Executive Summary

India: Technology Frontiers Research Report

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Table of Contents

1. Nuclear Fusion

Nuclear energy in India will expand its capacity from 8.2 to 22.5 GW by 2030 to meet growing energy demands and achieve environmental goals. Investors are primarily focused on pursuing investments in fission technology nuclear plants due to their easier control and technological maturity. Fusion has been explored as a potential alternative source since the 1980s, with significant efforts led by government agencies, research institutes, and emerging startups in India.

The Department of Atomic Energy (DAE) in Maharashtra funds the Institute for Plasma Research (IPR) in Gujarat and has established a Centre of Excellence in Nuclear Fusion Technology to advance fusion-based solutions across sectors.

The IPR is at the forefront of India's fusion research, having developed experimental plasma technologies such as the ADITYA Tokamak, which completed 30 years of safe operation in January 2020, and the SST-1. The IPR is also planning the next-generation SST-2 by 2027. Additionally, it conducts outreach programs to build awareness about plasma science and its applications in fusion energy. Complementing this, the Indian Institute of Science (IISc) in Karnataka contributes to plasma physics and materials science research, providing both theoretical models and experimental advancements in fusion studies.

The Bhabha Atomic Research Centre (BARC) in Maharashtra further supports this ecosystem through material development for fusion reactors and collaborative projects with the IPR. Academic involvement extends to Gurunanak Institutions in Telangana, which work under the Board of Research in Fusion Science & Technology (BRFST), focusing on quality assurance techniques for fusion reactor materials. On the startup front, Anubal Fusion in Haryana is pioneering a unique approach by experimenting with proton-boron (boron-11) fusion technology, aiming to overcome current challenges and establish a new pathway toward sustainable fusion energy.

2. Radioactive Waste Generation

With increasing energy demand and nuclear energy serving as a primary alternative to coal for electricity generation, the production of radioactive waste is anticipated to rise in the coming years. Traditional 540 MW nuclear plants generate 5 tonnes of waste annually, while 220 MW plants produce approximately 2.5 tonnes of waste each year, as explained by R K Sinha, director of Bhabha Atomic Research Centre, Mumbai.

This trend is also reflected in mining operations, with 220.86 tonnes of radioactive material supplied to nuclear power plants in 2024, expected to increase to 607.5 tonnes by 2030. Considering this, the Bhabha Atomic Research Centre (BARC) has developed Cold Crucible Induction Melting (CCIM) technology to vitrify high-level liquid waste, significantly extending melter lifespan and minimizing radioactive waste.

Additionally, BARC oversees nuclear fuel reprocessing facilities that utilize advanced vitrification technology to further reduce waste. They have also innovated a selective thorium extraction process using a novel ligand, which is crucial for thorium fuel cycle applications. Furthermore, BARC has successfully transformed 99Tc-bearing sludge waste into a geo-polymerized product, thereby

reducing its environmental impact. The IGCAR operates the DFRP, a facility that processes spent fuels from fast reactors, focusing on minimizing radioactive waste and advancing a thorium-based closed nuclear fuel cycle. NTPC Limited is partnering to deploy ANEEL™, a thorium-based fuel for PHWRs, which enhances safety and minimises waste. The Uranium Corporation of India Ltd. (UCIL) has developed an alkali leaching method for efficient uranium extraction from low-grade deposits, thereby reducing waste generation compared to traditional methods. Lastly, Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI) has developed fast neutron reactors like the PFBR, which produce more fuel than they consume and reduce radioactive waste, supporting India's thorium utilisation.

3. Direct Air Capture

The capacity expansion of each energy source and industrialization has directly impacted environmental emissions, which have increased by 669. 5 million tons since 2012, growing at a CAGR of 2.9%.

The nation's ambitious net-zero target for 2070 necessitates the integration of Direct Air Capture (DAC) research into the equation. While the concept was first suggested in 1999, India's development and deployment of DAC technologies are relatively recent, with initiatives like the National Centre of Excellence in Carbon Capture and Utilization (NCoE- CCU) at IIT Bombay and the Department of Science and Technology (DST) backing research and development in this area. Leading the DAC research and development, IIT Bombay and JNCASR focus on deploying cost-effective CO2 capture and conversion solutions, including a 3-ton-per-day CO2 capture pilot project.

