not considered a viable partner, on the assumption that its incentives and motivations may not be well-aligned. On the industry side, there is a tendency to treat government funded institutions as part of the larger bureaucracy, which limits a free flow of information and thereby the process of iteration. There is also a perception that the research produced is more theoretical and needs additional effort in terms of time and money to bring it to an industry or market-ready state. Since only a few large firms with deep pockets and a long-term horizon are willing to make this effort, most scientific research done in government funded institutions remains confined to labs and doesn't find applications in industry. Consequently, many in the corporate world

[q]The ranking for China reflected a view amongst business leaders that there were low levels of trust between industry and academia and that the intellectual property environment needed to be strengthened. 76% of R&D expenditure in China in 2016 was by industry which includes state-owned enterprises. State owned enterprises along with mixed ownership enterprises contributed to 65.8% of new product development expenditure in 2017.

believe that Indian academic institutions do not have the orientation to produce industry relevant research and applications.

This mistrust of mutual capacity and intent has resulted in limited networks of interaction and communication. However, given the extensive co-location of research institutions and industry, there is enormous scope to collaborate.

Moving Ahead: A Change in Mindset

In addition to these factors, India also suffers from a mindset that discourages failure. Very few ideas succeed in their first attempt, hence iteration and a willingness to adapt and refine ideas is crucial to scientific injury. Adoption of an attitude that failures are bound to occur and should be treated as learning moments, will enable researchers to pursue big picture, blue-sky research.

Indian science has a rich legacy of accomplishment with innovators and scientists such as C.V. Raman, Hargobind Khorana, Homi Bhabha and S.N. Bose lining its archives. Over the years, India has developed a tendency to look back and rest on the weight of such accomplishments rather than focusing forward to build on past achievements and creating the conditions for many more such science leaders to develop. APJ Abdul Kalam, 11th President of India (2002 to 2007)and former Principal Scientific Adviser to the government, wrote in 2003 of the "inertia that has gripped the national psyche."

Breaking this inertia and focusing on how to build on our legacy can have a transformational impact on the mindset for research.

Finally, India needs to move ahead of its resource-constrained form of innovation, especially since it now has the capabilities to pursue science research that focuses on big questions. This does not mean discarding the ability to innovate within constraints. This is a key competitive advantage that India can continue to exploit, while also pursuing research-led developments in science and technology.

Science & Technology in India's Future

It is estimated that in order to achieve its goal of becoming a $5 trillion (nominal GDP) economy by 2024, India would need a significant and sustained increase in its real annual GDP growth rate.[92] The Finance Minister Nirmala Sitharaman outlined a roadmap to take the country to the target rate. This included investments in areas such as infrastructure, digital economy and private sector development.[93] But the country would need a paradigm shift to drive and sustain rapid growth rates and S&T would need to be at the forefront of this change.

In addition to driving rapid transformation, S&T holds the potential to identify solutions to India's perennial problems. In its seventh decade of independence, India is still searching for answers on how to improve the lives of its 1.25 billion citizens. In order to solve important problems at scale, the country needs scientific and technological breakthroughs along with frugal and incremental innovation. Science & technology will help the country build new capabilities and stretch finite resources to serve its growing population. It also has the potential to inspire India's predominantly young population.

Leveraging Science & Technology - A Cluster Driven Framework

The potential of science and technology to play a transformative role in development and overall growth has been demonstrated. The need for a framework in India that will enable science and technology to be leveraged is critical. It is clear that modern science is highly collaborative, inter-disciplinary and resource intensive. Major scientific advances in the recent past such as the Large Hadron Collider and Human Genome Project have been multi-billion-dollar cross-country collaborations. Important technological advances in fields such as agriculture and telecommunications have come from multi-disciplinary labs within firms such as Apple, Bayer and Samsung. Hence, we are advocating a framework which will enable collaboration across a 'cluster' of organisations.

The objective of this cluster driven framework is to create collaborative ecosystems. 'Clustering' these organizations together into one 'shared ecosystem' (the cluster driven framework) is an effective method to leverage pre-existing pockets of strength and benefit from the untapped strengths of collaboration. This approach will entail less investment and hence is more attractive than other more 'greenfield approaches', such as setting up new multi-disciplinary centers. The success of these clusters will generate the requisite momentum and social capital for further investments. In the judgement of the committee, the best use of scarce resources is to leverage pre-existing pockets of strength.

Clusters have a long and successful history, with geographic clusters such as Silicon Valley, North Carolina's Research Triangle Park and Cambridge's cluster attaining national and global prominence. Research Triangle Park was formed in North Carolina in 1959 to leverage the intellectual and physical capital of three major universities in the region—Duke, University of North Carolina-Chapel Hill and North Carolina State. Over time, it grew to host over 250 companies with an annual investment of $350 million, apart from being home to IBM's second-largest facility in the world and housing major centers for Cisco and GlaxoSmithKline. The park has over 3,000 patents linked to it and has nurtured new products and technologies across disciplines such as life sciences and communications. These include Taxol, a leading anti-cancer medication, an anti-HIV drug Zidovudine, the 3D ultrasound and the universal product code, a barcode symbology which gained widespread acceptance in the retail industry.

