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Review Article

Recent Developments in Stimuli Responsive Smart Materials and Applications: An Overview

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The term "smart materials" can be used to refer a wide variety of different kinds of substances. One capacity that is shared by all of them is the capability to radically alter one or more aspects while operating inside carefully controlled conditions. The age of intelligent materials is arrived, and we are living in it right now. An older definition of smart material described it as a substance that responds swiftly to the environment in which it is located. It has been argued that the word "smart material" now refers to any substance that is capable of detecting, transmitting, or processing a stimulus in order to produce a beneficial effect. This idea has been put forward as a possible expansion of the original meaning of the term. The purpose of this research is to define and categorize different types of intelligent materials. Uses of smart materials are being contemplated in a wide variety of domains, spanning from the realm of technology to that of the modern environment.

1. Introduction

The term "smart materials" is difficult to describe in a manner that is free of ambiguity; however, these are typically conceived of as materials that respond to an outside physical or chemical stimuli in a controlled manner in order to carry out a task that has already been specified. Nevertheless, this definition is far too broad because virtually every material responds or reacts in some way to the kinds of stimuli described, and there is unquestionably a thin line that separates "smart" materials from other types of materials. Perhaps it is more helpful to think of the responding, also known as "smart behaviour," which occurs when a substance senses some stimulation from its surroundings and reacts in a way that is helpful, reliable, and reproducible. This type of response takes place when a material sensory perception some positive reinforcement from its environment [1, 2].

This report analyzes recent advancements in three subfields of smart manufacturing techniques: self-healing (SH) components, sensors and communication equipment and

sensing skins, and shape-changing materials. Self-healing materials are discussed first, followed by sensing and actuation materials and sensing skins, and finally shape-changing materials [3]. This study offers a comprehensive introduction to multifunction intelligent bio-based composites as well as the applications that can be developed using them. Natural resources of biopolymers such as cellulose, microbial cellulose, chitosan, collagen, cornstarch, polycaprolactone, and polylactic acid are introduced, and the active behaviors of these raw materials in terms of electrical and ionic working characteristics are discussed. The analysis also takes into consideration polymer matrices and gels as potential options. Recent years have seen a rediscovery of cellulose's potential as an active material, specifically in the form of electroactive paper (EAPap). This chapter describes the manufacturing and actuation basis of EAPap, as well as its three subareas, which may be broken down into capacitive EAPap, composite EAPap, along with their respective applications. In order to increase the usefulness of biopolymers even further, heterostructures of inorganic functional elements are being introduced by integrating graphene, carbon nanotubes, titanium dioxide, and tin oxide with biopolymers. These metal nanoparticles are also being included. Their dynamic responses in response to electrical or pH stimulation are also depicted here. Because natural polymers are bioactive, biodegradable, and capable of extensive chemical modification, there are many electrohydraulic implementations of multipurpose smart biopolymer composites that are possible. Some examples of these applications include biomaterials robotic systems, reconfigurable lens structures, and artificial muscles [4–6].

2. Two-Dimensional Smart Membrane Advancement

Artificial smart membranes based on the biosystems have garnered growing attention in the sectors of separation process, desalination, nanofiltration, healthcare, and environmental remediation due to their ability to govern mass transport and molecular conversion. Trade-off limits in polymeric membranes severely limit the implementation of intelligent membranes with porous structure and manipulability. In recent years, two-dimensional (2D) materials have inspired the development of 2D metal alloys smart membranes (2DSMs) capable of intelligent control under varied inputs [7, 8]. It is possible to create 2DSMs with numerous functional groups to vary their characteristics and produce adjustable interlayer spacings under varied external circumstances by modifying them through chemical modification. Using 2D materials as a foundation, we examine current developments in artificial smart membranes. 2DSMs are first described in terms of their conceptual design and practical implementation strategies. That is followed by the introduction and classification of the 2DSMs that have been produced and categorized by the sort of responsive stimuli that they respond to. Then there are the 2DSMs that have unique capabilities such as separation process, pressure transducers, blue energy generation, photoelectrochemical sensors, and biomimetic devices for harvesting energy from the blue. Finally, 2DSM development ideas and problems are examined [9].