Startups such as UrjanovaC and KARDLE Industries are developing scalable and cost-effective carbon capture solutions targeting hard-to-abate industries with modular and solar-powered technologies. Alt Carbon utilizes geochemical analysis, data science, and satellite imagery to quantify CO_2 removal, while Praan concentrates on industrial air purification using filterless, net-zero technology. Greengine Environmental Technologies is working on microalgae-based carbon capture solutions in collaboration with EIL.

The increasing implementation of Direct Air Capture (DAC) technology aims to decarbonize industrial sectors, enable low-carbon hydrogen production, and support India's coal gasification initiatives. CO_2 utilization pathways, such as enhanced oil recovery, green urea production, and conversion to chemicals and polymers, are under exploration.

A robust policy framework involving carbon credits, incentives, and financing through a Carbon Capture Finance Corporation is driving private sector investment, while emission monitoring bodies and production-linked incentives (PLI) align industry efforts with decarbonization goals. With a multi-pronged strategy encompassing R&D, technology transfer, and commercialization, India is positioning itself as a leader in CCUS innovation and sustainability.

4. Supercritical Geothermal Power Generation

Geothermal technology is one of the promising renewable energy sources. Since it is still in the nascent stage many institutes such as Geological Survey of India (GSI), CSIR-National Geophysical Research Institute (NGRI) and Pandit Deendayal Energy are contributing by conducting geological surveys and data analysis to locate and evaluate geothermal fields utilising multidisciplinary studies to assess geothermal resources, particularly in Ladakh and Chhattisgarh, focusing on supercritical geothermal power generation, while employing remote sensing and geological surveys to identify potential geothermal sites nationwide.

On the industrial side, ONGC is collaborating with Icelandic consultants to develop large-scale geothermal power projects that include supercritical potential, while Thermax in partnership with Reykjavík Geothermal, is establishing India's first geothermal power project in Puga Valley, Ladakh, exploring geothermal power and aiming to improve local energy access and living standards.

The Supercritical Geothermal Power Generation research scope will depend on the infrastructure development of geothermal power generation since there is only one company named The Singareni Collieries Company Limited in India, that implemented an experimental Science and Technology (S&T) project for 20 kW power generation using geothermal energy in Gollakothuru village, located in the SCCL Command Area of Manuguru Mandal, Bhadradri Kothagudem district, Telangana. The project deployed closed-loop Binary Organic Rankine Cycle (ORC) technology sourced from Renergizr Industries Private Limited (RIPL) to generate, supply, and utilize clean, reliable, and efficient electricity using geothermal fluid as the heat source.

Further implementation of such projects combined with the identification of potential geothermal sites for supercritical geothermal energy generation will further research prospects in the coming 10-15 years.

5. Native/Natural/Geologic Hydrogen

White hydrogen another source of clean energy, which is derived directly from the Earth's crust, is generated through a natural geochemical process, making it sustainable and inexhaustible, emerging as a critical source of clean and economically viable energy.

According to Geoffrey Ellis, a U.S. Geological Survey research geologist, the 'most probable' amount of gold hydrogen in the world is 5 million megatons. The scarcity of published literature impedes the understanding of its occurrence, sources, accumulation, generation mechanisms, and recovery techniques.

The research focuses on exploring sites suitable for white hydrogen production in India, particularly the Andaman Basin's Sea Floor Spreading Centre and Deccan Traps. IIT Dhanbad, the only Indian institution involved in natural hydrogen exploration, has partnered with Australia-based company Gold Hydrogen Ltd. and the Australia-based government agency CSIRO to advance natural hydrogen exploration in India.

Although the research is still in its nascent stage, necessary funding and interest from fellow researchers are not focal points due to the inclusivity of the field itself, leaving only leading institutes in mining specialization to conduct further research operations.

6. Quantum Technology

India is strategically positioning itself as a key player in the global quantum technology arena through a robust framework of government initiatives, academic research, and private-sector innovation. The Department of Science and Technology's (DST) National Quantum Mission, with an investment of INR 6003.65 crore (approximately USD 720 million), aims to develop intermediate-scale quantum computers and secure quantum communication networks by 2030, highlighting the government's commitment to advancing this field. This is further supported by initiatives like the QuEST program, which has already invested USD 9.68 million in quantum technology research.