Clusters can also be thematic and have a virtual element. Thematic clusters could pivot around a broad theme, such as energy efficiency or industrial artificial intelligence (AI). A virtual cluster has the potential to be flexible by bringing together organizations across regions and sectors to achieve a common mission. India has also seen some early attempts to adopt the cluster model.The Ministry of Micro, Small and Medium Enterprises (MSME) has developed MSME clusters to enhance their productivity and competitiveness. Similarly, the Department of Biotechnology has also established four bioclusters to spur innovative research, development and entrepreneurship activities in the biotechnology sector. Another example worth mentioning is the scientific instruments cluster in Ambala, Haryana.

Given the role of science and technology in economic development and the successful examples of geographic clusters **the committee proposes to build S&T-focused clusters in India.** These clusters could create strong linkages between existing networks of academic institutions and national research laboratories, along with the relevant ministries, industry partners, state governments, philanthropic foundations and international institutions of excellence. All existing institutions (academic and laboratories) or existing clusters supported by Government of India in the city/ region will automatically become a part of the S&T Cluster.

The objective is to bring together 'islands of excellence' spread across academia, industry and government to create a collaborative, enabling and flexible environment that breeds cutting edge scientific research in Indian universities and research labs, leading to technological innovation and entrepreneurship, through seamless leveraging of complementary strengths. Several applied research institutions such as C-DAC, IIITs, and MSME tool rooms, as well as some excellent CSIR Labs that are closely connected to industry and have qualified sector experts, will form an integral component of the clusters, and enable acceleration and translation of the science into market ready products.These clusters could also engage the general public with science and transform their perception towards science. Citizen science projects worldwide have been a great way to attract and connect people (including non-scientists) with science. The clusters could drive future economic growth, enable rapid knowledge exchange and create industry-ready researchers.[r]

This framework integrates top-down driven policy actions and bottom-up organic activities. Our report proposes measures which can help build a structure and key operating principles for the structure but is fluid enough to allow each cluster to adapt and evolve its operations as it evolves, depending on its specific features, strengths and requirements.

The success of collaborative efforts like clusters hinges on the buy in and motivation levels of stakeholders and their investment in the growth and success of the venture. The stakeholders for the proposed clusters span a broad spectrum from policymakers, administrators, industrial and commercial organizations, entrepreneurs and most importantly, scientists who have a desire to create a broad and lasting impact on society. It is vital for the scientists to see the benefit of participating in such clusters. Top-down driven policy actions should seek to function like an 'invisible hand' which helps create the base ecosystem and maintains guardrails as and when needed.

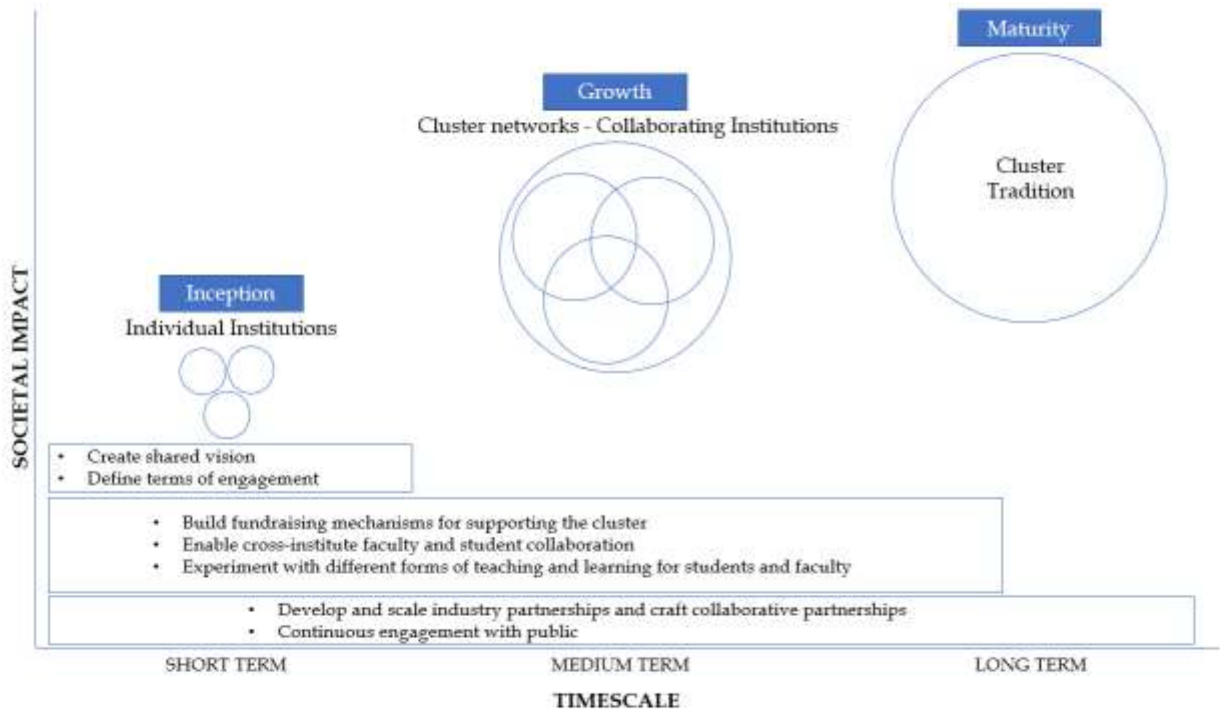
The cluster must have a culture of experimentation coupled with acceptance of failure. The framework does not claim to establish a definitive path to success. The initial phase of the cluster will involve continuous experimentation with different activities and then picking those which work and focusing on how to scale them. It is crucial to have a willingness to constantly adapt and reinvent.

