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STARTER

Towards a Sustainable Future with Materials

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The development of technologies to meet societal demands has always been inextricably intertwined with materials sciences and engineering. Banerjee and Williams[1] describe some facets of this relationship. The first tools used by our ancestors were made of stone in prehistoric times. Metal forming evolved around 3000–4000 BC with the heating of native copper to make tools and other items. In approximately the same period, copper was smelted from its ore in Timna in Israel. The third great innovation, alloying, appears to have occurred between 2000 and 3000 BC in Egypt, where the earliest bronzes have been found. Together, this triad of events laid the foundations for the paradigm of materials science: the relationship between composition, processing, structure, and properties.

The number of materials available to engineers in the nineteenth century was perhaps a few hundred. Today, this number exceeds 100,000[2,3]. Figure 1a, b show this extraordinary growth of materials choice in strength–density space.[4] The performance of a material in an engineering application depends not just on its composition but also on our ability to shape, join and finish, characterize and design material at scales varying from a few atomic dimensions to the width of a human hair and the most extraordinary sizes. It is this ability that has transformed the landscape of materials choice in virtually every engineering discipline, as seen in Fig. 1c.

Much of this explosive growth has occurred over the last 10 years and certainly owes a great deal to the emergence of materials science as an independent discipline in the 1940s. In keeping with this trend, the Indian Institute of Science established the Department of Metallurgy in 1945 after an effort initiated as early as 1910–1915.[5] Dr. Brahm Prakash, the first Indian professor and head of the department, was appointed in 1952. Early department projects included, for example, the separation of zirconium from hafnium, the metallurgy of nuclear grade zirconium, Al coating of steel, development of Al alloys for substituting Cu in electrical machinery, synthesis of Al by the electrolysis of aluminium chloride, and the measurement of elastic modulus of metals. The first batch of students was admitted in August 1947 to the Diploma of the Indian Institute of Science, specializing in metallurgy. A B.E. (Bachelor of Engineering) programme was initiated in 1957, an ME program in 1967, and the first Ph.D. was awarded from the department in 1971. Indeed, when I joined the department for a Ph.D. programme in 1974, there were just a handful of Ph.D. students, perhaps just 5 or 6. The department has since been renamed Materials Engineering, with research covering a broad spectrum of activity summarised in Fig. 2, with more than 100 Ph.D. students and 120 + masters and undergraduate students at any time.[6] At its initiation in 1945, The Government of India granted Rs. 1 lakh for building/equipment and Rs. 30,000 for staff. The Mysore government provided Rs. 50,000 as a non-recurring grant and an annual recurring grant of Rs. 15,000. Our research and facilities are today supported by funding of nearly Rs 50 Crores, and the department leads Indian academic institutions in international rankings.

As the department looks ahead beyond its platinum jubilee year, building a critical mass of expertise and capability in materials research supporting sustainability occupies a preeminent place in its vision.[6] In 2015, United Nations member nations committed to an agenda of sustainable development goals in a framework based on 17 objectives involving all countries, their governments, societal constructs, businesses, and academic institutions in a global partnership.[7] Of these objectives, affordable and clean energy, industry innovation and infrastructure, responsible consumption and production, and good health and well-being are particularly relevant to the materials enterprise. Figure 3 shows the academic commitment to sustainability goals in terms of the growth of sustainability literature in general and that related to materials development in particular. The figure also shows that the fraction of sustainability literature dealing with materials has also been increasing in relation to the general literature on sustainability, underlying the criticality of this effort. Various related journals such as Sustainable Materials and Technologies, Journal of Sustainable Construction

