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Review **ETCE**

A Review on Advanced Materials for Sustainable Innovation and Innovative Applications in Chemical Engineering

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Abstract

High level materials assume a vital part in driving feasible mechanical headways across different enterprises. This comprehensive review paper aims to provide an in-depth analysis of the properties, synthesis methods, and potential applications of advanced materials, focusing particularly on nanomaterials, biomaterials, and smart materials. These materials exhibit unique characteristics that render them indispensable for a wide array of applications, spanning energy storage, environmental remediation, healthcare, and electronics. Nanomaterials, characterized by their small size and high surface area-to-volume ratio, possess exceptional mechanical, electrical, and optical properties. They find utility in diverse fields such as drug delivery systems, sensors, catalysts, and coatings, where their enhanced performance attributes contribute to improved functionality and efficiency. Biomaterials, on the other hand, offer biocompatibility and bioactivity, making them ideal for medical implants, tissue engineering, and drug delivery systems. Their similarity with organic frameworks empowers progressions in regenerative medication and customized medical services. Smart materials, distinguished by their responsiveness to external stimuli like temperature or light, serve as key components in actuators, sensors, and adaptive structures, facilitating the development of intelligent systems with dynamic capabilities. Despite their promising applications, advanced materials encounter challenges related to scalability, cost-effectiveness, and commercialization. Conquering these obstacles requires deliberate endeavors from analysts, specialists, and policymakers. Innovative synthesis methods and manufacturing processes are being developed to address scalability issues and improve cost-effectiveness. Furthermore, policymakers play a vital role in fostering the adoption of advanced materials by implementing supportive regulations and incentives that encourage investment in research, development, and commercialization efforts. In conclusion, this review paper serves as a valuable resource for stakeholders involved in advancing sustainable technologies through the utilization of advanced materials. By comprehensively understanding the properties and potential applications of nanomaterials, biomaterials, and smart materials, and by collaboratively addressing the associated challenges, we can expedite the development of environmentally friendly technologies that benefit society as a whole

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INTRODUCTION

In today's dynamic landscape, the exploration and utilization of advanced materials mark a crucial frontier in propelling sustainable practices and fostering innovation across various industries. This article delves into three key categories of advanced materials: Nanomaterials, Biomaterials, and Smart Materials. Each category presents distinct properties, synthesis methods, diverse applications, accompanied by notable challenges and future prospects, shaping a promising trajectory for sustainable technological advancement. Nanomaterials epitomize a class of materials distinguished by their diminutive scale, typically within the range of 1 to 100 nanometers. The extraordinary properties of nanomaterials stem from their significantly increased surface area relative to volume, endowing them with distinctive characteristics. Nanomaterials exhibit exceptional physical, chemical, and mechanical attributes. Nanomaterials find wide-ranging applications across numerous sectors including medicine, electronics, environmental remediation, and civil engineering. They contribute significantly to medical equipment, serve as protective coatings, and pave the way for ground breaking advancements in diagnostics, drug delivery systems, and environmental remediation. However, challenges in their application revolve around risk assessment, safety concerns, and the need for sustainable large-scale manufacturing techniques. Biomaterials comprise a particular class of materials intended to communicate with natural frameworks for clinical, helpful, or demonstrative purposes. These materials exhibit compatibility with living tissues, promoting healing and medical advancements. Biomaterials present diverse properties, including biocompatibility, bioactivity, and tailorability to suit various applications. The synthesis of biomaterials involves multiple techniques, such as chemical processing, composite materials, and 3D printing, enabling the creation of structures suitable for tissue engineering, drug delivery systems, and medical implants. The uses of biomaterials reach out to tissue recovery, drug conveyance, and implantable clinical gadgets. Challenges encompass biocompatibility assurance, longevity, and refining manufacturing processes for enhanced efficiency and safety Smart Materials represent an innovative class of materials with responsive capabilities to external stimuli, adapting their properties in real-time. These materials exhibit extraordinary characteristics, including shape memory, piezoelectricity, and self-healing properties. The synthesis of smart materials relies on various methods, such as chemical synthesis, 3D printing, and nanotechnology. The uses of brilliant materials range different businesses, from aviation and structural designing to medical care and buyer gadgets. Their role in developing adaptive structures, responsive sensors, and self-repairing systems is instrumental in shaping the future of technology. Challenges involve integrating these materials effectively into practical applications, ensuring reliability, and addressing ethical and safety concerns.

NANOMATERIALS

An interesting new class of materials called nanomaterials is in great demand for a wide range of real-world uses. Five silicon atoms or ten hydrogen atoms arranged in a line, each measuring one nanometer, can be used to illustrate the length of a nanometre. Materials that fall between 1 and 100 nm in size or one of their dimensions are classified as nanomaterials. It is hard to pinpoint the precise history of human use of nanoscale things. Nonetheless, the usage of nanomaterials is not new; humans have employed them a long time back, unintentionally, for a variety of purposes. Humans used asbestos nanofibers to strengthen ceramic mixes about 4500 years ago [1]. The percentage of atoms at a material's surface increases proportionately as the size gets closer to the nanoscale, and this is when the material's surface-to-volume ratio becomes more significant [2]. This phenomenon of large surface area over volume ratio accounts for the distinctive properties of the nanomaterials [3]. Due to their small size, charge, surface roughness, and solubility, nanoparticles are better suited to drastically change how they interact with biomolecules and cells [4]. Over the past century, substantial progress has been made in biology, chemistry, physics, and engineering thanks to the use of these remarkable properties in nanomaterials [5]. This review will go over the basic mechanical, chemical, and physical characteristics of nanomaterials, synthesis methods, challenges, and prospects.

Properties

Physical Properties

Optical characteristics of the nanoparticle, such as its colour, light penetration, absorption and reflection capacities, and UV absorption and reflection capabilities in a solution or when deposited onto a surface, are examples of its physical qualities. It also comprises the mechanical attributes that are important to their use, such as flexibility, tensile strength, ductility, and elastic characteristics [6].

Additional qualities like hydrophilicity, hydrophobicity, suspension, diffusion, and settling characteristics have permeated many contemporary objects [7]. The nanoparticles' thermal conductivity in renewable energy applications and their conductivity, semi-conductivity, and resistivity in magnetic and electrical properties have paved the way for their employment in contemporary electronics [8].