Leading academic institutions, including IIT Madras and IISc, are at the forefront of quantum research. IIT Madras, for example, has established an interdisciplinary research centre focusing on quantum key distribution and quantum computing and has partnered with industry giants like IBM to leverage cloud-based quantum computing resources. IISc has developed critical components like the Scalable Quantum Control and Readout System, essential for controlling and reading quantum states, showcasing the country's capability in hardware development. Furthermore, institutions like TIFR have established dedicated labs, such as the Quantum Measurement and Control Laboratory, to investigate quantum phenomena in superconducting circuits.

The private sector is also actively contributing to this ecosystem. Startups like QpiAI are developing scalable quantum computers, with plans for 300-qubit systems, and Quanfluence is focusing on photonic quantum computers, demonstrating innovation in hardware development. Major companies, including Infosys, TCS, and IBM, are investing in quantum computing labs and cybersecurity solutions. For instance, IBM Research India has developed Quantum Heron-based systems, significantly reducing quantum circuit runtime, and has partnered with MeitY to further quantum computing capabilities.

This collaborative approach, combining substantial government funding, advanced academic research, and dynamic private sector involvement, is driving India's progress in quantum technology, ensuring the nation's participation in the next wave of technological innovation.

7. Next Generation Computing

India is making significant strides in neuromorphic computing and Brain-Computer Interfaces (BCIs), driven by strategic government initiatives and a robust ecosystem of research institutions and startups. The Ministry of Electronics and Information Technology (MeitY) is actively promoting digital transformation, funding projects like the development of Photonic Integrated Circuits (PICs) at IIT Madras for advanced computing and communication. The Office of the Principal Scientific Advisor is fostering collaboration and infrastructure development, particularly in neuromorphic computing, exemplified by research at IIT Delhi focusing on spiking neuron models for energy-efficient AI. The

Department of Science and Technology (DST) is providing crucial funding for BCI projects, supporting innovations that bridge the gap between theoretical research and practical applications.

Academic powerhouses like the Indian Institute of Science (IISc) are at the forefront of neuromorphic computing research, exploring brain-inspired systems using VLSI design and machine learning. IIT Madras is developing sophisticated models for ReRAM-based synapses, vital for low-power AI processing, while IIT Palakkad is focusing on EEG-based BMI systems for enhancing locomotion and cognition, with applications in stroke rehabilitation and driver safety. Further, IIT Kharagpur is creating hands-free man-machine interaction systems for motor-impaired individuals, and IIT Kanpur is developing exoskeletons for stroke rehabilitation controlled by EEG and EMG signals.

The startup landscape is equally dynamic. Companies like Nexstem are developing non-invasive EEG headsets for thought-controlled device interaction, targeting healthcare, gaming, and education. NeuroLeap is offering neurofeedback tools for cognitive training, and Dognosis is innovating by combining BCI technology with canine behaviour analysis. Niramai is using BCI for early cancer detection, and DeeDee Labs is creating immersive virtual environments controlled by thought.

These efforts are supported by advanced research in institutions like IIT Guwahati, exploring EEG decoding and neuroimaging big data analysis for Parkinson's disease, and IIT Gandhinagar, which is pushing the boundaries of deep learning and explainable AI in BCI. IIT Patna is developing privacy-preserving transfer learning for brainwave decoding, and IIT Indore is enhancing EEG-based motor imagery BCIs. IIT Mandi is leveraging multi-modal EEG systems for complex BCI applications, and BITS Pilani is creating BCI-based home automation and smart wheelchair systems.

Despite challenges like high capital expenditure and the complexity of quantum algorithm and AI model development, India’s strategic investments in research infrastructure, talent development, and a specialized startup ecosystem, coupled with ongoing research in quantum error correction and advanced materials science, are positioning the nation to capitalize on the convergence of these next-generation technologies. This integrated approach aims to bridge the gap between theoretical advancements and practical applications, fostering innovation in areas like neurorehabilitation, human-computer interaction, and ultra-high-speed communication networks, thereby establishing India as a key player in the global technology landscape.

8. Blockchain

India's strategic embrace of blockchain technology is driven by a multi-faceted approach, integrating governmental initiatives, academic research, and private-sector innovation. The Ministry of Electronics and Information Technology (MeitY) has established Centers of Excellence to spearhead blockchain research and development, while NITI Aayog is actively exploring blockchain's potential across sectors like supply chain and healthcare, conducting pilot projects to demonstrate its efficacy. The National Informatics Centre (NIC) provides Blockchain-as-a-Service, facilitating government projects and diverse use cases, aiming to enhance transparency and efficiency.