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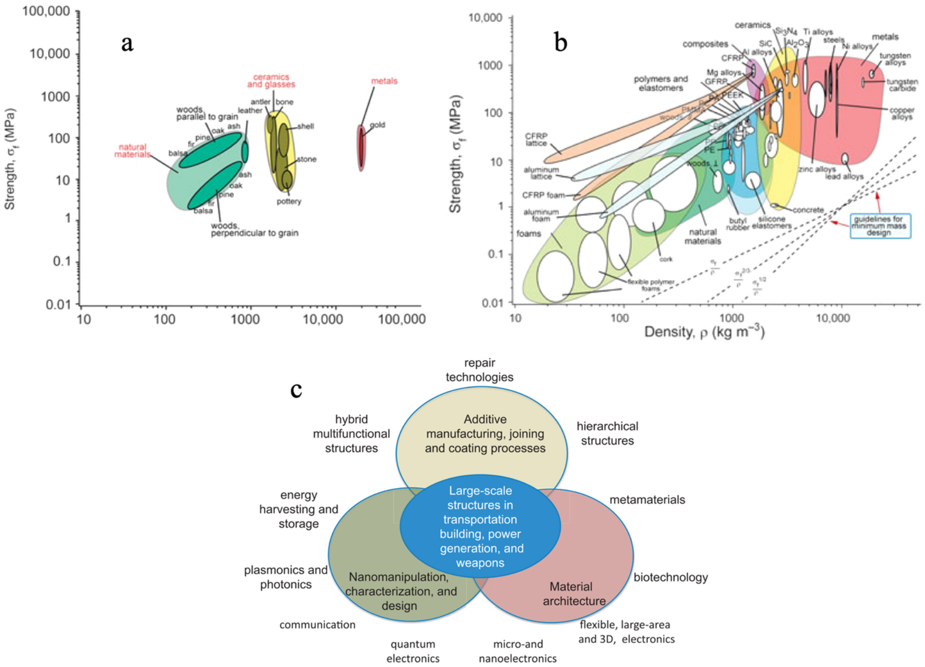

Figure 1: Materials in strength-density space in **a** prehistory and **b** present day,[4] **c** Evolution of materials science and engineering: the advent of the metal age allowed dramatic improvements in transportation, building, power generation, and weaponry. Increasing capabilities in nanomanipulation and characterization, architected and biomimetic and hierarchical materials structures, metamaterials, 3D printing, and manufacturing techniques have expanded the horizons of multiple engineering disciplines[1].

Materials and Technologies, Journal of Sustainable Materials Processing and Management, and the International Journal of Sustainable Materials and Structural Systems have emerged.

Sustainability must be assessed with respect to social, environmental, and economic factors. Society's demands and needs are supported by major commodities that include food, energy, clean air and water, and materials (Fig. 4). The availability of these commodities and their distribution are linked in complex ways. Materials selection, development, and implementation methodologies must maximize performance in a given environment. Emergent and novel approaches based on architected designs, metamaterials, biomimetic, and hierarchical structural concepts, supported by integrated computational science and engineering, data analytics, and artificial intelligence, have significantly increased the tools at our disposal to maximize performance in every application (Fig. 1). However, a sustainable materials effort must incorporate strategies based on complete life cycle analysis at every step along the way (Fig. 4). Such an analysis evaluates the flow of material from extraction to manufacturing and product utilization to discards, recycling, reuse in alternative applications, environmental and societal effects, and can include design for ecology, security of supply, substitution, and energy recovery. An example of supply risk assessment in materials for clean energy is given in Fig. 5.

Miodownik[11] discusses the future of materials development and application in relation to these needs. The production of steel, cement, plastic, paper, and aluminium accounts for 55% of carbon dioxide emissions from global manufacturing. The energy efficiency of manufacturing these materials can be improved by just perhaps 10–20%.[12] Therefore, approaches that implement materials systems integrated with reuse, repair, and recycling are of utmost importance. Greater than 60% of the projected world population of about 10 billion will live in cities. There is no resource constraint on most construction materials; concrete, steel, and glass. However, novel materials-based design concepts will help reduce energy consumption in buildings and homes or generate energy from renewable sources, reduce water usage in buildings, and conversely collect water from the environment for use. Access to food involves storage, transportation, and