Chemical Properties

Applications are determined by chemical characteristics like the nanoparticles' reactivity with the target, stability, and susceptibility to heat, light, moisture, and environment [9]. The nanoparticles' cytotoxic, antibacterial, antifungal, and disinfectant qualities make them perfect for use in environmental and medicinal applications [10]. The properties of the nanoparticles—flammability, oxidation, reduction, and anti-corrosion—determine their specific applications [11].

Mechanical Properties

Nanoparticle volume, surface, and quantum effects give nanomaterials their superior mechanical properties [12]. When added to a common material, nanoparticles will partially refine the grain, creating an intragranular or intergranular structure that will enhance the grain boundary and improve the mechanical properties of the materials [13].

Synthesis

Nanomaterials synthesis can be classified into two main groups : Top-down Approach, Bottom-up Approach

Top-down Approach

In the synthesis using a top-down approach, the destructive method is used. The larger molecule (bulk material) decomposes into smaller molecules and then these smaller molecules transform into nanoparticles [14]. Grinding or milling, physical vapor deposition, and other destructive approaches are examples of Top-down synthesis [15]. Some methods for the synthesis of the top-down approach are given below.

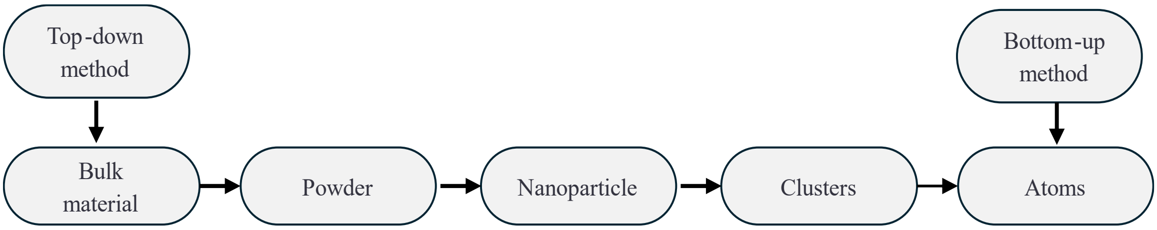


Figure 1. Synthesis processes of nanomaterials.

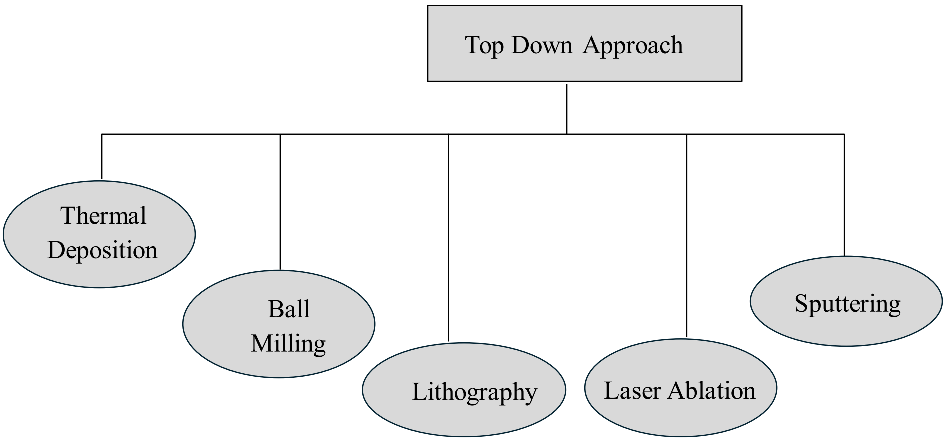


Figure 2. Top-down Approach Synthesis.

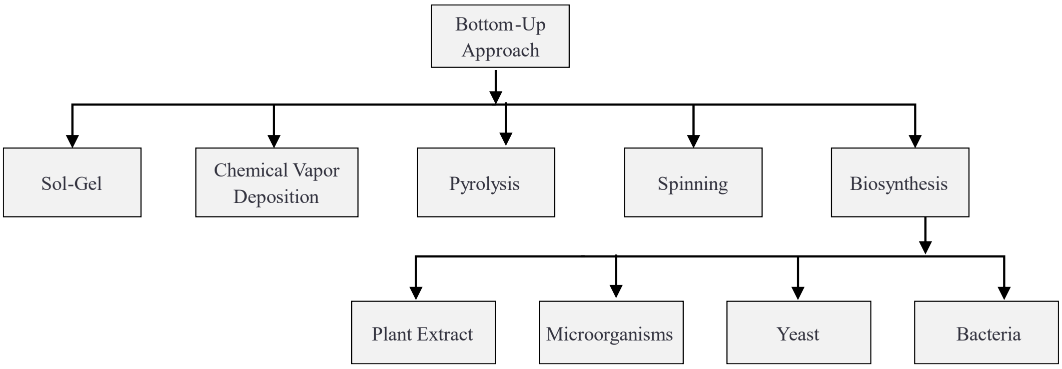


Figure 3. Bottom-up Approach Synthesis methods.

Thermal Decomposition Method

Thermal decomposition is an endothermic substance disintegration created by heat that breaks the synthetic securities in the compound [16]. The deterioration temperature is the exact temperature at which a component goes through compound breakdown. The metal is separated at specific temperatures, causing a substance response that yields optional mixtures, and this cycle makes the nanoparticles [17].

Mechanical Milling/Ball Milling

Mechanical milling (MM) involves the use of a high-energy mill with a suitable milling medium and a powder charge (usually an elemental blend). Reducing particle size and mixing of particles in new phases are the goals of milling. The production of nanomaterials using various ball milling techniques that affect the powder charge is possible [18]. The balls have two possible outcomes: either they fall freely and hit the powder and balls below, or they roll down the chamber's surface in a succession of parallel layers. Mechanical milling is a more cost-effective method for producing grain on a wide scale with nano-size grains [19].

Lithography

Many top-down chemical fabrication techniques, like anodizing, are common industrial processes and are always simple to scale up [20]. Lithographic techniques, as we all know very well, are top-down techniques that can produce features that are typically micron-sized, while being energy-intensive and needing expensive facilities and equipment. For many years, printed circuits and computer boards have been created using lithography [21]. Future efforts to shrink will be expensive since they call for stronger sources (such as shorter wavelength sources and high energy electron beams), facilities, and support equipment.

