PERSPECTIVES ON THE FUTURE OF MODERN MATERIALS – A BRIEF REVIEW

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ABSTRACT

New synthetic materials and those derived from modifying existing ones designed to possess new or improved structural or functional properties are emerging because of the recent research activities in the field. This paper provides an overview of materials science to inspire researchers in the chemical field to develop perspectives on advances in development and applications, the discovery of materials that could transform future manufacturing and innovative processing and fabrication technologies of novel materials. Multiple perspectives on characterization, materials science, materials engineering, materials technology, nature-inspired materials, materials design research, and materials waste management are presented in this paper. *[African Journal of Chemical Education—AJCE 15(1), January 2025]*

INTRODUCTORY PERSPECTIVES

Modern materials science includes the fundamental principles and concepts of a wide range of materials from brick to biomaterials, ceramics to composites, catalysts to conducting materials, timber to textiles, paper to polymers, stone to stainless steel, rubber to rare-earth materials, metamaterials to magnetic materials, and nanomaterials to smart materials. It is essential to understand the preparation, composition, structure, properties, structure-property relationships, mechanism of material changes, control of transformations, bonding features, applications in different fields, fabrication, and benefits-costs-risks analysis [1-3]. Further, microstructure, substructure, atomic structure, crystal size, density, porosity, imperfections, thermal expansion, thermal conductivity, mechanical strength, electrical conductivity, absorption, reflection, transmission, luminescence, tensile strength, stress, phase transformations, and so on play a pivotal role in having proper functional needs in the domestic or industrial sectors [4,5]. The recent advancements in materials characterization techniques and microstructural investigation including mechanical testing and non-destructive testing of materials, have improved research outcomes in the field. Further, advances in the instrumentation and applications of transmission electron microscopy (TEM), scanning electron microscopy (SEM), and atomic force microscopy (AFM) as well as atomic and molecular spectroscopies such as atomic absorption, infra-red, and Raman spectroscopies helped in the determination of impurities. Low energy electron diffraction (LEED), X-ray photoelectron spectroscopy (XPS/ESCA), energy dispersive analysis of X-rays (EDAX), Thermal analysis techniques like differential scanning calorimeter and thermal mechanical analyzer have contributed to the furtherance of research [6-9].

MATERIALS SCIENCE

A trip towards breakthrough innovations in engineering materials allows us to explore the pathways to different applications in a new era of modern materials to transform every aspect of modern living [10,11]. Advanced functional materials like ferromagnetic, piezoelectric, and ferroelectric materials have superior performance that is critical for specific applications in the domestic and industrial sectors. Smart materials, including shape memory alloys and piezoelectric, photoelectric, thermoelectric, and magnetoelastic materials have properties that can be significantly changed in a controlled manner by an external stimulus such as electricity, heat, light, magnetic fields, or stress. The goal of materials science/engineering is to design novel materials with a predetermined set of properties using proper design concepts and suitable processing techniques to obtain materials with a particular microstructure and desired performance characteristics. The art of materials selection for automotive, aerospace, marine, and defense applications, and the design of integrated systems, smart materials, or advanced composite materials for military and space applications requires specific knowledge, additional skills, practical experience, and fabrication technologies. Advanced materials with highly specific properties include aerogel, biodegradable plastic, carbon concrete, cellulose nanofibers, composite metal foams, self-healing gel, spider silk, platinum-gold alloy, and titanium fluoride phosphate cathode material. The top ten materials industry trends include additive manufacturing, advanced nanocomposites, graphene and 2D materials, lightweight materials, material informatics, sustainable materials, smart and responsive materials, and surface engineering. Material safety and materials management 4.0 are incredibly fast-developing fields of material science. Thin film solar cells like amorphous silicon, copper indium gallium selenide, cadmium telluride, and dye-sensitized solar cells are other examples of important novel materials. Innovative scientific developments could lead to taking the subject to higher levels of understanding, an understanding of the complex structure-property relationships, molecular mechanisms of material transformations, the development of active products, processes, or systems, to arrive at practical science-based solutions, customized products/solutions, and finally better materials management solutions. The future of materials engineering is to obtain optimal performance by combining material design innovations with advances in technology involving several smart features for multiple applications. Maintaining competitiveness in the age of materials is challenging because of the interdisciplinary nature of research and the difficulty in delivering innovative materials with totally different properties or substantially improved functionalities.