The clusters will operate on an innovative and self-sustainable business model, ensuring financial participation by all stakeholders. For example, the Government could initially fund 100% of the costs, and over a five-year period reduce its contribution, with industry and other stakeholders increasing their contribution.

Another important goal of the framework is to establish a time-based roadmap for clusters to scale successfully as illustrated in exhibit 3. It is important to see evidence of early success to generate momentum and enthusiasm amongst stakeholders and 'social capital' for their subsequent activities. In a democratic framework where one needs to compete for resources and bandwidth, it is crucial to ensure sustained support for clusters.

[r] Drawn from the Science and Technology Cluster of Global Best-in-Class Concept Note.

Exhibit 3: Time-based roadmap for cluster growth and development



Hence, this committee proposes to set up a prototype cluster framework in Bengaluru, National Capital Region (NCR)-Delhi, Pune and Hyderabad — cities that already have a critical mass of S&T-focused organizations and institutions, apart from well-developed diverse industries. The framework envisages that each cluster will have a central management office which will coordinate activities for all participating organizations and also report into a S&T Cluster Apex Committee.

The four chosen locations represent a diverse set of academic and government organizations, as well as a broad base of industries. From an industry perspective, Bengaluru is dominated by IT&ITES, Heavy engineering (including aerospace and defence), and biotechnology. Pune 's strengths are in automotive, software and pharmaceuticals and life sciences. The NCR-Delhi has a strong presence in automotive as well, along with a presence in agriculture and food processing, while Hyderabad is well represented in software, metals and life sciences. The distributed nature of public investments also ensures that each location has a reasonable number of state-run companies and public organizations.

This diversity presents an opportunity to perform, or at least witness, natural experiments in collaboration which can then help the committee learn some key take-aways within a quick time period of about 18-24 months which it can apply at a national level.

The cluster maps highlight the diverse range of institutions at these four locations, as illustrated in exhibits 4, 5, 6& 7 for mapping of institutions and organizations across Bengaluru, National Capital Region (NCR)-Delhi, Pune and Hyderabad.

