DESIDOC Bulletin of Information Technology, Vol. 23, No.2, March 2003, pp. 11-23

Materials Science Research and Development in India: A Scientometric Analysis of International Collaborative Output

S Mohan, B M Gupta & S M Dhawan

Abstract

Materials science research in India is analysed for a period of five years (1995-1999), based on a study of papers published by Indian scientists in collaboration with foreign researchers, as covered in Material Science Citation Index (MSCI). The results indicate that materials science in India is broad based and covers most of the important sub-areas, and is based on inherent strength. Most of the work involved bilateral rather than multilateral collaboration. The top collaborating countries were the US, Germany, France, UK and Japan. Collaborative linkages with developing countries accounted for only about 10% of the total papers. Ten top Indian institutions contributed nearly 50% of the collaborated papers. The major areas of collaboration were theoretical studies, metals & alloys, electronic materials and super conducting materials.

1. RELEVANCE OF MATERIAL SCIENCE RESEARCH

The materials revolution, together with information technology and biotechnology is considered to be the major driving force of a new industrial paradigm. It is characterised by two decisive breaks with past practice: (i) greater input of knowledge in the materials industry, as opposed to inputs of raw materials and energy, and (ii) creation of specific properties for materials according to need. Advances in areas, such as the theoretical understanding of physical and biological matter, experimental techniques, and processing technology have now enabled us to have materials designed to meet specific demands, and these are called the 'new' or 'advanced' materials. Examples of these can be found in the new ceramics, composites, polymers, etc. But there are other approaches as well. Pre-existing materials might be adapted or changed to meet differing requirements (e.g. alloys). Materials might be investigated and found to meet new requirements such as in energy savings, pollution control, safe packaging, etc. New uses might be found for abundantly available materials or waste materials. Traditionally used materials might be upgraded to perform their functions better. These advances might enable us to increase human welfare without increasing energy and materials input while controlling pollution.

Materials science research has thus become one of the major driving forces for change in the modern era, and in order to maintain or create global competitiveness, all countries are interested in investing in R&D in this new area, with the hope of creating new industrial opportunities. India has also started major research programmes in the material science area, involving a large number of universities and research agencies.

2. THRUST AREAS IN MATERIALS SCIENCE RESEARCH

The thrust areas of materials science research follow from the possibility of designing new materials based on our understanding of the structure of matter. Here, our limitations are basically in thinking of new applications and seeing whether specific structures can be designed for meeting these requirements. A second approach is to strive for understanding of new physical phenomena such as superconductivity; applications will follow in a serendipitous manner. A third approach is to contribute to currently discernable trends for reduction in use of materials and energy. All three approaches can contribute new and productive research in the area of materials science.

One of the major aims of materials science research, is to create new 'functional materials'. This term indicates a class of materials, which are used in various branches of industry because of the specific tasks that they perform, for instance, electrical, electronic, magnetic, optical and other functions. Examples might be considered of materials for integrated circuit electronics, superconductors, optical fibers, integrated optical circuits, photovoltaics, piezoelectrical and other electromechanical materials, thermo-electric materials, memory metals (i.e., those that when deformed can be restored to the original shape by heating), sensing devices materials, conducting ceramics, magnetic materials and so on. All these materials, perform specific functions, and new and advanced industries come into being as a result of their use. All of them need a good theoretical understanding of atomic and molecular processes and can thus be termed knowledge intensive. Also there are new materials, which are designed, modified and changed as a result of understanding of the underlying processes. Thus polymer composites, advanced alloys, metals and metal matrix composites, materials specially designed to be thermally stable, corrosion resistant, etc. come into the picture. The tendency for most modern materials is to become knowledge intensive, i.e., use in lesser qualities and with greater sophistication in processing to yield improved materials. The improvement is defined in terms of useful properties such as high strength, wear, corrosion and chemical resistance, and a number of new functions such as magnetic, conductive and photonic properties.

Developments in manufacturing technology, and superior technical properties offered by the new materials often make it possible to use mineral resources much more economically. For example, in metallurgy, near net-shape casting and powder metallurgy can reduce machining requirements by more than 50% and materials by about 30%. The integration of the information industry with manufacturing offers further scope for materials saving. The use of CAD/CAM, adaptive robot systems and computer modeling of functions will help to reduce over-design and give just adequate strength where needed. Such advances in manufacturing methods and processes constitute a second major area of research.