State governments are at the forefront of blockchain implementation. Rajasthan has launched blockchain-enabled electronic health records, and Telangana is developing a "blockchain district" in Hyderabad, focusing on land records and startup incubation. Tamil Nadu has established a blockchain centre of excellence in collaboration with IIT Chennai, aiming to deliver secure government services. Uttar Pradesh is experimenting with blockchain for solar energy trading and land records, partnering with UNDP. These initiatives demonstrate a tangible commitment to leveraging blockchain for improved governance and service delivery.

Academic institutions like IIT Madras, IIT Bombay, and IIT Kanpur are conducting advanced research in blockchain security, smart contracts, and decentralized systems. For instance, IIT Madras developed 'BlockTrack' for secure medical data exchange, aligning with the National Digital Health Mission, and IIT Kanpur is researching malicious account detection and privacy-preserving blockchain applications. These institutions are critical in developing robust and scalable blockchain solutions.

The private sector plays a crucial role through companies like IBM, Oracle, and Microsoft, which offer blockchain platforms and services, enabling businesses to adopt this technology. Startups such as SoluLab and Deqode are providing specialized blockchain solutions to various industries, including finance and healthcare, demonstrating agility and innovation. This collaborative ecosystem, combining government support, academic rigour, and private sector dynamism, is positioning India to harness blockchain technology for enhanced security, transparency, and operational efficiency across diverse sectors.

9. Artificial Intelligence

India's artificial intelligence sector is experiencing rapid expansion, projected to reach USD 20 billion by 2030, propelled by a strategic confluence of government initiatives, academic rigour, and private sector innovation. The Indian government is a key driver, evidenced by initiatives like the National Education Policy 2020 and the establishment of entities such as NITI Aayog, which actively integrates AI into critical sectors like healthcare and agriculture, and MeitY, which fosters AI research and adoption through programs and centres of excellence. NITI Aayog's collaborations with tech giants like Microsoft and AWS, showcased in initiatives like the AI algorithm for diabetic retinopathy detection and the RAISE 2020 summit, underscore the government's commitment to leveraging AI for societal benefit.

Academic institutions such as the Indian Institutes of Technology (IITs) and the Indian Institute of Science (IISc) are pivotal in advancing AI research. For instance, IIT Madras's work on "Byzantine Spectral Ranking" and IIT Delhi's research in AI for Healthcare and Multilingual AI, published in prestigious forums like NeurIPS 2022, demonstrate the depth of India's academic contributions. IISc's focus on unsupervised learning and federated learning further solidifies the nation's research capabilities.

The private sector, including established companies like Infosys, Accenture, and Wipro, and innovative startups such as Arya.ai and Krutrim, are vital in translating research into practical

applications. Infosys, through its Infosys Nia platform, offers AI solutions for automation and data-driven decisions across finance, healthcare, and retail. Accenture's collaboration with IIT Bombay and IIT Patna in language processing and deep learning highlights the industry's engagement with academic research. Startups like Krutrim, which focuses on developing foundational AI models and cloud infrastructure supporting 22 languages, including generative capabilities for Hindi, demonstrate India's growing capacity in AI innovation. Additionally, the establishment of the Robert Bosch Centre for Data Science and Artificial Intelligence at IIT-Madras, funded with 4 crores annually for 5 years, is a prime example of industry and academia collaboration.

This cohesive ecosystem, where government policies foster growth, academic institutions drive research, and private enterprises implement and innovate, is propelling India’s AI sector towards its ambitious 2030 target, positioning the nation as a significant contributor to the global AI landscape.

10. FoodTech

India is making significant strides in sustainable agriculture and food technology, fueled by strategic government support, pioneering research, and dynamic startup innovation. Government bodies like the National Bank for Agriculture and Rural Development (NABARD) are actively funding sustainable agricultural practices, demonstrated by a ₹4.55 lakh grant to Krishi Vigyan Kendra for developing vertical farming and integrated livestock units, enhancing resource efficiency and promoting sustainable rural livelihoods.