Laser Ablation

Laser ablation is a procedure which combines melt ejection with vaporization, and it has several uses in metals, ceramics, glasses, and polymers. It involves using a pulsed laser to remove molecules from a substrate surface in order to generate micro/nanostructures [22]. By concentrating a laser beam above a substrate, LA is a top-down technique for removing the material from it. Ablation happens just when a material takes in sufficient energy to liquefy or dissipate [13]. The general process of laser ablation is constant in laser machining applications such as high-precision drilling, laser beam milling, and laser cutting [10].

Sputtering

The process of depositing nanoparticles on a surface by ejecting them through ion collisions is known as sputtering [23]. In the process of sputtering, ions are blasted at a cathode or target, driving off atoms through momentum transfer. After spewed atoms hit a substrate, they continue to travel until they form the desired layer [24]. The simplest source of ions for sputtering is the widely recognized glow discharge phenomenon, which results from the application of an electric field between two electrodes in a low-pressure gas [25]. When a minimum voltage is reached, the gas disintegrates and begins to conduct electricity. Plasma is the name for such an ionized gas. A strong electric field accelerates the plasma's ions as they approach the target.

Bottom-down Approach

The bottom-up method is referred to as the constructive methodology. it is completely opposed to the top-down approach. Nanomaterials with distinct sizes, shapes, and chemical composition are created as a result of atoms and molecules growing and self-assembling as their fundamental components [24]. Some of these processes are discussed below:

Sol-Gel Process

The Sol-Gel process is a wet chemical method used in the synthesis of metal oxides that involves immersing the molecular precursor (typically metal alkoxide) in alcohol or water, heating it, and stirring it to cause alcoholysis, or hydrolysis, which turns the precursor into a gel [26]. The hydrolysis/alcoholysis process produces a wet or damp gel, which needs to be dried using the appropriate methods depending on its intended use and properties. For example, if the fluid is alcoholic, burning it finishes the drying process. After the drying phase, the generated gels are crushed and then calcined [27].

Chemical Vapor Deposition

The process of chemical vapor deposition (CVD) produces thin solid films by reacting one or more precursors in the gas phase or on a substrate's surface. Reaction initiators can take the form of heat, high-energy radiation, or plasma [28]. This process is regarded as one of the primary techniques for creating two-dimensional materials in the last several years. In the areas of electronic, photoelectric, thermoelectric, and bionic devices, they have enormous development potential [29].

Pyrolysis

Pyrolysis is a thermochemical process where matter breaks down into smaller pieces at a high temperature without the presence of oxygen [30]. This process is made even more promising by the potential to convert all byproducts of pyrolysis, such as black char [31], pre-condensation fumes [32], and post-condensation gas, into carbon-based nanomaterials [30, 33]. Although more research is necessary before such a process can be commercialized, reports have described the pyrolysis technique's use in the creation of carbon nanotubes [34]. This procedure demonstrates the enormous advantages of turning waste materials into valuable resources.

Spinning

The synthesis of nanoparticles by spinning takes place in the spinning disc reactor (SDR), which consists of rotating discs where physical parameters such as temperature can be controlled, is used to create the nanoparticles [20]. Nitrogen or other inert gases are pumped into the reactor to prevent chemical reactions and eliminate oxygen. Pumped into the chamber or reactor is a liquid, such as water and precursor [35]. The process of spinning molecules or atoms into nanoparticles involves the following steps: fusion, precipitation, collection, and drying [6].

Biosynthesis

In biological synthesis, plant extract and microorganisms like bacteria and fungi are used to produce nanoparticles. [36]Due to their unusual optical, chemical, photoelectrochemical, and electronic properties, the synthesis of nanoparticles using biological entities is of great interest. The development of “green chemistry” processes that are safe, non-toxic, and environmentally acceptable would be beneficial for these nanoparticles [37].

Applications

- In contrast to many dyes and pigments, silver nanoparticles have a color that varies according to their size and shape. They are also incredibly effective at both absorbing and scattering light. In textiles and wound dressings, medical equipment, and appliances like refrigerators and washing machines, it has grown in popularity as an antibiotic agent [38].

- The best method for preventing erosion and corrosion is to use coatings, whether they are nanostructured or conventional. In the present era, the thermal spray process is a more popular and suitable method of deposition for coatings with a variety of parameters, giving large throughput in the shortest amount of time. The development of hard protecting coatings began with the invention of chemical and physical vapour deposition. For example, chrome carbide with nickel chrome Cr3C2-25NiCr and Cr3C2-20NiCr, and tungsten carbide with various binders like WC-Co, WC-CoCr, etc., are widely used for high temperature applications [39].
- Numerous biomedical applications of nanotechnology have been developed, including tissue engineering, drug delivery, biological detection, and diagnostic imaging. The challenge of precisely identifying and eliminating impacted cell populations has led to a significant enhancement in the diagnostic and therapeutic efficacy of these approaches in cancer diagnosis and treatment [50].
- In terms of environmental science, nanomaterials (NMs) have a variety of environmentally friendly uses, including materials that, in large-scale and portable applications, provide clean water from contaminated water sources and ones that identify and remove environmental contaminants (waste and toxic material), a process known as remediation [40]. “Bioremediation” is a course of utilizing different natural specialists, like microbes, growths, protists, or their protein, to break down ecological foreign substances into less harmful structures. “Remediate” “ means to take care of the issue. Bioventing, bioleaching, bioreactors, bioaugmentation, fertilizing the soil, biostimulation, land cultivating, phytoremediation, and rhizofiltration are among the most generally utilized bioremediation advancements [41]” signifies to take care of the issue. Bioventing, bioleaching, bioreactors, bioaugmentation, fertilizing the soil, biostimulation, land cultivating, phytoremediation, and rhizofiltration are among the most broadly utilized bioremediation advancements [41]
- Nanotechnology has applications in numerous structural designing fields, like plan and development methods. Items for lighter designs and more grounded underlying composites, like those utilized in spans, are among them. negligible upkeep covering upgraded techniques and materials for pipe joining, further developed cementation material characteristics, diminished pace of intensity move among protection and fire retardant improved acoustic absorber sound absorption, enhanced glass reflectivity, water repellents, Nanomaterials solar cells [37].
- Smart nanomaterials can serve as a replacement for sensors in the detection of pesticides. The use of sensors to identify pesticide residues in soil may be rendered unnecessary by smart nanomaterials and nano pesticides, which function as both an initiating and indicative sensor. Farmers could use the nanomaterial as an advanced alert system to determine the dosage rate and frequency, as it would have a slow, targeted release of the material and also indicate a deficiency of nutrients in the soil through color changes [49].
- The majority of applications of nanostructures in food that have been documented include (i) enhancing food quality; (ii) fortifying food with bioactive substances; (iii) releasing bioactive compounds under controlled conditions by the use nanocarrier encapsulation; (iv) modifying the textures and structures of food; and (v) utilizing intelligent packaging systems to detect and counteract biochemical, microbiological, and chemical changes [50].