A third thrust area emerges from the study of possible substitutions of one material with another in order to achieve some given target. The scope for such substitution is quite great. Generally the motives are saving of a scarce and therefore costly resource, or weight reduction and increased strength with consequent energy savings in use of a particular equipment or component. Other goals may be prevention of corrosion, environmental compatibility, and specific properties such as fracture resistance, ease of processing, ability to function in some specific environment, etc. It is seldom that the absolute unavailability of a resource prompts a substitution. A more common need is to reduce costs.

3. R&D IN MATERIALS SCIENCE IN INDIA

Among developing countries, India has an edge in R&D in materials science, in terms of number of institutions, facilities and competent researchers. Table 1 lists some of the major institutions carrying out research in

Table 1. R & D base in India for new materials

	Name of R&D center	Areas of research relevant to new materials technology
A.	**Metals & Alloys**	
1.	VSSC, Trivandrum	High strength alloys, Titanium, Aluminum, Magnesium-Lithium alloys, casting of Mg alloys
2.	MIDHANI, Hyderabad	Nickel-Iron superalloys, Titanium, Tungsten and Molybdenum alloys
3.	IIT, Bombay	Rapid solidification techniques, superalloys, intermetallics, high strength alminium alloys, continous casting, electro-refining
4.	NML, Jamshedpur	Specialty steels, high strength temperature and creep resistant steels
5.	IISC, Bangalore	Chilled core casting, high strength auminium alloys, powder metallurgy
6.	BARC, Trombay	Refractory and reactive metals, Al-Zr alloys, corrosion control surface coatings and alloys, inert atmosphere milling and processing
7.	DMRL, Hyderabad	High strength alloys for tank armour, superalloys, lithium alloys
8.	IDL Chemicals Ltd, Hyderabad	Explosive cladding and forming techniques, explosive compaction of powders
B.	**Polymers**	
1.	NCL, Pune	Engineering polymers, polycarbonates, drag reducing polymers, liquid crystal polymers, hydrogels, polymer blends and alloys, polymer resins for composites, high performance polymer catalysts
2.	IPCL, Baroda	Engineering thermoplastic blends, ultra high impact polyoleofin blends, high performance fibers, polymerisation catalysts
3.	NPL, New Delhi	Conducting polymers, PAN fibres
4.	IIT, Bombay	Conducting polymers
5.	CLRI, Madras	Bio-polymers
6.	Sree Chitra Medical Centre, Trivandrum	Bio-implants
7.	Petrofils Corpn, Bombay	Polymer fibers, Specialty polymers and blends
8.	IIT, New Delhi	Filled polymers, metallo-polymer films, liquid crystals, polymer blends and alloys, thermally stable polymers
9.	Polyoleofin Industries Ltd., Bombay	Polymer blends and alloys, polymer property modifications, particulate filled polymers, ultra high weight HDPE
10.	Shri Ram Institute of Industrial Research, New Delhi	SBS elastomers, specialty elastomers, plasticised paper
C.	**Ceramics**	
1.	CGCRI, Calcutta	Ceramic gas sensors, metallised ceramics, high temperature ceramics, nonlinear optics
2.	NPL, New Delhi	Glassy Carbons, biosensors, non-linear materials, opto-electronic materials
3.	BARC, Trombay	Ceramic clads for nuclear fuels and control rods, neutron shielding materials
4.	Grindwell Norton, Banglore	Advanced ceramic abrasives
5.	IIT, Bombay	Silicon nitride and silicon carbide

6.	Bharat Electronics, Bangalore	Transducer ceramics, insulator and semiconducting ceramics
7.	CMET, Pune	Thick film materials, photonic, magnetic and ferroelectric materials
8.	Associated Cement Companies Ltd., Bombay	High strength cements
D.	**Composites**	
1.	DMRL, Hyderabad	Metal matrix, ceramic matrix and polymer matrix composites
2.	NPL, New Delhi	Carbon-carbon composites, carbon fibres for reinforcement
3.	IIT, Bombay	Metal matrix, ceramic matrix and carbon-carbon composites, Al-SiC particulate composites
4.	RRL, Bhuvaneswar	High strength gypsum board as wood substites
5.	RRL, Trivandrum	Metal matrix and natural fibre-reinforced polymer composites, high temperature resistant polymers