Research institutions, including the Indian Council of Agricultural Research (ICAR) and the Indian Agricultural Research Institute (IARI), are at the forefront of technological advancements. ICAR's VEGFAST technology, along with IARI's sensor-based integrated vertical farming and aquaponics systems, is revolutionizing urban agriculture by optimizing space and resource utilization. Furthermore, institutions like the Central Marine Fisheries Research Institute (CMFRI) and the Centre for Cellular and Molecular Biology (CCMB) are developing lab-grown meat technologies, aiming to provide sustainable protein alternatives, with CMFRI partnering with Neat Meatt Biotech to advance cultivated fish meat.

The startup ecosystem is equally vibrant, with companies like Balcony Crops and Urban Kisaan democratizing urban farming through innovative hydroponic gardening kits and vertical farming solutions, making sustainable food production accessible in urban environments. In the alternative protein sector, startups such as Plantmade and GoodDot, along with companies like Blue Tribe Foods, are scaling up production of plant-based meat alternatives, catering to the growing demand for sustainable and ethical food choices. These startups are not only focusing on product innovation but also on building direct-to-consumer platforms to reduce food waste and improve supply chain efficiency. Companies like Agresearch Labs and Akarshak Hydroponics are developing and researching advanced farming techniques like aeroponics and optimized hydroponic systems, showing the growing sophistication of India's agricultural technology sector.

This integrated approach, combining substantial government funding, advanced research, and dynamic startup innovation, drives India's progress towards a more sustainable and resilient food

system, positioning the nation as a key player in the global sustainable agriculture and food technology landscape.

11. Biomanufacturing

India's biomanufacturing sector presents a dynamic landscape characterized by strategic government interventions and robust contributions from both academic and industrial entities. The newly approved BioE3 Policy and Bio-RIDE scheme, alongside the ongoing National Biopharma Mission, signify a concerted effort to translate research into commercially viable bio-based products through the establishment of BioEnablers and shared infrastructure.

Research institutions, exemplified by the National Institute of Immunology's work on dendritic cell-based immunotherapy and ICGEB's CRISPR-edited rice mutants, are driving innovation in critical areas such as healthcare and agriculture.

The private sector, featuring established companies like Biocon and Bharat Biotech, is focusing on scalable biomanufacturing through recombinant protein expression and optimized viral vaccine production, respectively. Furthermore, emerging startups, such as Aspartika Biotech and Sea6 Energy, are exploring novel bio-industrial applications, leveraging genomic technologies and sustainable resources. This collaborative research ecosystem, supported by targeted government funding and policy frameworks, fosters a fertile ground for translational research, facilitating the development of affordable healthcare solutions, sustainable agricultural practices, and innovative bio-industrial applications.

12. Living Device

India's living device sector, encompassing bioprinting and biosensors, is rapidly evolving, driven by government support, academic innovation, and startup dynamism. Government initiatives, through agencies like BIRAC and DBT, provide crucial funding and policy frameworks, such as the BioE3 policy, to foster innovation in bioprinting and biosensor technologies. Leading research institutions like IISc, IITs, and IISER Tirupati are pioneering advancements in 3D bioprinting and biosensor development, focusing on applications ranging from tissue engineering to point-of-care diagnostics. For instance, IISc's 3D Bioprinting Centre of Excellence and IIT Madras's work on advanced fibre optic biosensors highlight the nation's research capabilities.

Private companies and startups, including Alfatek Systems, iSENS Biosensors, and PathShodh Healthcare, are translating these research advancements into commercial solutions. Alfatek Systems provides comprehensive 3D bioprinting ecosystems, while PathShodh Healthcare develops affordable diagnostic biosensor devices, showcasing the sector's commercial potential. Additionally, startups like BioCompute are exploring innovative areas such as DNA data storage, pushing the boundaries of living device applications.

Despite the sector's promising growth, challenges such as regulatory complexities and high manufacturing costs need to be addressed. To fully realize the potential of living devices in India, a focus on accessibility and affordability is essential, ensuring these technologies benefit underserved

communities. Strengthening collaborations between academia, industry, and startups, coupled with the development of robust ethical guidelines, will be crucial in positioning India as a global leader in living device innovation.

13. Software as a Medical Device

India's Software as a Medical Device (SaMD) sector is experiencing rapid expansion, driven by advancements in digital therapeutics, robotic surgery, and genomic analysis. Government bodies like the Central Drugs Standard Control Organization (CDSCO) and the National Health Authority (NHA) are establishing regulatory frameworks and digital health infrastructures to ensure the safety and accessibility of SaMD technologies. Research institutions such as IIT Delhi are contributing through the development of advanced tools like ChemGenome for genomic research and the mPRAGATI initiative for medical device development.