Challenges and Future Prospects

The challenges faced in the field of nanomaterials include:

- Quantifying the impacts of the circular economy on nanomaterials, manufacturing, and economies.
- Scaling up laboratory or pilot technologies for commercialization, including maintaining the size and composition of nanomaterials at large scale [41, 51]
- Addressing the risks associated with nanotechnology and nanomaterials, including their impacts on health, safety, and the environment.

Table 1. Synthesis, Properties and Applications of Nanomaterials.

Nanomaterials	**Properties**	**Synthesis**	**Applications**	**References**
Carbon nanotubes	high strength and electrical conductivity.	chemical vapor deposition or arc discharge methods,	Used in electronics, energy storage, composites, and biomedical devices.	[42]
Gold nanoparticles	Excellent optical properties, high stability, and biocompatibility	Chemical reduction, seed-mediated growth, and electrochemical deposition	Diagnostics, therapeutics, imaging, and catalysis.	[43]
Silver nanoparticles	Antimicrobial properties and electrical conductivity and optical properties	Chemical reduction, electrochemical deposition, and photochemical synthesis	Antimicrobial coatings, sensors, catalysis, and drug delivery.	[44]
Quantum dots	Size-dependent fluorescence and electronic properties	Colloidal synthesis methods	Optoelectronics, imaging, solar cells, and bioimaging	[45]
Silicon nanoparticles	Quantum confinement and enhanced optical properties.	Laser ablation or plasma-based methods,	Energy storage, biomedical imaging, and electronic devices.	[46]
Graphene	High conductivity and strength, excellent mechanical strength, and exceptionally large surface area	Mechanical exfoliation or chemical vapor deposition	Electronics, energy storage, sensors, and composite materials.	[47]
Titanium dioxide nanoparticles	High photocatalytic activity, wide bandgap, and stability.	Sol-gel method, hydrothermal synthesis, and chemical vapor deposition.	Photocatalysis, sunscreens, self-cleaning surfaces, and water purification.	[48]

- Characterizing nanomaterials as they exist in products or in various environmental compartments, which is extremely challenging [51].
- Developing sustainable large-scale manufacturing techniques for cost-effective production of clean and reliable nanomaterials [52].

The possibilities of nanomaterials are promising, as they can possibly upset different fields like medication, gadgets, energy, and ecological remediation. A portion representing things to come possibilities of nanomaterials include:

- Development of advanced drug delivery systems that can target specific cells or tissues, improving treatment efficacy and reducing side effects [41].
- Integration of nanomaterials into electronic devices, leading to smaller, faster, and more efficient technology [35].
- Utilization of nanomaterials in energy capacity and change advances, like batteries and sun oriented cells, to further develop productivity and maintainability.
- Application of nanomaterials in environmental remediation, such as water purification and air pollution control, to address pressing environmental challenges [53].

BIOMATERIALS

Biomaterials are substances with bioactive properties that interact with biological systems and can potentially be easily compacted into human tissue [54]. The objective of all initial biomaterials was to 'create a suitable blend of physical qualities to match characteristics of the replacement tissue with a low toxic reaction in the host [55]. Biomaterials serve a significant part in tissue engineering due to their ability to elicit certain mechanisms in cells and direct cell-cell interactions in both implant-free and cell-supported implants. Based on bio adhesive receptor-binding peptides and mono and oligosaccharides, these materials can construct model multicellular tissue frameworks. Natural polymers, such as recombinant polymers, have also been utilized to accelerate natural processes such as wound healing, trigger cellular responses, and prevent natural processes such as immunological rejection or growth stimulation signal activation [56]. They are environmentally advantageous, as they can be harvested from biological resources or generated with green technology. They have been utilized successfully in a variety of biological sectors, as well as in non-biomedical applications such as cancer therapy, surgical equipment, and ophthalmic applications [54]. Their properties, synthesis methods, applications challenges and future prospects are thoroughly discussed.

Properties

Thermal Properties

Conduction is usually the most important factor in determining heat transfer within a biomaterial. The capacity of a biomaterial to move energy by conduction is best ordered in the consistent state by warm conductivity and in the non-consistent state by warm diffusivity because of the mind boggling construction of most biomaterials, there are no suitable minute hypotheses like those for solids and, less significantly, fluids that permit direct estimation [57].

Mechanical Properties

The overall average relative properties of the iron-, cobalt-, and titanium-based alloys are summarized in Figure 3.1.2 (a) [58].