Source: Rohatgi, P.K. & Mohan, S. Materials for sustainable development. *In* Materials for the Third Millenium, *edited by* R.K.Ray, *et al.* Oxford and IBH Publishing Company, New Delhi, 2001. pp. 355-84

the area of materials science. Many of them are in high technology areas, which are currently considered important internationally. In addition, there are many universities where materials science research is carried out. Private industry also contributes its own share of research, especially in specific areas, such as rubber products, synthetic textiles and cement. Most of the funding for research in India comes from the various government agencies, such as the Department of Science and Technology (DST), Defence Research & Development Organisation (DRDO), Department of Atomic Energy (DAE), Council of Scientific & Industrial Research (CSIR), All India Council of Technical Education (AICTE), University Grants Commission (UGC), etc. Under the DST, Scientific & Engineering Research Council (SERC) has promoted major research programmes in frontline materials areas with inputs from industrial, research and academic institutions. Representative areas include smart materials, nanoprocessing, advanced ceramics and composites, surface engineering, powder metallurgy, computer controlled fabrication techniques, etc. The CSIR has also contributed substantially to materials development in different areas, such as photovoltaic materials, high performance composites & ceramics, carbon fibers, advanced polymers, super conducting and magnetic materials and so on. The DRDO is also a major player in the field, as are the Department of Space and the DAE in their respective areas. A significant effort has been the development of the Light Combat Aircraft (LCA), a multi-role combat aircraft incorporating state of the art technology especially in the areas of lightweight high strength alloys and composites[1]. Table 2 lists the number of projects and the amount of investments made by different research agencies in materials science funded through extra-mural programmes from 1996-97 to 1998-99. There is also significant investment in this area in various research laboratories and university departments, which is not shown here. Thus, while there may be a need for some reorientation of research, India lacks neither the resources nor trained manpower for a significant programme of research into the development of materials for various purposes.

In accordance with a general policy of creating a wide spectrum competence, India carries out materials science research in a wide variety of fields. A previous study of published literature found Indian research in materials science to be broad based and carried out in a number of governmental and non-governmental research institutions and universities[2]. According to the study, polymers were the most prolific area of research, with 32.43 % of published papers, followed by metals and alloys (26.35%), glass (8.05%)

Table 2. Major extramurral funded-projects approved by central Government departments/agencies

Research Schemes	1996-97		1997-98		1998-99	
	No. of projects	Amount spent (in lac)	No. of projects	Amount spent (in lac)	No. of projects	Amount spent (in lac)
AICTE – R&D	36	161.35	12	068.00	15	148.93
AICTE – TAPTEC	23	173.00	12	117.00	29	441.58
CBIP – RSOP	1	002.42			3	051.80
CSIR – ES	3	014.43	2	008.02	3	00.04
CSIR – EXTRM	21	080.77	22	124.95	14	096.29
CSIR – SS	1	006.52	3	018.38	1	005.98
DAE – BRNS	17	220.79	7	041.31	15	334.46
DOC – SAT					3	079.31
DOE	2	024.85	4	068.75		
DRDO – ARDB	15	102.32	9	066.08	4	057.37
DRDO – GIA	3	060.90	4	047.21	8	081.18
DRDO – R&T	7	125.68	3	071.30	2	016.89
DST – CTP	2	019.01				
DST – IDP	3	018.58	3	005.98	7	124.00
DST – JTP			1	029.30	6	82.91
DST – NF&C	1	025.50				
DST – SERC	51	622.95	44	606.55	34	452.73
DST – USERS			2	004.18		
DST – YS	6	012.06	6	018.05	7	018.35
DST – YSS	1	001.91				
ISRO–RESPOND	4	028.98	1	006.89	9	067.34
MIT					5	176.12
UGC – MJRP	32	123.54			34	015.39
ICMR – AD HOC	1	007.32			1	011.94
Total	**230**	**1832.88**	**135**	**1301.95**	**200**	**2262.61**

Source: Directory of Extramural R&D Projects approved for Funding by Selected Central Government Agencies/Departments for 1996-97, 1997-98, 1998-99. New Delhi; DST. 1998,1999. 2000

and composite materials (5.43%). In 1996, the Technology, Information, Forecasting and Assessment Council (TIFAC), which is set up under DST came up with a list of priority areas of research in advanced materials[3]. The major priority areas were considered to be:

- Metals, alloys and surface engineering
- Composite materials
- Glasses and ceramics
- Building materials
- Photonic materials
- Polymeric materials
- Nuclear materials
- Super conducting materials
- Biomaterials

Significant research efforts are going on in all these areas. In addition, efforts are being made in other application areas, such as strategic industries with a bearing on defence, space or nuclear related fields, advanced sensors, cryogenics, robotics, artificial intelligence systems, and new manufacturing techniques such as powder metallurgy. An advanced center for powder metallurgy has also been set up. However, production capabilities in advanced materials areas are yet to be realized.

4. IMPORTANCE OF COLLABORATIVE RESEARCH

Despite its efforts at self-reliance, India has understood the benefits of cooperation with other developed and developing countries in scientific research. International cooperation strengthens national capability by gaining access to latest developments, modernising infrastructure, enhancing skills and promoting the capability of generating new products and processes[1]. Its greatest benefit could, however, be in benchmarking, knowing where we stand in a specific field in comparison with others. It can also be a means of promoting joint ventures, and for sharing of capabilities. To take only one example, India's success in the software field would not have been possible without extensive prior academic and industrial contacts. Advanced countries also benefit by the collaboration, since in many areas, observation of phenomena and control of variables in a large number of experiments is essential to eventual success and the relatively less expensive brainpower in the developing countries can make a critical contribution. In many developing countries, and especially in India, good science co-exists with outmoded industry, and collaboration may be one means of recognising and eventually bridging the critical gaps.

Cooperation in S&T areas is effected through a number of means including exchange of scientists and technical personnel, joint research and development projects, exchange of information at various levels, through organising joint seminars, and so on. Training of scientists and technicians and technical assistance programmes are also important. The collaboration could be bilateral, regional or multilateral, and initiated at the government levels or through individual academic contacts. Bilateral programs for India exist now with around 45 countries. The most prominent collaborations are, of course, with the advanced countries, such as US, UK, Japan, France, etc. But, a number of programmes with developing countries and regional groupings like SAARC also exist. Collaboration at individual level, through academic linkages, is very important in the case of the US. In case of Russia, which has made a very significant contribution to defence related materials science, collaboration is mainly at government levels, through joint programmes and training programmes, although much of it is not accessible through published literature.

5. OBJECTIVES

This paper aims to identify the major areas, sectors and institutions involved in Indian materials science research that have collaborative linkages with developed and developing countries. The areas of collaborative research are compared with national needs and also priority areas identified by TIFAC. This will help us to understand to what extent the collaborative research is helping to meet our national objectives, conforms to the general international trends, as well as to learn about new technological developments taking place in this area.

6. DATABASE AND METHODOLOGY

Publication data for the study was derived from the CD-ROM version of the *Materials Science Citation Index* (MSCI), brought out by Institute of Scientific Information (ISI), Philadelphia, USA for a period of five years, i.e., from 1995 to 1999. The database covers around 2000 significant world journals in all fields of S&T, focussing on materials science research. The journals covered by MSCI represent mainstream science. The study was restricted to co-authored articles, arising out of India's collaborative research with all major developed and developing countries. The number of such papers was 2587 for the period 1995-1999. Each paper was analysed under two broad subject classification categories, developed at NISTADS and given in Tables 3 and 4. In this classification, the first classification category identifies the research paper in terms of a particular material, group of materials or work area. The second classification category identifies the nature of work that was being done on or for a specific item in category 1, such as analysis

& characterization, metallurgical operations, corrosion studies, etc. Together, the two classification categories would specify the kind of research taking place in a specific area, and would uniquely identify the research reported in a particular paper. In the classification used, there are 36 items in Subject Category 1 and 14 items in Subject Category 2.