Exhibit 4: Mapping of institutions and organizations – Bengaluru

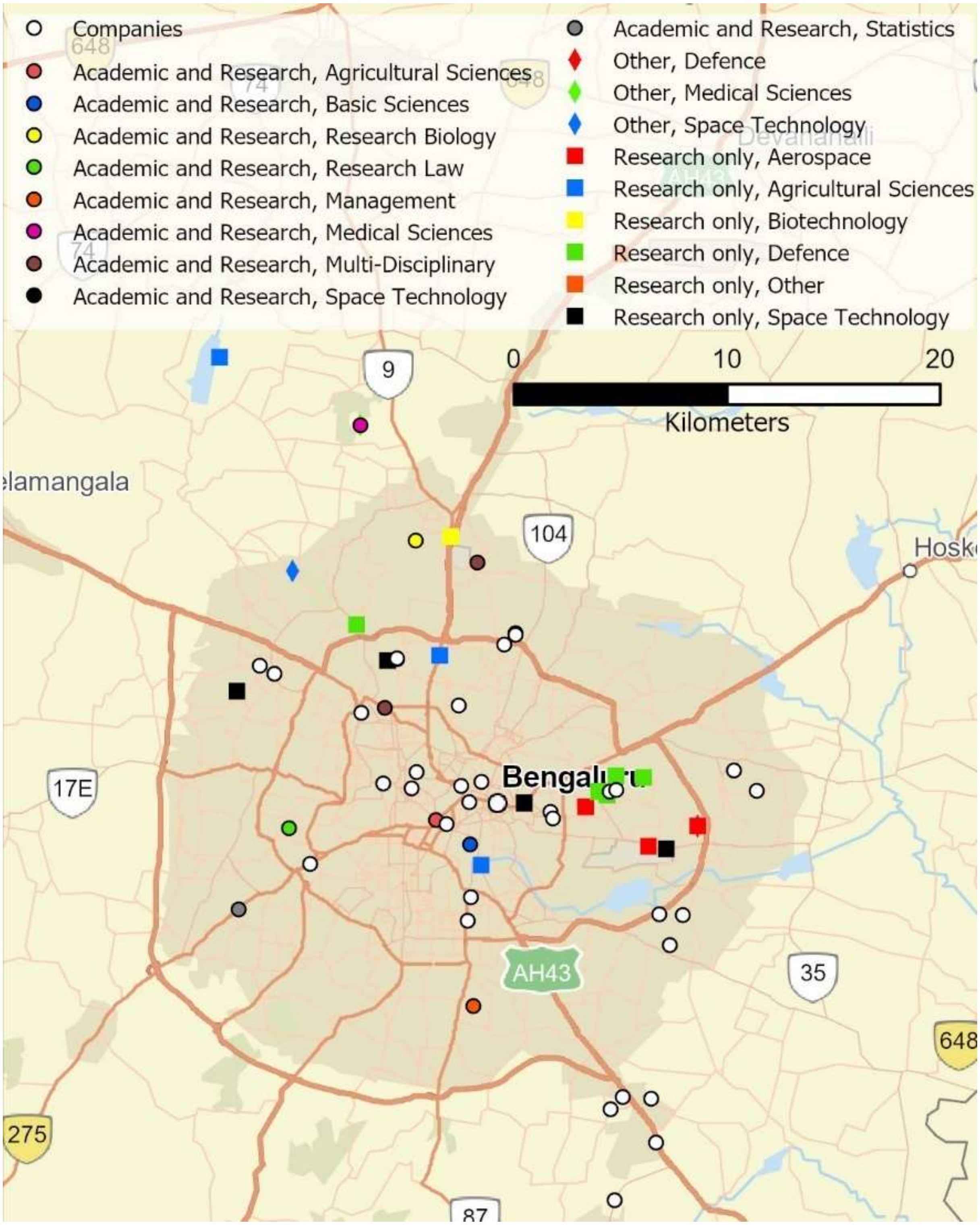


Exhibit 5: Mapping of institutions and organizations - National Capital Region (NCR)-Delhi