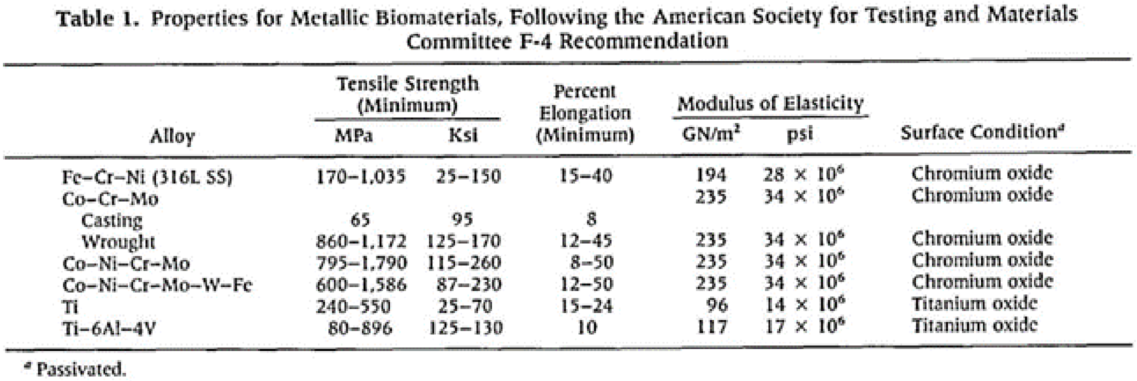


Table 1. Properties for Metallic Biomaterials, Following the American Society for Testing and Materials Committee F-4 Recommendation

Alloy	Tensile Strength (Minimum)		Percent Elongation (Minimum)	Modulus of Elasticity		Surface Condition[a]
	MPa	Ksi		GN/m^2	psi	
Fe–Cr–Ni (316L SS)	170–1,035	25–150	15–40	194	28 × 10^6	Chromium oxide
Co–Cr–Mo				235	34 × 10^6	Chromium oxide
Casting	65	95	8			
Wrought	860–1,172	125–170	12–45	235	34 × 10^6	Chromium oxide
Co–Ni–Cr–Mo	795–1,790	115–260	8–50	235	34 × 10^6	Chromium oxide
Co–Ni–Cr–Mo–W–Fe	600–1,586	87–230	12–50	235	34 × 10^6	Chromium oxide
Ti	240–550	25–70	15–24	96	14 × 10^6	Titanium oxide
Ti–6Al–4V	80–896	125–130	10	117	17 × 10^6	Titanium oxide

[a] Passivated.

Figure 4. Properties of Metallic Biomaterials.

Synthesis Methods

Biomaterials can be synthesized using various methods of synthesis. Some of them are discussed below in brief:

Sol Gel Synthesis of Biomaterials

Materials which are synthesized by sol-gel method are incredibly pure and homogeneous, featuring controlled multiphase microstructures, net-shape forming, and as-cast surface features produced at lower temperatures than other processes [59]. The sol-gel technique yields a range of easily prepared, high-purity oxides of inorganic substances or hybrid inorganic-organic materials by the condensation and hydrolysis of metal or silicon alkoxides [60]. Preparation of biomaterials using sol-gel method can be done by using the following processes (1) Hydrolytic sol-gel process (2) Non hydrolytic sol-gel process [61]. The NHSG (Non-Hydrolytic Sol-Gel) process produces homogenous and precisely specified products by enabling atomic-scale reaction control. Because this technology may be used to develop specialized materials, it has been used in many other sectors [62].

Microfluidic Synthesis of Biomaterials

Microfluidic processes are being studied for a wide range of applications including materials production, chemical detection, medication administration. These processes are highly regulated, manage small fluid volumes, provide quick mass and heat transport, and allow for the direct and rapid synthesizing of new materials with homogeneous characteristics [63]. Some system requirements of microfluidic systems are (1) The channel's size causes most fluid flow in microfluidic devices to be laminar [64]. (2) Unless there is diffusion via the interface, multiple streams that are running in contact with each other will not mix [65]. (3) Coaxial flow forms in microfluidic channels primarily because of phase separation, and fibers may be made by solidifying the center flow through the use of ion linkage and photopolymerization techniques [66].

Enzymatic Synthesis of Biomaterials

Enzymatic synthesis is a type of catalytic synthesis method in which naturally occurring Enzymes of various living organisms are used as catalyst instead of other chemical compounds. This technique does away with the requirement to stabilize enzymes against being inactivated by non-aqueous solvents, by localizing them in the aqueous phase. It shifts the equilibrium of reactions that create water as a reaction product towards products by allowing for endlessly low water contents. Important sources of equilibrium shift are also provided by the system's two phases, such as the free energy involved in the transfer of reagents from one phase to the other. This method greatly increases the enzymes' stability in non-aqueous solvents [68]. Let us discuss further with the example of fungal laccases. The ligninolytic enzyme laccase is most commonly present in fungus. It carries out pigment production, polymerization, depolymerization, and catabolism. Laccases are strong molecule-coupling enzymes that produce large yields of low-molecular-weight products. In biotechnology, they are being utilized more and more to derivatize physiologically active molecules gently and to synthesize fine chemicals in an environmentally responsible manner [69].

Applications

Biomaterials have acquired numerous applications, notably in Tissue Engineering, contact lenses, heart valve replacements, dental implants for tooth fixation, artificial ligaments and tendons, bone plates, and breast implants. Let us discuss in brief about some of these applications.

Tissue Engineering

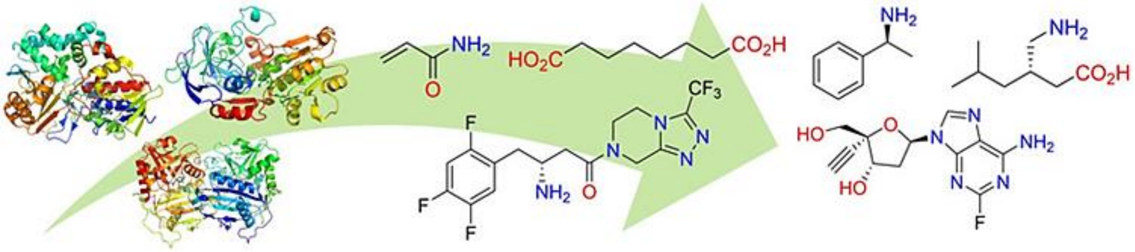
For more than 20 years, tissue engineering has improved cell and growth factor transplantation through the use of biomaterial scaffolds. Recently, a potentially potent paradigm for regenerative medicine has emerged: biomaterials that may stimulate tissue repair and regeneration on their own without requiring the delivery of cells or other therapies. A biomaterial scaffold can, if properly engineered, induce the invading cells to behave in a way that promotes tissue repair or regeneration, or it can generate a new microenvironment in sick tissue that resembles the original healthy extracellular matrix [70]. Tissue regeneration and repair rely heavily on immunosuppression, and biomaterials can communicate with the immune system by supplying physiochemical signals and interacting with it biologically. Fig.6. provides an overview of the research on biomaterials that have been employed to inhibit the immune system and promote tissue regeneration [65].