7. RESULTS

In all, 2587 research papers were published in materials science by Indian scientists in collaboration with scientists from 62 developed and developing countries during 1995-1999. Materials science research is considered as an important area among national priorities and involves participation from a very large number of Indian institutions representing various sectors, agencies and areas. The research output of these

Table 3. Subject category code 1 (Materials)

No.	Material Category	No.	Material Category
01	Organic materials	15	Building materials such as cement, concrete
02	Inorganic materials	16	Catalytic materials
03	General (unspecified) materials/ structures/agglomerates	17	Liquid crystals
03A	Theoretical materials/structures	18	Thin films
04	Metals and alloys (general)	19	Fullerenes
05	Polymers (general)	20	Plasmas and gases
06	Ceramics	21	Rocks and soils
07	Electronic/ionic materials	22	Polymeric membranes
07A	Molecular electronics	23	Crystalline materials
08	Superconducting materials	24	Instrumentation/equipment/structures
09	Magnetic materials	25	Ores and minerals
10	Optical/photonic materials	26	Quantum wires, quantum dots and other quantum materials
10A	Optoelectronics	27	Liquids, gels, foams, colloids, solutions, aerogels, suspensions, surfactants, etc.
11	Photovoltaic materials	28	Coating materials, surface materials
12	Composite materials/fibres (general or unspecified)	29	Electrochemical materials and electrodes, electrochemical processes
12(1)	Carbon fibers and composites	30	Glasses
12(1)A	Other carbon materials including diamonds	31	Thermoelectric materials
12(2)	Ceramics composites	32	Shape memory alloys
12(3)	Metal matrix composites, metal composites such as layered metals	33	Superfluids
12(4)	Polymer composites	34	Porous, microporous and mesoporous materials
12(5)	Nanostructures, microstructural materials, clusters	35	Sensors and actuators
13	Materials used in energy production, including fuels	36	Organometallics
14	Biomedical materials/biomat./ biomolecules /natural materials		

Table 4. Subject category code 2 (Operations, functions, applications)

No.	Subject Category
01	Analysis and characterisation (crystallographic studies, chemical analysis, structure analysis, spectroscopic analysis, SEM/STM/polarizing microscope/phase contrast microscope, etc.)
01A	Theoretical calculations of structure and properties, explanations and theoretical understanding, observation of new phenomena
02A	(Synthesis, chemical manipulation, manufacturing, processing, catalysis etc_) of the material
02B	Used in (…) of other materials
03A	Mechanical studies, fluid flow, absorption, diffusion, degassing, etc.
03B	Temperature distribution, heat transfer, phase changes, specific heat, thermal stability studies, etc.
04	Metallurgical operations, heat treatment, etc.
05	Strength of Materials (elasticity, shear strength, fracture, fatigue, crack propagation, etc.)
06	Other property measurements (Optical properties, electrical and electronic properties, magnetic properties, etc.)
07	Surface studies
08	Corrosion studies, wear
09	Membranes related applications
10	Electrical and electronic applications
11	Energy related applications
12	Mechanical operations
13	Pollution control
14	Reviews, bibliographies, comments, literature surveys and other information

institutions in materials science, as seen through MSCI, forms approximately, on an average, 32 % of all overall Indian science output covered in SCI database from 1995 to 1999 (Table 5). This is considered as significant, reflecting the inherent strength and importance of the research in this field in India.

Table 5. Proportion of materials science output in overall Indian science output

Year	No. of papers in SCI database	No. of papers MSCI database	% of papers in materials science
1995	11084	3583	32.32
1996	11177	3768	33.71
1997	11067	3647	32.95
1998	12128	3759	30.99
1999	12521	3751	29.56
Total	**57977**	**18508**	**31.92**

7.1 Priority Areas of Research

Among the 36 subject classification areas, the major focus of collaborative research was as follows. General organic materials (synthesis as well as characterisation), a field which is more linked to general chemistry, produced the maximum output of 285 papers, followed by general metals & alloys (238 papers), electronic/ionic materials (235 papers), super conducting materials (230 papers), magnetic materials (208 papers), general polymers (140 papers), and optical/photonic materials (125 papers). The theoretical study of materials & structures also formed an important category (123 papers). Other identified areas of research were composite materials, with emphasis on metal-matrix composites, carbon fibers and carbon-carbon composites, polymer composites, and nanophase structures.

Research into properties of liquids, gels, foams, etc., which are expected to be important in newly emerging clean technology processes, is also significant. Polymeric membranes and fullerenes, which have great potential in new technologies, are yet to take off significantly in India. Certain areas of industrial importance, such as building materials, energy related materials, ores & minerals, etc., are under-represented in the Indian collaborative research, presumably because most of the work in this area is being done without international collaboration. However, some newly emerging areas, such as organometallics, shape memory alloys, and thermoelectric materials are rather poorly researched.