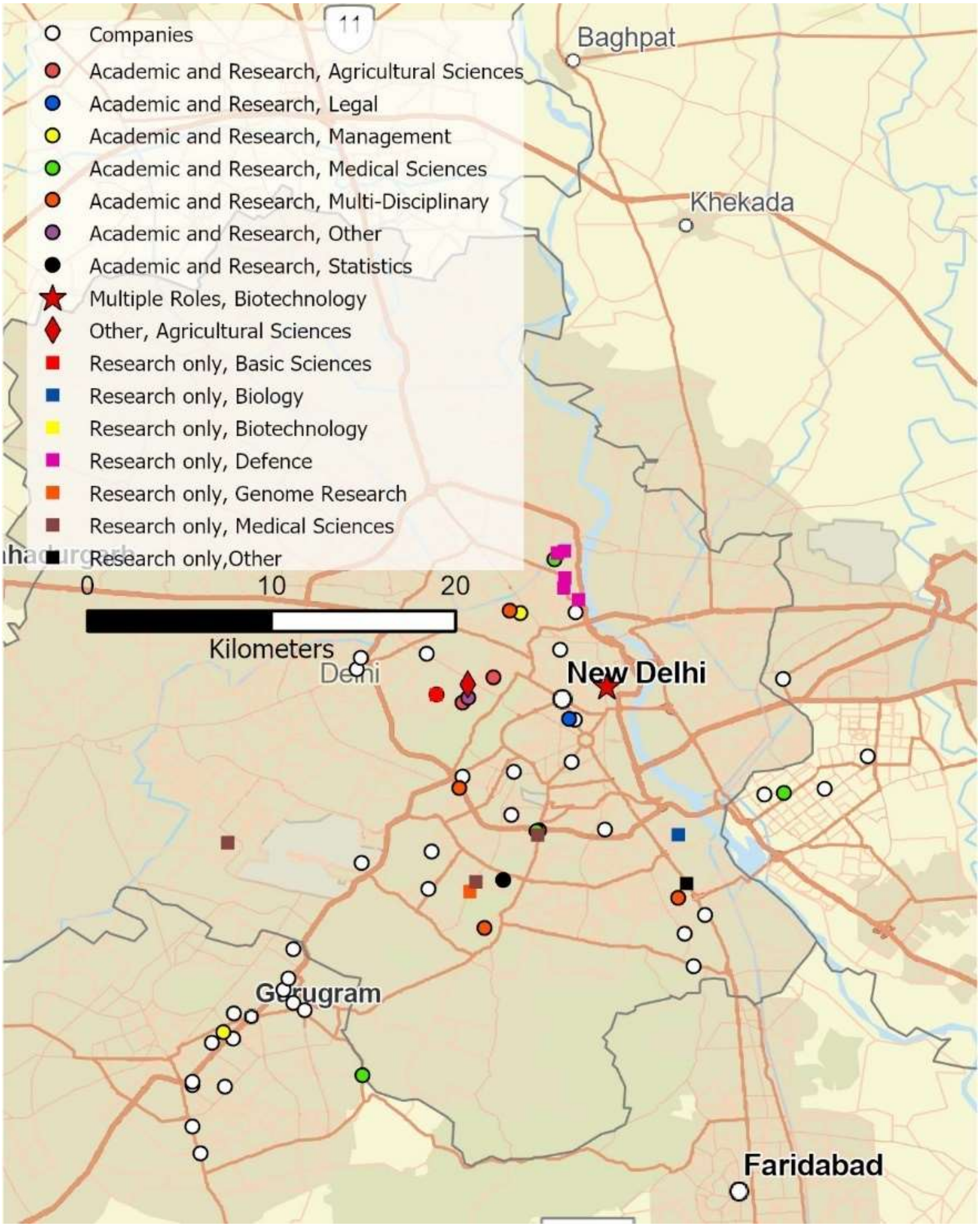


Exhibit 6: Mapping of institutions and organizations – Pune

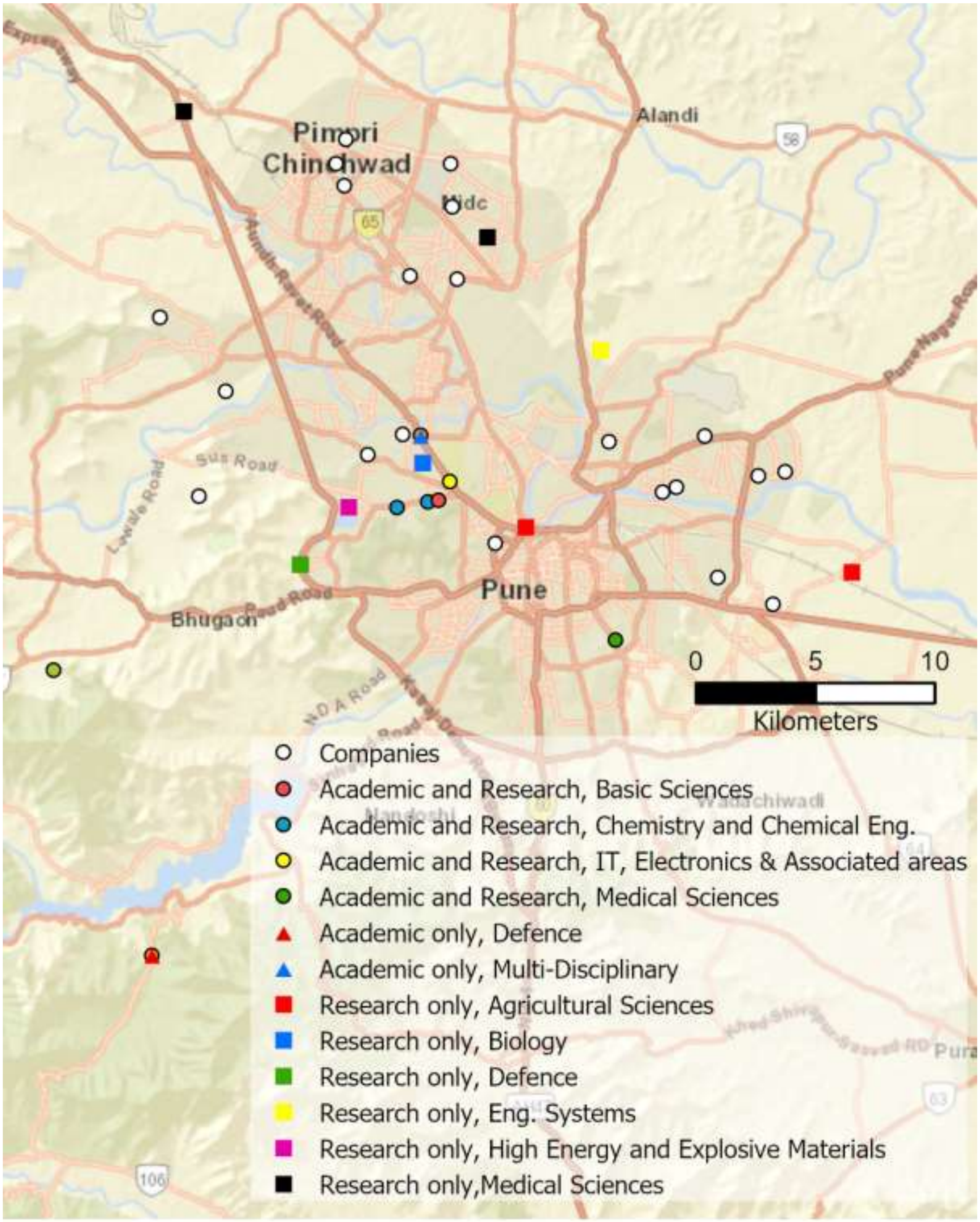
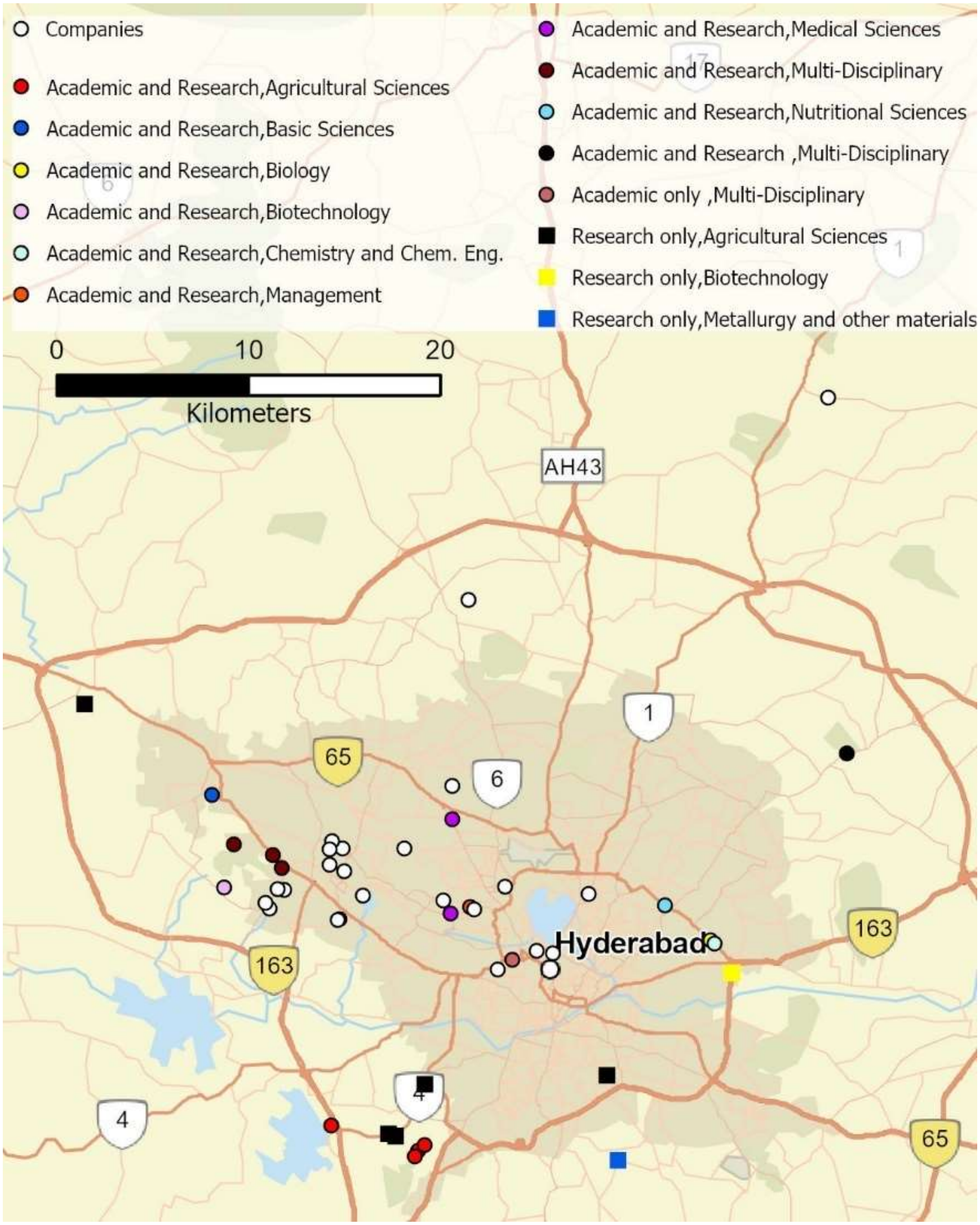