MATERIALS ENGINEERING

Ceramics, metals, and plastics are used to create new materials for aircraft wings, biomedical devices, computer chips, and golf clubs to improve quality of life and reduce environmental impact [12-14]. Materials synthesis research focuses on electrochemical deposition (electrolysis), plasma processing, combinatorial synthesis, chemical vapor deposition (CVD), arc discharge, laser ablation, hydrothermal synthesis, and hydrocarbon-flame synthesis. Additive manufacturing techniques can be used to create 3D materials layer-by-layer. Comprehensive materials processing analyzes the methods and processes in converting raw materials into finished parts to improve materials' performance. This requires an understanding of the properties of raw materials, processing behaviors, scale-up performance, and product bonding/stability of product design and manufacturing of advanced functional materials.

MATERIALS TECHNOLOGY

Modern composite materials that are lightweight but have high-temperature strength, stiffness, and toughness are in great demand [15-17]. The developments in nanomaterials with special optical/electrical/mechanical properties can be viewed from a materials perspective. The application of electrochemical engineering in the production and processing of many different materials, microstructure studies in industrial research, and hydrothermal processing of composites have great prospects for making various advanced materials. It is essential to study how a material changes with time under the influence of different bonding forces (chemical kinetics). Sustainable moisture energy harvesting is an approach for obtaining cold, electricity, and heat from moisture.

NATURE-INSPIRED MATERIALS

Natural materials require less energy to produce and are more than artificial alternatives, leading to a lower carbon footprint and sustainability. Nature-inspired materials to harvest solar energy in a system having flower-like nanostructures produced from copper phosphate nanosheets in which TIO_2 nanoparticles were embedded over the petals of a flower is an emerging trend [18-20]. Spider silk is a strong natural material that has inspired synthetic fibers. Nature-inspired designs are becoming more common in biomimetic architecture projects using biological materials. Nature-derived metamaterials are sustainable, biodegradable, and self-repair/stimuli response qualities. Bioinspired design can create hybrid materials with unique predetermined properties by combining multifunctional, multiscale, and multilayer organized structures. Research is in progress to develop biocompatible materials and bioactive materials to address human problems. Thus, nature is a rich source of inspiration for materials design as it evolved to optimize efficiency and sustainability. Bioinspired wound healing dressing materials are designed to mimic the natural extracellular matrix to improve the healing process. An integration of 3D printing, nanotechnology, and bio-fabrication techniques in the future could result in biocompatible materials for customized medical devices tailored to the specific needs of individual patients.

MATERIALS DESIGN RESEARCH

The role of materials science research, engineering, and innovations extends to almost all fields of human activity, and this particular domain has a transformational effect on the development in many areas which include aerospace, defence, energy, food processing, healthcare service, housing, metals, and minerals [21,22]. The current trends in materials science research include advanced functional materials, biosafety materials, composite materials, catalyst materials, ceramic nanomaterials, dental materials, ionic liquids 4.0, recycled materials, materials that minimize environmental impacts, multifunctional materials, multi-catalytic hybrid materials, smart materials, sustainable materials, semiconductor materials, and superconducting materials. The improved materials enable people to explore the use of new finished products to improve their quality of life. Advanced research helps us to understand the fundamental concepts and principles of various materials such as polymers, liquid crystals, ceramics, nanocomposites, biomaterials, and thin films, explain how functional needs are related to structure and bonding, apply experimental design techniques to material production, define different types of materials and provide properties of various kinds of materials, understand the essential concepts used in nanomaterial synthesis, and discuss the applications of nanomaterials in different fields. The materials of the future include aerogel, artificial spider silk, bioplastic, carbon fibers, carbon nanotube, cross-laminated timber, graphene, metamaterials, metal foam, metallic glass, molecular superglue, nanocomposite materials, and transparent alumina. Supermaterials of the future include amorphous metal, aerogel, carbon nanotube (CNT), e-textiles, graphene, metamaterials, transparent alumina, room-temperature superconducting material, and nano-diamonds. Better design of modern functional materials depends on our understanding of concepts underlying materials fabrication, fine-tuning of specific properties, and field applications of multifunctional materials, processes, and systems in different situations for the future development of societies. Incorporation of nature's design and development in the higher science education curriculum design and research practice is very important to attract and inspire the younger generation towards materials science research [23]. There are no limits to what materials science can explore, and the changing face of materials science lies in the design and development of new functional materials at the core of multiple applications and start-ups in the area helping to move inventions into innovations in the market. Emerging research trends in sustainable materials include the development of bio-based polymers, self-healing/self-cleaning materials, and recycled materials.