Perusal of the classification category 2 (functions, operations and applications) reveals that under all types of materials classified according to subject category 1, analysis & characterisation forms an important aspect of the research. Most of the work in organic materials pertains to this type of work (259 out of 285 papers). For other areas, such as metals & alloys, electronic/ionic materials, superconductors and magnetic materials, similar kind of work also constituted a substantial fraction (about 33% of the papers). Theoretical analysis, calculations of structure & properties, observations of phenomena & explanations also form a very significant category of work. Predictably, metallurgical operations, heat treatment and measurement of elasticity related properties form a significant activity in metals & alloys category. Similarly, measurement of electrical & magnetic properties is significant in super conducting and magnetic materials. Research results indicating the utilisation of any of the studied materials in collaborative research for a specific application in some process are quite rare, indicating that materials science research in India is not yet of much commercial importance.

7.2 Nature of Collaboration

Out of the 2587 collaborated papers, 2237 were bilateral in nature, involving participant(s) from India and at least one other country. The rest (350 papers) were multilateral in nature, involving the participation of India and at least two or more countries.

Among the bilateral collaborative papers, the largest number (997 papers involving 30 countries) is published by Indian scientists in collaboration with scientists from Europe, followed by North America (705 papers involving 2 countries), Asia (424 papers involving 11 countries), Oceania (52 papers involving 2 countries), Latin America (24 papers involving 5 countries), Middle East (20 papers involving 4 countries), and Africa (18 papers involving 8 countries).

Among North America countries, there are two preferred collaborating partner USA and Canada, with 636 and 69 papers respectively. Among European countries, the important collaborating partners were Germany (266 papers), France (232 papers), UK (227 papers), Italy (84 papers), Spain (30 papers), Sweden (22 papers), The Netherlands (18 papers), Russia (16 papers), Belgium (15 papers), and Poland (15 papers). Among Asia, the more preferred collaborating partners were Japan (216 papers), followed by Malaysia (88 papers), Singapore (43 papers), China (20 papers), and Bangladesh (15 papers). Among other regions, the preferred collaborating partners were Brazil (17 papers), and Israel (16 papers). Collaborative research with developing countries formed only about 10% of the total papers.

7.2.1 Multilateral Collaboration

Among 350 multilateral papers, the largest collaboration of Indian scientists was with USA scientists with 148 papers, followed by Germany (93 papers), Japan (68 papers), UK (59 papers), France (59 papers), Italy (48 papers), The Netherlands (19 papers), Brazil (18 papers), Russia (18 papers), Canada (16 papers), Sweden (16 papers), China (16 papers), and Spain (15 papers).

In these countries, the scientists are participating in a group consisting of 3 to 7 countries per paper. The scientists participating per paper in a group of 3 and 4 countries accounted for 297 papers and 43 papers, respectively out of 350 papers, forming majority of papers. Similarly, there was a participation of institutions in a group ranging from 3 to 8 per paper. Again, it was observed that the group of papers having institutional participation of 3 and 4 institutions per paper account for 179 papers and 93 papers, respectively out of 350 papers.

7.3.2 Bilateral vs Multilateral

West Europe as a whole has nearly 50% more collaborations than the US and Canada taken together. Eastern Europe, including the ex- Soviet Union countries, accounted for only about one-tenth of the collaborations as West Europe or North America. Bilateral collaborations out-number multilateral collaborations by a factor of 3 in West Europe and North America, but interestingly they are more or less equal in Europe and Latin A merica.

7.3 Areas of Priority with Specific Collaborating Partners

The specific distribution of collaborative papers under the different subject areas in any particular country could be due to a number of factors: (i) a specific requirement from the Indian side, reflecting the priorities in Indian research, (ii) a reflection of the research priorities in the collaborative country, (iii) indicative of the attitudes in the collaborating country, that they may permit collaboration only in general academic or pre-commercialisation areas, and (iv) a mere utilization by Indian researchers of whatever collaborating opportunities existed. Which of these either single or in combination, contributes most to the observed pattern needs to be investigated.