Private companies are at the forefront of innovation, with Wellthy Therapeutics and Lupin Digital Health demonstrating the efficacy of digital therapeutics in managing chronic conditions. Companies like Comofi Medtech and SS Innovations are advancing robotic surgery, enhancing surgical precision and accessibility. Genomic analysis is also a key area of growth, with companies like MedGenome, Strand Life Sciences, and Mapmygenome providing crucial insights for personalized medicine. Startups such as Fitterfly are specializing in digital therapeutics, offering personalized programs for chronic conditions, and Genome India is creating a comprehensive genetic map of the Indian population to further personalized medicine.

Despite the sector's potential, challenges such as regulatory complexities, infrastructure limitations, and data privacy concerns remain. Addressing these challenges through strategic investments and collaborations is crucial for ensuring equitable access to SaMD technologies and realizing their transformative potential in India's healthcare system.

14. Longevity

India's emerging longevity domain is marked by promising advancements, spearheaded by initiatives like the Indian Institute of Science's (IISc) Longevity India, which aims to deepen the understanding of ageing through fundamental and applied research, and startups like Decode Age, which provides personalized health insights via microbiome and blood age tests.

Research institutions are contributing significantly: IITs are developing cutting-edge wearable sensors, such as IIT Madras's wearable SpO2 monitor and IIT Guwahati's stretchable organohydrogel for motion sensing, while CSIR-CECRI has innovated a low-cost sweat sensor for real-time biomarker analysis. The Department of Biotechnology (DBT) is funding research into Genome Editing Technologies (GET) with a focus on healthcare applications.

Despite these advancements, achieving widespread longevity requires addressing socioeconomic disparities and enhancing healthcare infrastructure. A collaborative approach between research institutions, private enterprises, and government bodies is crucial to translate these technological innovations into accessible and equitable health solutions for India's ageing population.

15. Microbiome

India's microbiome research landscape is rapidly expanding, fueled by strategic government support and cutting-edge technological advancements. Institutions like BRIC-THSTI, through its Centre for Microbial Research (CMR), are deeply investigating human-microorganism interactions, particularly in antimicrobial resistance (AMR), with programs leveraging genomics and mass spectrometry. IISc has developed novel computational methods to predict microbial community compositions, enhancing our understanding of complex microbial interactions. The Centre of Excellence in Microbiome (CoEM) in Kerala is utilizing multi-omics approaches, including genomics, proteomics, and metabolomics, to decode microbe-host interactions and develop live biotherapeutics. The National Centre for Cell Science (NCCS) Pune, is conducting large-scale studies on the human microbiome, including the impact of diet and geography on microbiome composition, and leveraging next-generation sequencing technologies. The Indian Council of Agricultural Research (ICAR) is driving the Indian Soil Microbiome Project (ISMP) to map microbial diversity across India, aiming to develop region-specific microbial inoculants.

Private companies like Microbiome Research Pvt Ltd are developing point-of-care diagnostic tools, while startups like Xome Life Sciences are focusing on microbiome-based diagnostics and therapeutics for conditions like celiac disease.

These data points underscore India's growing capacity to leverage microbiome research for advancements in health, agriculture, and environmental sustainability, positioning the nation as a significant contributor to this burgeoning field.

16. Next Generation Materials

India's materials research landscape is dynamically expanding, driven by strategic governmental support through the Department of Science and Technology (DST) and the Materials Research Society of India (MRSI), which collectively steer policy and funding.

Premier institutions like the Indian Institute of Science (IISc), Indian Institutes of Technology (IITs), and Council of Scientific and Industrial Research (CSIR) laboratories are spearheading innovations across diverse sectors. For instance, IISc is advancing precision manufacturing of oxide ceramics and developing graphene-based heat spreaders with thermal conductivity exceeding 3000 W/m-K. IIT Kanpur is focused on brazing ultra-high temperature HfB_2-ZrB_2 ceramics for aerospace, while IIT Madras is exploring scalable graphene platelet exfoliation. CSIR-AMPRI is innovating bio-inspired surface functionalization of carbon nanostructures for biosensors, and CSIR-NCL is developing MXene-based composites for enhanced charge storage. In healthcare, Hindustan Latex is developing metal-reduced carbon nanomaterials for malaria detection, and various institutions, including IIT Bombay, are researching advanced biomaterials for tissue engineering. Energy applications are also a significant focus, with IIT Bombay exploring hafnium-loaded proton conducting oxides for solid oxide fuel cells. In telecommunications, IIIT Kottayam is developing highly isolated antenna arrays for 5G and beyond.