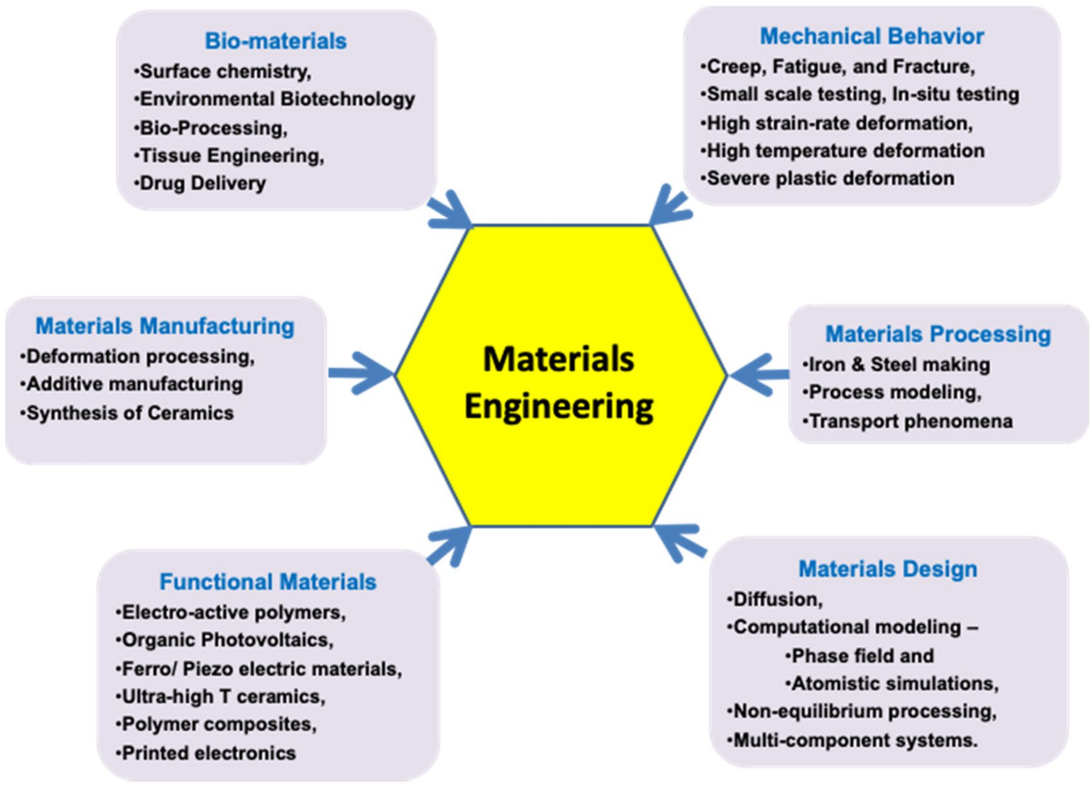

Figure 2: The Department of Materials Engineering in recent years.

distribution of food grains, vegetables, and meats. All food that enters households is packaged in some form or other, involving enormous quantities of aluminium or steel cans and plastic. The development of sustainable packaging materials that will prevent interaction with food and liquids and allow recycling or reuse is an important requirement for food distribution practices. One-third of humanity lives in countries where water is scarce, and 1 billion people lack access to clean water.[13] As described in this and subsequent United nations reports, there are many facets to the water crisis: walking long distances every day to fetch enough water, inadequate sanitation leading to malnutrition and disease, floods, and management of water use and allocation. Materials, including natural materials such as leaves, wood, and soil, play a critical role in covering every aspect of the water cycle, from precipitation to water flows on land, and evaporation from water bodies and oceans. Of particular importance are techniques for water and wastewater purification, desalination, the prevention of evaporation, and sensors in the detection of water flow patterns and leakages.

Global spending on health continually rose between 2000 and 2018 and reached US$ 8.3 trillion or 10% of global GDP. Indian expenditure on health care is estimated at 64USD per capita at a GDP of per capita of 2115 USD in 2019.[14] Affordable access to health care is imperative for the well-being of the citizens of our country, and involves materials technologies from the replacement of diseased or damaged tissue, drug

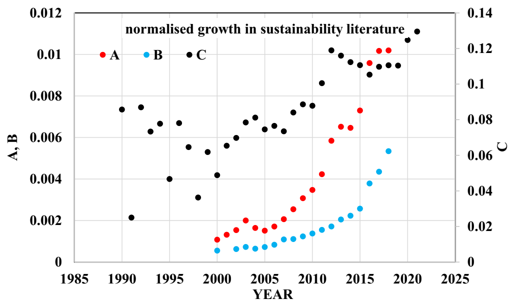

Figure 3: Growth in sustainability literature. **A** Literature on materials sustainability (obtained from the Web science) normalised by all literature in materials science obtained from.[8] **B** Literature on sustainability (obtained from the Web of Science) normalised by all literature in science and engineering.[8] **C** Ratio of literature on materials sustainability to the literature on sustainability.