In 784 papers resulting from Indo-US collaboration, superconductivity (80 papers) and metals & alloys (79 papers) were the areas of maximum choice, followed by magnetic materials (65), electronic materials (64) and polymers (51). Analysing the functional categories, we see that the largest segment of the collaborated papers in the area of superconductors was in the theoretical area, calculations of structure & properties or explanations of observed phenomena (35 papers). Analysis and characterisation of prepared samples comes next with 27 papers, followed by property measurements (9 papers) and chemical manipulation of the material (6 papers). For metals & alloys, magnetic materials and electronic materials, the largest segment was analysis and characterization, followed by theoretical calculations and explanations, and then property measurements and synthesis.

In 359 papers resulting from Indo-German collaboration, the priority areas were metals & alloys (51 papers), followed by electronic materials (40), magnetic materials (31), and super-conducting materials (22), and polymers (20). Characterisation and analysis, and theoretical studies were again the two largest categories, but there was greater emphasis on synthesis & chemical manipulation of the material as compared with the case of the Indo-US collaborations.

In 291 papers from India-France collaboration, the significant collaborative areas were super conductivity (43 papers), followed by magnetic materials (41), electronic materials (23) and polymers (21), but optical materials (20), and thin films (15) were also significant. Here, though the two areas of analysis and theoretical studies formed the largest two categories, there was a greater emphasis proportionately on property measurements and synthesis than in the case of US and Germany.

In 286 papers resulting from Indo-UK collaboration, major emphasis was on super conductivity (43 papers) and magnetic materials (35 papers) followed by electronic materials (26 papers), metals & alloys (17 papers), optical materials (12 papers), and thin films (11 papers), but there was also a greater emphasis on purely theoretical structures (31 papers), than in the case of the other significant collaborating countries.

In 284 papers from India-Japan collaboration the main areas were superconductivity (45 papers), electronic materials (45 papers), metals & alloys (27 papers), magnetic materials (24 papers), optical materials (18 papers), and thin films (17 papers). The category of general organic materials chemistry had less emphasis in the case of Japan. Photonics and thin films research, both of which are of great industrial importance in the coming future, was proportionately greater in the case of Japan than in case of other collaborating countries.

A surprisingly large fraction of the collaborated papers with Malaysia (95 out of 98) were in the area of general organic chemistry. This might reflect a tie-up of specific universities or academic institutions in India and Malaysia for research in this particular area.

Collaborations with all these countries also include substantial activity in general organic materials as well as theoretical studies. In general, the bilateral collaborated papers give greater emphasis on theory and sample characterisation than other areas.

7.4 Contributions of Major Collaborating Institutions

A total of 154 Indian institutions, including universities and national laboratories participated in collaborative research. The major collaborating institutions with their output, number of collaborating countries, and major areas of their collaboration are given in Table 6. Of these, 5 institutions contributed more than 100 collaborative papers each, while 85 contributed in the range of 1-5 papers. The first 10 institutions accounted for about 50% of the collaborative papers (1304 out of 2587 papers). The Indian Institute of Science, Bangalore had contributed 286 papers, the largest number among all participating Indian collaborating institutions, followed by the Tata Institute of Fundamental Research, Bombay (191 papers) and the Indian Institute of Technology, Bombay (149 papers).

Comparing with Table 1, we can see that some of the most important research institutions in material science do not figure highly in the list of collaborating institutions, since their work is more based on self-reliant efforts. This indicates that material science research in India is built on a solid foundation of national research capability. Collaboration with different countries has played only supplementary role.

CONCLUSION

Materials science research has taken off in India in recent years, but the research is still confined to academic level. Application oriented research is minimal. Substantial activity takes place within the theoretical area. The preferred areas of collaboration with major countries were superconductivity, metals & alloys, and electronic and magnetic materials. The collaboration appears to be driven more by academic interest and opportunities rather than by any consideration of national priorities for India.

Comparing the collaborated papers with the thrust areas identified by TIFAC, one could see a broad concurrence, but not by any means a one to one correspondence. The areas identified by TIFAC for research actually presuppose a higher tech scenario for India than is warranted by the actual industrial status of the country. It is basically driven by the wish to catch up with the advanced technological sectors. Research in India also, being done more in universities and research establishments rather than by industries, follows the same trends. Thus, one could see that while the most important current area from the industry standpoint, namely metals and alloys, does top the list of collaborated papers, it is closely followed by electronic and superconducting materials which are as yet rather speculative areas from the Indian industry status.