Exhibit 7: Mapping of institutions and organizations – Hyderabad



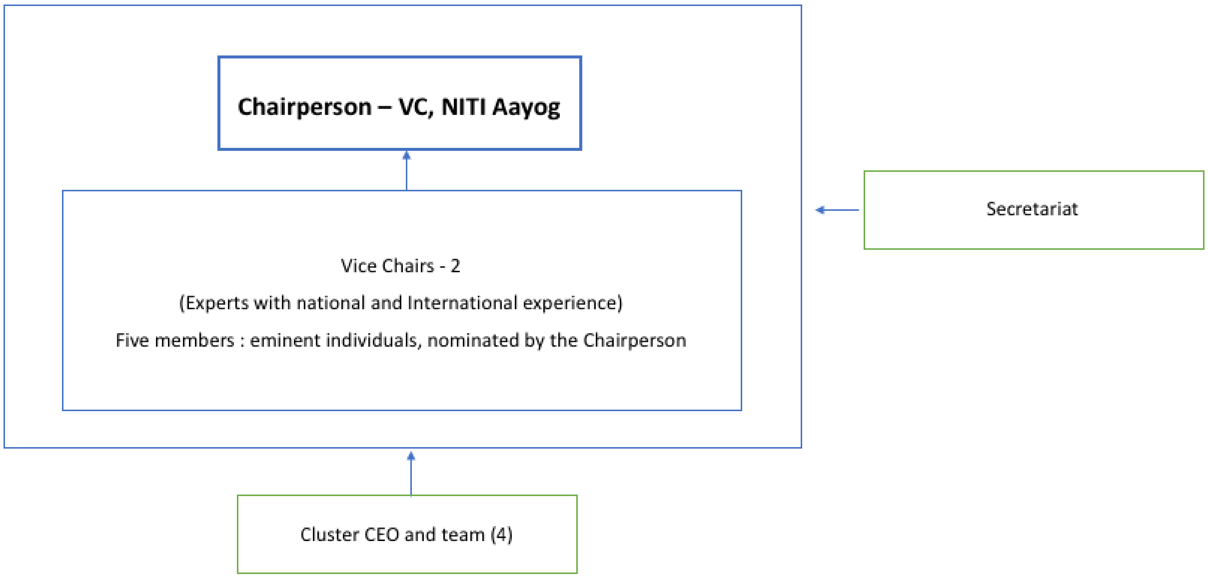
S&T Cluster Apex Committee

The Science and Technology Cluster Apex Committee will be the apex body for managing Science and Technology Clusters in India. The S&T Cluster Apex Committee will work in close coordination with the Prime Minister's Science Technology and Innovation Advisory Council (PM-STIAC), to enable convergence of the Clusters with the specific science and technology domains laid down by the PM-STIAC. The S&T Cluster Apex Committee will coordinate and formulate a framework and guiding policies for establishment, execution and monitoring of the autonomously operating clusters. The committee will work in close coordination with the individual clusters and will enable and empower the clusters to experiment with new interventions, as per their specific local requirement. For example, if a cluster wants to create a joint degree program across two participating academic institutes, the local cluster management office would craft the agreement based on local requirements while adhering to certain policy guardrails around areas such as minimum financial contribution from each partner.