Contact Lenses

The capacity of polymers to balance their qualities with the ocular environment is crucial for contact lens design. The cornea, tear film, and eyelid control oxygen permeability, modulus, and surface characteristics. The success of silicone hydrogels in this application is attributable to their capacity to satisfy oxygen consumption requirements. The wear modalities of contact lenses make the field difficult, however silicone hydrogels have demonstrated a tendency towards characteristics more akin to those of traditional hydrogels [73]. In contact lenses, keratoprostheses, and intraocular lenses, poly (methyl methacrylate), cellulose acetate butyrate, and siloxane-containing polymethacrylates are some of the biomaterial lenses that are often used [74].

Heart Valve Replacements

Mechanical or prosthetic heart valves made of synthetic materials are long-lasting and durable [75]. Nevertheless, problems with their biocompatibility and the ensuing thrombosis, inflammation, or thromboembolism may restrict their usage. Furthermore, after a prosthetic valve transplant, prosthetic valve endocarditis (PVE) may also develop, which may necessitate surgical prosthesis removal [76]. It is anticipated that the biomaterials industry would be dominated by cardiovascular biomaterials in 2014, with a projected value of $20.7 billion [77].



The above Fig.5. illustrates Enzymatic synthesis [67]

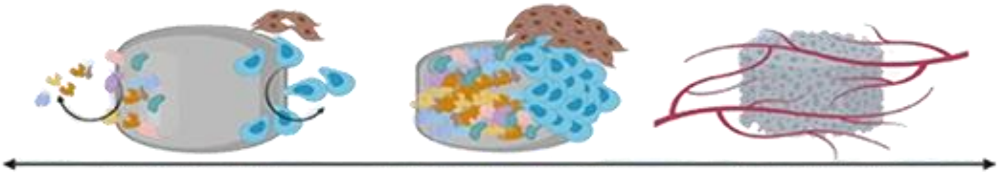


Figure 6. Explains the working of biomaterials in wound healing [71].

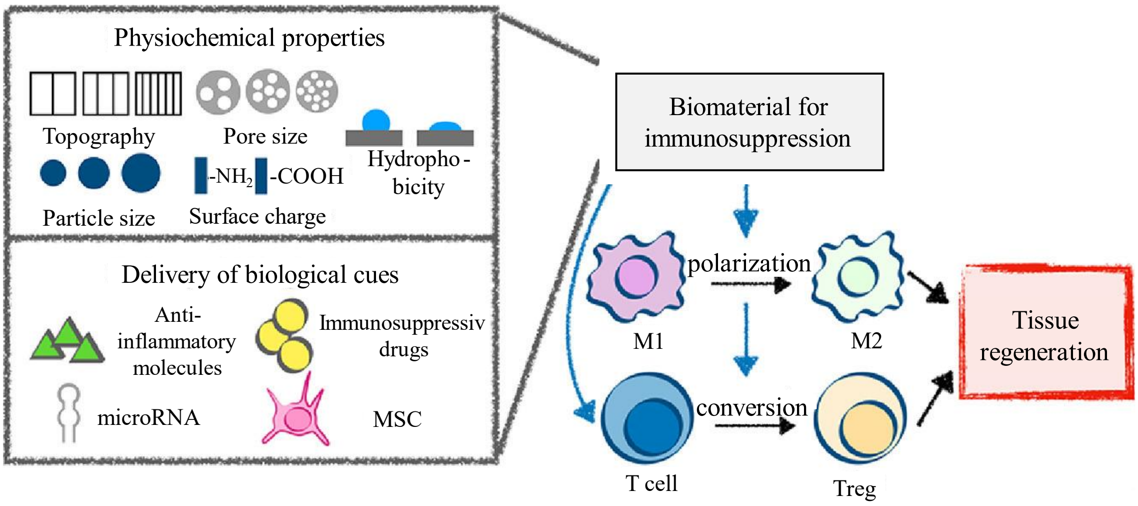


Figure 7. Tissue regeneration.

Dental Implants

The American dental affiliation frames some acknowledgment rules for dental inserts: (1) Assessment of actual properties that guarantee adequate strength;(2) Show of simplicity of creation and sanitization potential without material corruption; (3) Wellbeing and biocompatibility assessment, including cytotoxicity testing and tissue obstruction characteristics;(4) Independence from defects;(5) No less than two autonomous longitudinal imminent clinical examinations exhibiting viability [78].The material of choice at the moment is yttria stabilized tetragonal zirconia, which has outstanding mechanical and tribological characteristics as well as bio compatibility [79].

Bone Implants

Achieving the ideal bone-implant contact has been achieved via modifying the bulk material composition, implant surface topography, chemistry, energy, and charge. The perfect bone implant material has a chemical composition that is biocompatible to prevent negative tissue reactions, excellent corrosion resistance within physiological bounds, acceptable strength, a high resistance to wear, and an elastic modulus that is comparable to bone's to reduce bone resorption around the implant [80]. Collagens, Demineralized bone matrix, Bone morphogenic proteins are some of the biomaterials used in bone implants [81].

Challenges and Future Prospects

The major challenges in the field of biomaterials in the industrialized world are as the population ages quickly, the clinical success of bioinert, bioactive, and resorbable implants has been a crucial answer to their medical demands. Nonetheless, studies on the survival of mechanical heart valves and the majority of bone prostheses reveal that between one-third and half of them fail after ten to twenty-five years [82,83].

Future Prospects of Biomaterials Include

1. The chemistry of biomaterials is crucial to their performance in the therapeutic context, and efforts are always being made to design appropriate biomaterials that can enhance human tissue regeneration and repair. Chemistry has advanced, giving researchers unprecedented opportunities to study and work with single molecules as well as small groups of molecules to create effective materials for tissue regeneration [84].
2. A thorough understanding of the characteristics, benefits, and drawbacks of different biomaterials and scaffolds will expedite the development of appropriate scaffolds for applications involving skin tissue regeneration [85].
3. Adaptive biomaterials-based systems for the treatment of bacterial infections are a burgeoning trend that provide significant opportunities for the development of innovative antimicrobial treatments [86].