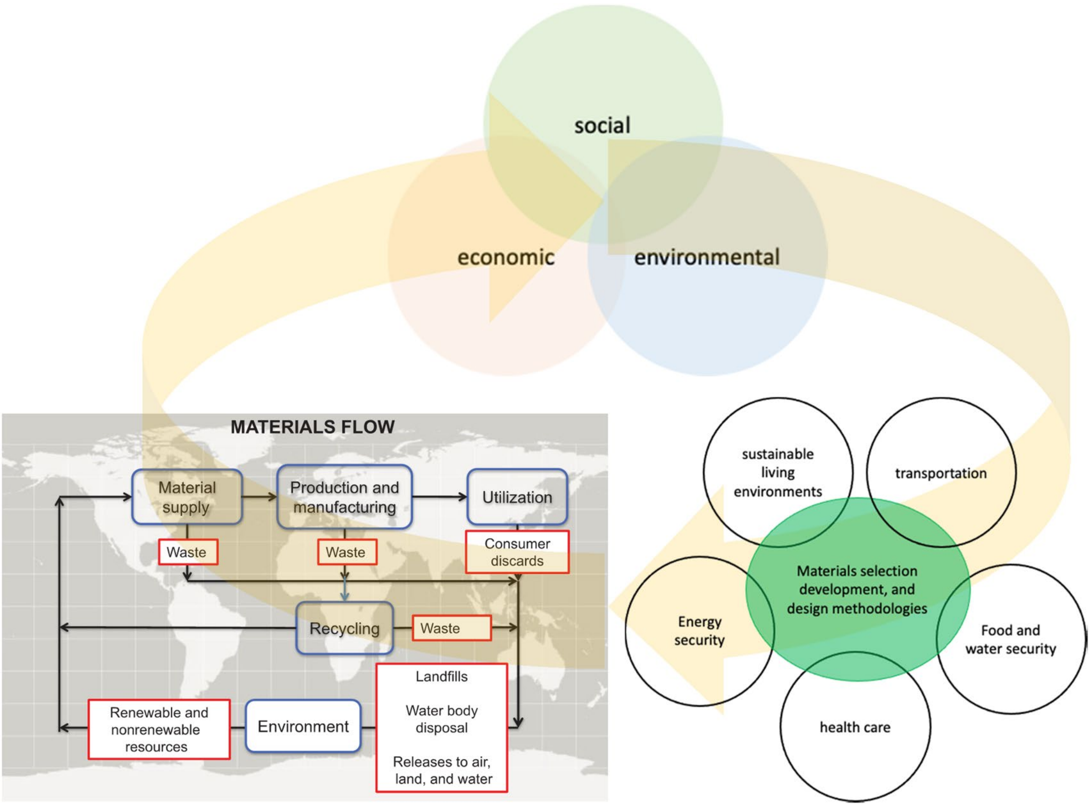

Figure 4: Sustainability goals must meet societal, economic and environment needs. Materials selection, development and implementation address the key goals of sustainability, and must also be subject to a full life cycle analysis (adapted from[9]) to evaluate sustainability metrics.

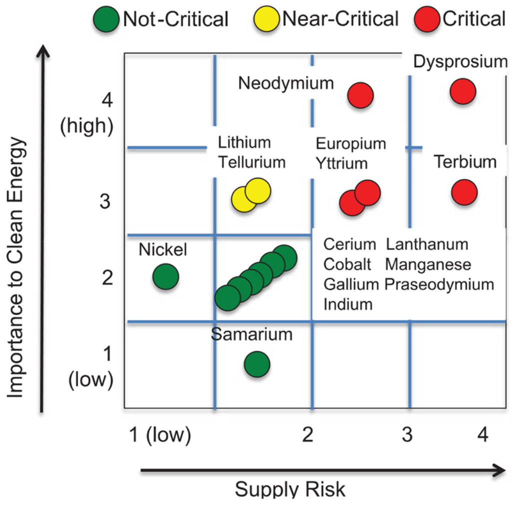

Figure 5: A life-cycle analysis must include analysis of the security of the materials supply in defined time horizons. An example is shown for materials for clean, renewable energy[10].

delivery, diagnostic techniques and biosensors, and finally, 3d printing for customized devices. Much has been written about materials development in relation to energy, and we only summarise here for the sake of completion. The key areas in which material science will play an enabling role include energy generation through nuclear fission with particular emphasis on waste reprocessing, alternative fuels, and efficiency improvements through fast breeder reactors, or nuclear fusion in the distant future. Materials innovation will support ultra-supercritical thermal power technology, renewables such as wind power or solar energy, energy storage and an emerging role for a hydrogen economy coupled with fuel cells.

Education, awareness and research in all aspects of sustainable materials implementation will form a cornerstone of shaping our collective future. This issue marks a small beginning in this direction.

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