Furthermore, quantum materials research is gaining traction, with JNCASR investigating 2D layered metal chalcogenides for thermoelectric energy conversion and exploring topological quantum materials. This data underscores India's robust commitment to materials science, with research initiatives poised to deliver significant technological advancements across multiple industries.

17. Photonics

India's photonics research and development landscape is experiencing substantial growth, fueled by strategic government investments and cutting-edge research across diverse sectors. Government bodies, including the Department of Science and Technology (DST), the Ministry of Electronics and Information Technology (MeitY), the Defence Research & Development Organization (DRDO), the Department of Atomic Energy (DAE), and the Indian Space Research Organization (ISRO), are playing pivotal roles in funding and conducting strategic research. For instance, MeitY is sponsoring the establishment of the Silicon Photonics Centre of Excellence (CoE-CPPICS) to boost the electronics sector, while ISRO is investing in the development of Quantum Key Distribution (QKD) Photonic Integrated Chips (PIC) for enhanced communication security.

Leading academic institutions, such as the Indian Institutes of Technology (IITs) and the Indian Institute of Science (IISc), are at the forefront of technological innovation. IIT Indore, for example, is developing multiband UV photodetectors based on oxide semiconductors, and IIT Bombay is focusing on photonic and energy materials research, including novel 2D organic-inorganic hybrid halide perovskites for solar energy applications. IISc has developed high-power laser modules and photonic systems for industrial, defence, and medical applications, highlighting its significant contributions to advanced photonic technologies. Furthermore, research institutions like the Central Glass & Ceramic Research Institute (CGCRI) are advancing optical fibre technologies for telecommunications, and the Centre for Materials for Electronics Technology (C-MET) is developing optical isolators using quantum dot-based photonic glasses. Startup companies like Lightspeed AI Labs and AGNIT Semiconductors are contributing innovative solutions in optoelectronic processors and Gallium Nitride devices, respectively, demonstrating the burgeoning entrepreneurial spirit within the sector.

While challenges such as limited access to advanced fabrication facilities and skill gaps persist, the collaborative efforts between government, academia, and industry are positioning India for significant growth in the global photonics landscape, particularly in emerging fields like quantum computing and 5G. This concerted approach underscores India's commitment to becoming a key player in the advancement of photonics technology.

18. Molecular Nanotechnologies

India's molecular nanotechnology sector is demonstrating promising growth, validated by strategic government investments through the Ministry of Electronics and Information Technology's support for advanced infrastructure at IISc and IIT Bombay. These efforts fuel research into critical applications, including nanobots for targeted healthcare interventions, as evidenced by IISc and

Theranautilus's work on dental infections and cancer. Furthermore, institutions like IIT Kharagpur are developing innovative solutions for environmental challenges, focusing on antibiotic residue reduction.

While facing hurdles such as regulatory framework development and workforce training, the emergence of startups like Cell Works Research India, which leverages virtual proteomics for drug discovery, highlights a dynamic innovation ecosystem.

Ongoing collaborations between academic institutions, burgeoning startups, and government initiatives, coupled with sustained investment, are crucial for translating these research advancements into tangible societal benefits across healthcare, energy, and environmental sustainability.

19. Next-Generation Measurement

India is experiencing a surge in next-generation measurement research, propelled by strategic government initiatives like the National Quantum Mission and significant contributions from premier institutions. Optical measurement research is particularly robust, demonstrated by a doubling in publication output from 2,103 to 5,318 between 2007-2015 and 2015-2019, respectively, with a strong focus on advanced optical sensor development, especially for gas detection.

Quantum measurement research is also gaining momentum, spearheaded by institutions like TIFR, which is actively developing quantum sensors for applications in medicine, environmental monitoring, and navigation. In contrast, nano measurement research, while present, is less pervasive, primarily concentrating on sensor development for specific applications and requiring further advancement, especially in evidence-based medicine applications.

Collaborative research efforts, as evidenced by the high degree of collaborative publications, coupled with sustained government support, are pivotal in driving innovation across these critical measurement domains.