MATERIALS WASTE MANAGEMENT

Materials waste management perspectives include municipal solid waste services, landfills, organic composting, waste valorization, and vermicomposting. Waste minimization using the reduce, reuse, recycle, and recover principle is the most desirable activity that should be supported by governments and non-government organizations. A sustainable circular economy model aims to reduce waste through physical/chemical recycling, biodegradable packaging, and smart waste bins using sensors and artificial intelligence to identify, segregate, and compress solid waste materials. Data analytics can provide insights into recycling habits, waste streams, and pollution levels that help reduce the burden on ecosystems [24-26].

CONCLUDING REMARKS

Materials science will be the global innovation engine in the next two decades, creating future-ready tailor-made materials (**Figure 1**). Advanced functional materials can have a significant influence on the future of energy conversion technologies, improving medical diagnostics and treatments, developing next-generation electronics, and global warming-related solutions. Advanced functional materials are used in energy storage systems, sustainable construction materials, sustainable and biocompatible composites, nanomaterials, carbon fiber, and 3D printed materials because of their unique physicochemical/mechanical properties. Smart materials can change their properties in response to external stimuli like heat, light, or pressure. Three-dimensional printing technology provides new possibilities for smart materials. Smart nanomaterial prospects include nanosensors, nanomachines, and nanocomputers that respond to their environment. Smart textiles used in defense sector, piezoelectric materials to get electrical signals, solar photovoltaic materials for renewable energy, and shape memory polymer materials have attracted the attention of researchers, and innovations in developing these materials will pave the way for modern high-tech living. Smart and reactive gels and synthetic rubbers can easily adjust their shape in response to heat or acidity. This feature is useful in designing intelligent materials for sensors and drug-delivery devices. Emerging trends in advanced functional materials include the development of additive fabrication techniques and strategies to increase the precision, speed and scalability of the process.

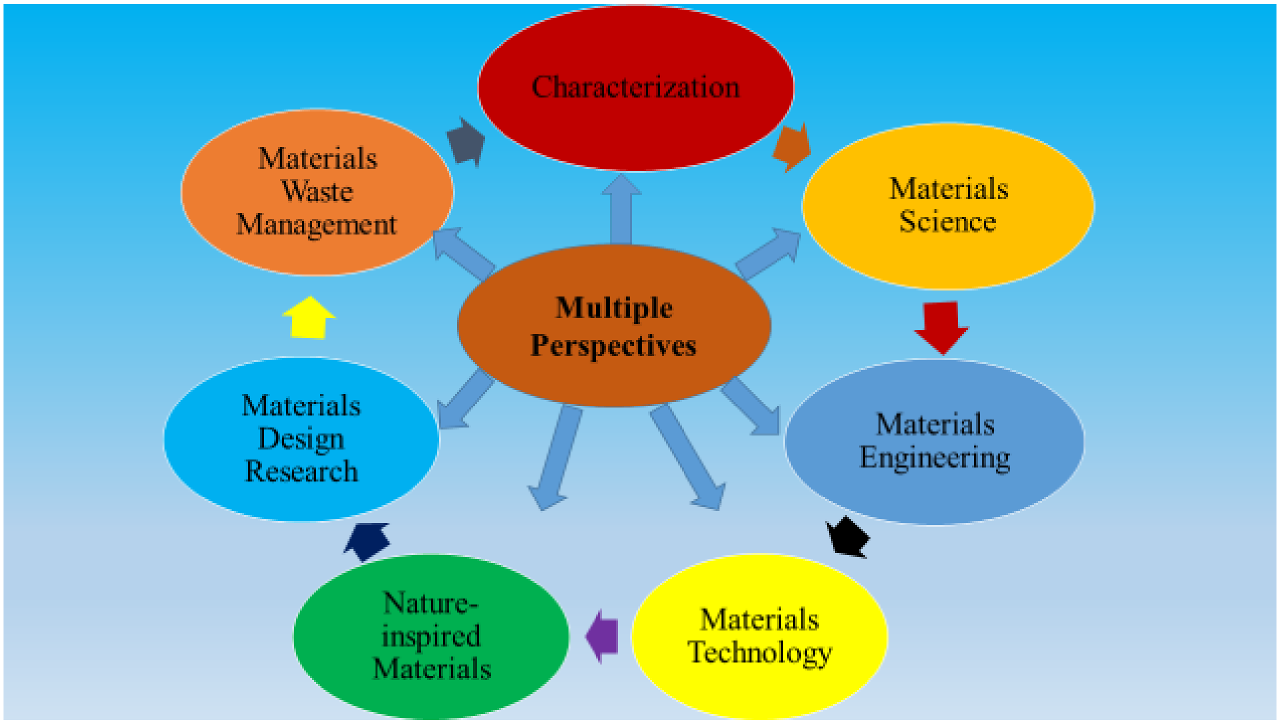

Figure 1. Multiple perspectives on the future of modern materials.

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