Areas such as polymer, ceramic and metal matrix composites need to be strengthened much further since they are capable of contributing to industrial production much more than other areas such as superconducting materials. Certain areas such as nuclear materials will not be reflected in the collaborative research output since the efforts in this area would be almost entirely within the country, due to strategic considerations.

Table 6. Major collaborating institutions and thrust areas

Name of Institution	No. of collaborating papers (countries)	Thrust areas of collaboration with number of papers
Indian Institute of Science, Bangalore	286 (28)	Theoretical materials & structures (34), magnetic materials (34), Electronic materials (31), metals & alloys (25), Superconducting materials (8)
Tata Institute of Fundamental Research, Bombay	191 (20)	Superconducting materials (69), Magnetic materials (58), Electronic materials (26), Optical/Photonic materials (11)
Indian Institute of Technology, Bombay	149 (22)	Magnetic materials (22), Superconducting materials (18), composites (17), Metals & alloys (12), Electronic materials (12), Thin Films (11)
Bhabha Atomic Research Center, Bombay	124 (22)	Metals and alloys (24), Superconducting materials (21), Electronic materials (10), Magnetic materials (10)
Indian Institute of Technology, Kharagpur	120 (19)	Organic chemistry (33), Electronic materials (13), Metals & alloys (10), Polymers (5)
Indian Institute of Technology, Kanpur	102 (17)	Metals & alloys (16), Electronic materials (11), Instrumentation & equipments (8), Superconducting materials (8), Magnetic materials (7)
Indian Institute of Technology, Madras	99 (16)	Metals & alloys (20), Magnetic materials (17), Superconducting materials (9)
Anna University, Madras	83 (15)	Organic chemistry (43), Electronic materials (11), Crystalline materials (8), Optical/Photonic materials (7)
National Physical Laboratory, New Delhi	79 (14)	Superconductors (18), Electronic materials (18), Composites (11), Liquid Crystals (8)
University of Madras	71 (10)	Organic materials (66)
Indian Institute of Technology, New Delhi	63 (20)	Polymers (12), Electronic materials (11), Optical/Photonic materials (10)
Saha Institute of Nuclear Physics, Calcutta	59 (19)	Superconducting materials (14), Theoretical materials (6), Electronic materials (5), Optical materials/Phonic materials (5)
Indian Association for the Cultivation of Science, Calcutta	56(16)	Organic materials (12), Magnetic materials (9), Electronic materials (6)
University of Hyderabad	53 (15)	Organic materials (21), Optical/Phonic materials (6), Threoretical materials & structures (5), Metals & alloys (5)
Indira Gandhi Centre for Atomic Research, Kalpakkam	50(15)	Metals & alloys (15), Magnetic materials (6)
University of Pune	50 (8)	Composites (7), Thin films (6),
University of Delhi	49 (19)	Organic materials (28)
Jawaharlal Nehru Center for Advanced Scientific Research, Bangalore	48 (13)	Superconducting materials (7), Electronic materials (6), Organic materials (6)

REFERENCES

1. Mohan, S. & Jain, Ashok. Science and technology: Status, growth and development. B R Publishing Corporation, New Delhi, 1999, pp.104, 127 and 203. (India: Fifty Years of Independence 1947- 1997 series, vol. 24).
2. Kochhar, V B; Subba Rao, A.; Arora, A M & Elhance, D. Materials research in India: A quantitative analysis. *In* Bibliometrics, Scientometrics and Informetrics, *edited by* B M Gupta, Segment, New Delhi, 1996, 153-184. (Handbook of Libraries, Archives, and Information Centers in India series 13).
3. Technology Information, Forecasting & Assessment Council (TIFAC). Materials & processing: technology vision 2020. TIFAC, Department of Science and Technology, New Delhi, 1996. (TIFAC:V:08:V:ESDR).

Contributors: **Dr. S Mohan** , Scientist F, National Institute of Science, Technology and Development Studies (NISTADS), Dr K.S Krishnan Marg, New Delhi-110012.

Dr. B M Gupta, Scientist F, NISTADS, New Delhi-110012.

Dr. S M Dhawan, Scientist F, National Physical Laboratory, Dr K.S.Krishnan Marg, New Delhi-110 012.