SMART MATERIALS

Smart materials are advanced materials that can sense external signals and autonomously perform specific tasks. They are often referred to as smart, intelligent, or adaptive materials because they incorporate sensors and actuators. Additionally, these materials possess distinct features that set them apart from other materials [87-91]. Smart materials can be split into two primary categories: passive materials and active materials [92-93]. Passive smart materials refer to substances capable of transmitting certain forms of energy, such as being utilized as fibre optics that can convey electromagnetic waves. Additionally, active smart materials are categorized into two types. The initial type encompasses materials that can modify their properties when subjected to external influences, for instance, like Photochromic glasses that change their color when exposed to sunlight [94]. The second category has the ability to convert energy from one form, which includes thermal, chemical, nuclear, mechanical, electrical, and optical, into a different form. For instance, solar cells (also known as photovoltaic cells) and LEDs serve as two illustrations capable of transforming solar energy into electricity and electrical energy into light, respectively [95-96].

Types and Properties:

Shape Memory Alloys and Properties

Shape memory alloys (SMAs) represent a widely encountered example of smart materials. Their unique trait lies in their capability to alter shape with temperature fluctuations, setting them apart from conventional materials by their ability to recall their initial form when subjected to external triggers, like stress. They are commonly termed intelligent materials. The transformation of shape occurs between two phases—martensite and austenite. The martensite phase remains stable at lower temperatures, while the austenite phase retains stability at higher temperatures [97].

Piezoelectric Materials

Piezoelectricity, coined from the Greek term “piezo,” meaning pressure, combined with “electricity,” denotes the phenomenon where piezoelectric materials convert mechanical energy into electrical energy and vice versa when subjected to stress or strain. Likewise, piezoelectric actuators translate electrical signals into mechanical movements, serving purposes such as adjusting mirrors, lenses, and various components in the automotive industry. The combination of piezoelectric materials can possibly upgrade the exhibition of flow items [98].

Electro-rheological Fluids

An electro-rheological fluid (ERF) consists of minuscule particles suspended within an electrically insulating fluid. When subjected to an electric field, these particles swiftly assemble into a solid-like structure aligned with the direction of the field [99]. They exhibit the ability to transition between states, moving from a gel-like state to a liquid and vice versa upon the application or removal of an electric field [100].

Magnetostrictive Materials

Magnetostrictive materials have the capacity to become magnetized when stress is applied or deform in response to a magnetic field [101]. They are commonly known as transducers. The alteration in length is a result of the magnetization process. These materials are typically categorized as positive or negative Magnetostrictive. Depending on their classification, they either contract or expand due to changes in the magnetic field [102]. These materials demonstrate nonlinear characteristics and exhibit frequency-dependent hysteresis. This behaviour poses several challenges in accurately capturing their complex properties. The mechanical properties of Magnetostrictive materials include workability, moderate saturation magnetization [103], high coercivity, high chemical stability, high Curie temperature, and high cubic magneto-crystalline anisotropy [104].

Optical Fibers

Optical filaments are adaptable, straightforward strands made by attracting glass or plastic to a breadth somewhat thicker than that of a human hair. They are usually utilized to send light between the closures of the fiber and track down broad use in fiber-optic correspondences. These fibers play a crucial role in monitoring various structures such as mechanical blades, shafts, and civil infrastructures for any variations in strain resulting from cracks or damages [105–108]. They are particularly prominent in Structural Health Monitoring (SHM) as smart materials. Fiber-optic sensors and piezoelectric wafer active sensors are among the most utilized for SHM purposes. In the beyond twenty years, broad examination has zeroed in on two sorts of fiber-optic sensors: Fiber Bragg grinding (FBG) and fiber-optic polarimetric sensors (FOPS). FBGs are specifically employed for localized strain measurements [109].

Synthesis of Methods

The properties of smart-responsive materials typically rely on the chosen synthesis method. Various approaches for producing such materials have been documented, including hydrothermal, emulsion polymerization, ionic polymerization, reversible addition-fragmentation chain transfer polymerization, among others [110, 111]. The hydrothermal method, in particular, has been developed for synthesizing smart materials, particularly ceramic-based ones, and offers several advantages in the synthesis process. These advantages include: (1) The ability to conduct the reaction at lower temperatures to prevent extensive agglomeration and excessive component evaporation; (2) Easier control of size down to the nanometer scale; (3) Eco-friendliness as chemicals can be recycled in a closed system; (4) Adaptability to large-scale industrial production, thus reducing costs [110]. Senthil et al. (2019) reported the synthesis of BiFeWO6/MoS2 composite materials for visible-light responsiveness in degrading organic pollutants using a low-cost and straightforward hydrothermal process [112]. The material was synthesized at 200°C for 24 hours, demonstrating good crystallinity and the successful loading of BiFeWO6 onto the surface of MoS2. This method has great potential for producing responsive nanomaterials [113, 114].

Another commonly used method for smart material synthesis is emulsion polymerization (EP). This technique was derived from radical chain polymerization to create latex with a narrower particle size distribution. Emulsion polymerization systems typically consist of water, surfactant, monomer, and a water-soluble initiator [115]. An ongoing challenge with this method is the removal of surfactant at the end of the reaction. However, alternative approaches include omitting emulsifiers during the synthesis process or controlling surfactants using a cationic azo initiator [116]. Additionally, atom transfer radical polymerization (ATRP) is a widely employed synthesis method. ATRP is a controlled revolutionary polymerization (CRP) procedure that guarantees a serious level of command over the polymerization cycle. In ATRP, growing radicals are reversibly deactivated, resulting in inactive species that can initiate the formation of new polymer chains through the involvement of a transition metal catalyst. ATRP enables the production of polymers with controlled mass and low dispersion [117]. Currently, an alternative method to reduce surfactants at the end of the reaction is not added emulsifiers during the synthesis process or it can be controlled by a cationic azo initiator [118]. One other synthesis method which is commonly used is atom transfer radical polymerization (ATRP). This method is one of the strongest controlled radical polymerizations (CRP) techniques so that the polymerization process is more controlled. ATRP is the result of the formation of growing radicals, but in the process, these radicals are reversibly deactivated to form inactive species. This inactive species may act as an initiator for the formation of new polymer chains through the action of a transition metal catalyst. By using the ATRP synthesis method, polymers with controlled mass and low dispersion are highly possible [118].