Structure and Operation

The Science and Technology Cluster Apex Committee, chaired by the Vice Chairman, NITI Aayog, will be the apex body for managing Science and Technology Clusters in India. Under the chairmanship of VC, NITI Aayog, the Committee will play a transformative role towards enabling seamless collaboration amongst the cluster institutions, along with coordination with ministries, state governments and other international institutions. For operational purpose, the Chairperson will be supported by two Vice Chairs; with national and international experience. The Principal Scientific Adviser to the Government of India, will be the ex-officio member and national vice chair. The national and the international vice chairs will work together to coordinate with multiple Science and Technology ministries, ensure smooth implementation across all stakeholders, and will bring an independent international perspective and enable benchmarking with global standards. Additionally, the committee will include five eminent individuals, as nominated by the Chairperson, VC, NITI Aayog. The Secretaries of S&T ministries, higher education, MHRD and other relevant department and ministries may be included as special invitees, as and when required. The cluster committee will be embedded in the Office of the Principal Scientific Advisor in New Delhi, and shall be driven under the guidance of the Vice Chairman, NITI Aayog. It will be supported by a Secretariat, that will have an annual operating budget for funding its operations as well as that of the reporting cluster offices. The secretariat shall assist in the creation of independent legal entities for each of the clusters, and will ensure participation of the private sector and other relevant stakeholders. The governance framework of the cluster is illustrated in exhibit 8a.

Exhibit 8a: Governance Framework of Cluster

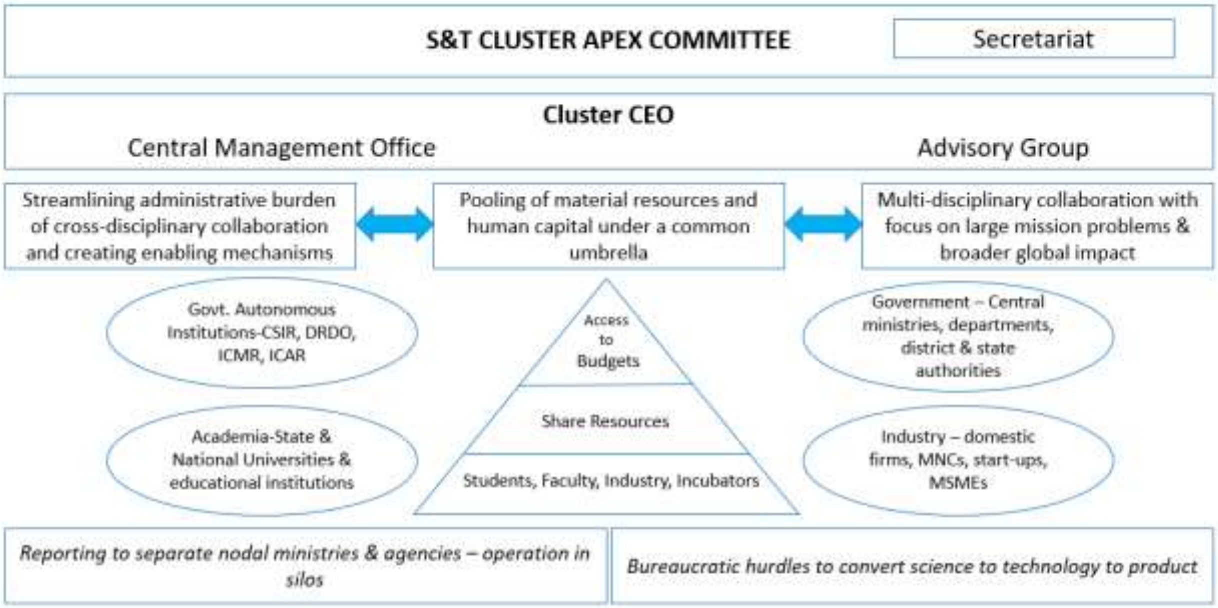


The Terms of Reference of the S&T Cluster Apex Committee will be as follows, and the operational framework is illustrated in exhibit 8b

- The S&T Cluster Apex Committee will periodically interface with various ministries/departments of Government of India in outlining the national science and technology priority goals and accordingly create a mission statement for the clusters, using a consultative approach. The Apex Committee will coordinate to channelize required support to the individual clusters for mega-science mission mode projects for complex problem solving.
- The Apex Committee will enable alignment and integration of the S&T Clusters with the national missions and initiatives of the Government of India, such as the recently approved National Education Policy 2020, the Institutes of Excellence, the Waste to Wealth Mission, the Jal Jeevan Mission, etc.
- The Apex Committee will nominate or support selection of the 'Lead Institution' within each cluster, which will be responsible to create a legal entity for that cluster and will initially act as an umbrella organization for the cluster, enable participation from other institutions, private industry, and other relevant stakeholders.
- The Apex Committee will lay down the guiding principles for selection of the CEO for all the clusters.
- The Apex Committee will coordinate and formulate a framework and guiding policies for establishment, execution and monitoring of the autonomously operating clusters, including financial self-sustainability, international linkages, extensive industry partnership, advocacy for science literacy, intellectual property guidelines for joint ownership amongst the participating institutions.
- The Apex Committee will also lay down operational guidelines to enable functional autonomy for the clusters in a manner that is aligned with the General Financial Rules 2017 (GFR) and recommend any additional measures required for structural reforms.

- The Apex Committee will design a framework for evaluating and benchmarking cluster performance at a national and international level, through measurable outcomes. The performance may be measured on a annual basis.

Exhibit 8b: Operational Framework of S&T Cluster Apex Committee



Setting Up a Cluster

Each cluster will be supported by a legal entity, which will act as a central pivot and oversee the cluster's development. The cluster can be formed as a Section 8 organization, trust or society. An institution who can set up the legal entity may be identified as the principal institution for the cluster. Existing societies which have been setup by any participating institution can also be leveraged for this purpose. The cluster will act like an umbrella organization and will include members from all institutions in the cluster. Each cluster will be headed by a full-time dynamic CEO, who shall be selected as per the guiding principal laid down by the S&T cluster apex committee. The cluster CEO will directly report to the S&T cluster apex committee.

The Terms of Reference of the Cluster CEO are as follows:

- Creating synergy among participating institutions for solving complex problems of international/ national/ regional/ local priority.
- Establishing and successfully running the S&T city cluster, along with a dynamic team of professionals.
- Creating a strategy and implementation plan to develop a vibrant and collaborative ecosystem of research and innovation across all participating institutions in the cluster.
- Building global partnerships with industry (MSME, start-up, large corporations), other academic institutions, government ministries, state authorities, philanthropic foundations, international institutions and other stakeholders.
- Creating a robust and real time governance structure, reporting to the S&T cluster apex committee.

- Experimenting and piloting new ideas in field, with a problem-solving approach, towards promoting science and technology-based innovation and entrepreneurship, within academia, industry and government (central/ state/ local authority).

Cluster: Proposed Activities

The cluster needs to focus on activities that encourage collaboration, resource sharing, idea generation and engaged participation. Detailed below are five suggested focus areas -that will foster a fruitful environment for all and lead to technological innovation and entrepreneurship. Although a brief description has been provided under each focus area, it may be treated only indicative. The S&T Cluster Apex Committee will have the autonomy to propose newer focus areas and more activities with time, based on the feedback received from four clusters. Such an iterative model will enable finetuning of the cluster model, in a dynamic manner.

A key imperative is to integrate research, teaching and academic coursework. The most powerful institutions in the US are those where research, teaching, and students are integrated as the act of teaching is itself clarifying. Ideally each project should inspire good research, good teaching, and cultivate curiosity. India has tried this successfully in the Indian Institutes of Science Education and Research(IISER) model, which emphasises links between teaching and research. The initiatives are mapped separately from a planning and administrative perspective. An integrated delivery will ensure that the quality of research, teaching and students are of the highest level. It will also cultivate a powerful culture of accomplishment which will enhance the appeal of the cluster.

The five focus areas shared below need to happen with speed.

1. *Establishing cluster governance*
2. *Creating a Shared Vision*
3. *Facilitating Interdisciplinary Education and Research*
4. *Engaging with Stakeholders*
5. *Framing Intellectual Property Guidelines for Clusters*

Benefits to participating organizations

Organizations which join a cluster will benefit in four ways:

1. Open access to common facilities and services
2. Amplified R&D efforts
3. Preparation for future consortium-based funding proposals
4. Improved global ranking

The committee hopes that over time the success of the 4 initial clusters will motivate other cities to follow this path.

Measures

The clusters should be evaluated and ranked based on their performance regularly, using parameters as designed and approved by the S&T Cluster Apex Committee, and funding may be discontinued in case of non-performance of clusters. The evaluation metrices need to encourage multi-disciplinary, intra-institutional, inter-institutional, multi-stakeholder and global collaboration. The initial 4 clusters being proposed may be used as a test bed to create successful models for clusters, which may subsequently be replicated. The individual clusters should aim to be sustainable beyond 5 years.

The success of the clusters would be measured using both subjective and objective parameters. Some of the indicative measurable outcomes would include:

- Successful commercial deployment of at least two or more solutions developed, by the local and state authorities, towards solving city specific problems
- At least two or more industry -academia partnerships
- At least two or more international academia partnership
- At least one local government partnership
- At least one inter-institutional training/ workshop or any capacity building event per month
- Ease of access to inter-institutional sharing facilities, at least amongst 10 different institutions
- Launch of at least one science-based entrepreneurship course
- No of industry sponsored research and graduate projects
- No of science blogs/ videos/ podcasts produced
- No of patents successfully commercialized and generating royalty
- Societal value creation though science based entrepreneurship
- Improved ranking in global science, export of royalties, copyright, license fee, increased FDI inflow into R&D
- Driving future economic growth and creation of wealth

Conclusion

India's strong economic growth over the past two-and-a-half decades has resulted in significant improvements in the socio-economic condition of millions of its citizens, but vast challenges remain. The country boasts of a diversified base of science and technology focused organizations with strong capabilities across a number of disciplines such as agriculture, medicine, life sciences, communications and nanotechnology.

Harnessing the potential of these S&T focused organizations through increased collaboration, both within academia and through increased engagement with the private sector, can have a game-changing impact on India's socio-economic trajectory. Clusters represent an effective mechanism to achieve this in a short span of time.

This committee has proposed a framework for conceptualizing and executing this vision and it hopes that all relevant stakeholders will find value in this as they take this forward.

* * * * * *

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