Applications

Smart materials play a pivotal role in modern civilization, prevalent in various technological domains including civil engineering and construction, medicine, military applications, robotics, aeronautical technology, industrial settings, nuclear power plants, artistic ventures, and in active research groups. The following sections delve into specific applications.

Aeronautical Technology

Aeronautical technologies make extensive use of advanced materials across various sectors. The sheer variety and use of these materials surpass the scope of this review paper. Hence, only a few key examples are highlighted.

The first instance involves the utilization of an ultrasound fuel probe, an accurate indicator in aeronautics. This probe incorporates piezoelectric technology to generate ultrasonic waves. When these waves encounter the surface of the liquid fuel, a transducer piezoelectric sensor detects the reflected wave, enabling precise measurement of the fuel level [119].

The second example pertains to Shape Memory Alloy (SMA)-based wings, also known as smart wings. These wings use Shape Memory Effect (SME) to alter their shape during the ascent and descent of an airplane. This technology renders hydraulic motor systems obsolete, leading to more adaptable wings and a reduction in noise production [120].

Nuclear Industries

Smart materials offer several advantages within the nuclear industry, a sector known for its risks and high costs. Their use in this industry provides increased efficiency at reduced costs, and they can be integrated into automation systems to minimize human exposure to hazardous radioactive materials. Nevertheless, the ability of these materials to withstand and effectively respond to radioactive radiation, as well as the management of exposure rates, remains a significant challenge within this field [121].

Nano Systems

Nano materials are more dynamic than their mass partners, on account of higher proportion of surface per unit volume [122, 123]. Besides, size impact on the other actual amounts have being researched, for example, warm conductivity [124-125], cross section consistent, volume per molecule, liquefying temperature [126], Debye temperature and more [127, 128]. Nano-designed materials are manufactured in either zero aspect (quantum speck), one aspect (nanowire), two aspects (slender film), or even three-layered carbon nanotube (CNT). CNT has an electromechanical component that could be utilized as an actuator in a connected size [129]. Nanotweezers arm are made of CNT, which can be utilized for snatching miniature articles in high exact current magnifying lens. Tweezers arms are flexibly twisted by applying a voltage and they can back to the casual structure while the biasing voltage get zero [130].

Biomedical Applications

In the field of medicine, there is a growing need for accurate diagnostic tools to visualize and assess various organs within the human body. One notable application involves the use of inchworm robots for colonoscopy, which rely on Shape Memory Alloy (SMA) actuators. Back in 1999, Reynaerts and colleagues introduced a prototype featuring SMA actuators with three degrees of freedom. Figure 1 illustrates a schematic diagram of an inchworm-like robot, measuring a mere 95mm in length and 15mm in diameter [131]. These gadgets offer the possibility to alter operations and improve the finding and treatment of illnesses.

Astute Material

Material is one of significant developments of humankind, to get our bodies far from daylight and keep our body worm in cool days. Notwithstanding, in the cutting edge society, consolidating materials with savvy material can give them further functionalities like changing variety as a reaction to encompassing fomentations. Shape memory polymers (SMPs) can upgrade the nature of these kind of astute garments [132]. The sub-atomic volume of polymer is stretched out above glass progress temperature (Tg), and thus, it opens more space to trading vanished water, which is one of significant element to chill off the internal heat level's in hot days. In the other hand, these breathable polymer materials have waterproofed highlight. They can be planned such, the particles of material have least volume at room temperature, so the material keep any entrance of dampness from encompassing to body or vanishing from body to surrounding, Notwithstanding, in a higher temperature (Tg), the atoms expanded and in this manner making a few little openings for ventilation [133]. The water fume porousness has been more improved by implanting multi walled carbon nanotube [134].

Future Outlook and Perspectives

Shrewd materials are ready to assume an essential part in the progression of Computerized reasoning (man-made intelligence), the Web of Things (IoT), and brilliant clinical consideration. Their exceptional sensing and responsive capabilities outshine those of traditional materials like metals and polymers, laying the groundwork for transformative technological advancements [135]. It's foreseeable that devices built upon smart materials will introduce novel interactive experiences for people, heralding a new era in technological innovation [136, 137]. As research and development in this field continue to progress, the integration of smart materials into various applications is likely to revolutionize industries and reshape how we interact with technology in the future.

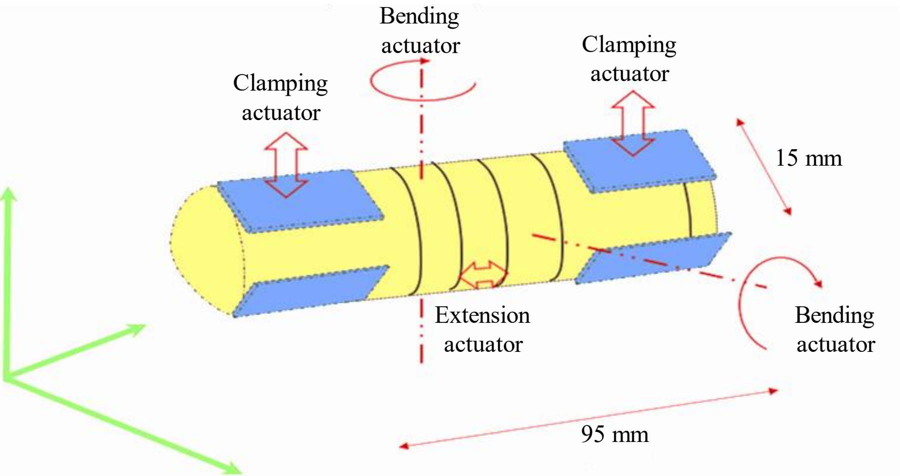


Figure 1. Schematic outline of inchworm robot with three levels of opportunity to move [131].

CONCLUSION

In conclusion, the domains of Nanomaterials, Biomaterials, and Smart Materials represent a continuum of innovation and advancement, each contributing significantly to sustainable practices and technological evolution. As these advanced materials pave the way for ground breaking applications across multiple industries, addressing challenges and harnessing their vast potential is key to realizing a future marked by sustainability, innovation, and enhanced societal well-being.

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