2.1. Smart, Active, Biodegradable Food Packaging Materials. An overview of the advancements in food-safe recyclable smart, dynamic, and smart packaging by highlighting the problems and limits of each. The use of aromatic plants and plant extracts in the creation of food packaging that is both intelligent and active has been a great success. For intelligent and active packaging, anthocyanins (particularly) play a crucial role in signaling changes in food properties or enhancing shelf life. Research into smart biodegradable packaging, which differs significantly from its two predecessors that is a developing and promising field, has gained momentum in recent years. Improved regulated release of bioactive substances in active packaging, reduction of reliance on pH change, and development of ways to protect film integrity are all needed in intelligent packaging [10].

2.2. Green Materials for Bioanalysis Sample Preparation. It is difficult to analyze biological samples because of their complexity as well as the decreased level of target analytes. Therefore, a variety of bioanalytical sample treatment strategies have been presented, with a focus on microextraction methodologies. Using microextraction and smart materials in combination delivers ecologically friendly sample treatment options with better selectivity, sensitivity, and reuse. In addition to antibodies and antigens, other types of smart solid materials comprise aptamers, nanostructured polymeric materials, metal organic frameworks, and materials with restricted access. In contrast, bio-based fluids, biomolecules solvents, ion exchange, and polar aprotic solvents are among the smart liquid materials employed in bioanalysis sample preparation. A sustainable analytical chemistry approach has been used to analyze the synthesis and use of smart materials [11].

There will be a growing impact on human health and well-being from the development of materials and gadgets during the next decade. Smart materials are not any exception. Smart materials are the foundation for many new scientific innovations due to their unique characteristics of neural stimulation and autonomous activity. Smart materials, which include electromechanical polymers and shape-memory materials, have revolutionized the design process and broadened their range of applications. In robotics, for example, the transition from rigid-bodied robots to soft robots made of flexible materials has been swift. Bioengineering and mechanical engineering will need to work together to create new kinds of robots that can grow and alter shape and function as their physical and chemical environments change. Smart materials may also be used to create artificial systems that work in concert with biological species, blurring the line between the two. Innovative medical applications, such as physiological monitoring, minimally invasive surgery and medication administration, as well as human–computer interface and rehabilitation, rely on smart materials in addition to more traditional fields like environmental sensors and actuators. It is possible that future intelligent materials will be even more useful to humans due to

their increased functionality, controllability, and biocompatibility [12–16].

2.3. Smart Material Manufacture in Additive Manufacturing Utilizing IoT for Industry 4.0. There is a major impact of Industry 4.0 on mass customization and personalization. There is no way to mass produce the 3D printed work using additive manufacturing (AM) technology, despite the fact that they can produce personalized items. A further drawback is their incapacity to carry out production operations for large-sized products. Therefore, the industries are reluctant to use AM methods for commercial manufacturing. Research-based investigation intends to increase AM processes' dependability as well as mass 3D print advanced materials for businesses across the world by using Industry 4.0 technology. Industry 4.0 technologies are examined, and the advantages of using information technology (IT) in AM operations are examined. This is followed by an examination of IoT-integrated additive manufacturing processes and their impact on industry and material producers [17–19]. The documentation, on the other hand, is limited to theoretical work alone. Because AM automation is still a new idea, there is not much research material to work with. A reduction in manufacturing waste and a higher level of customer satisfaction may be expected when IoT is used in AM. As a result of AM's role in product invention and development, improvements are needed to make the technology more user-friendly [20].

3. Types, Qualities, and Applications of Smart Materials

The immediate development of smart materials for use in fields such as self-sustaining wireless communication, self-tuned vibrating energy recovery devices, seismic applications, and other similar fields is a necessity at this point in time. These kinds of advanced materials have the ability to be used in the construction of smart buildings and smart materials. Piezoelectric materials, polymer materials alloys, electrorheological fluid, and magnetorheological fluid are examples of smart materials that respond to external stimuli. Smart materials form a diverse group of materials that may be utilized for vibration control. There is a considerable degree of parallelism that can be drawn between biological systems and intelligent materials [21–23]. For example, piezoelectric hydrophones that show a resemblance as that of ears with which fish sense piezoelectric material, substances that can cause with an amalgamation of electromechanical coupling, shape-memory materials with the potential to recollect the original shape, techno fluids with deceitful viscosity strength, and so on are some examples. This potential drew the attention of researchers and gave them the opportunity to consider and incorporate a wide variety of additional technologies into compact, multifunctional packages. Their end goal is to develop more advanced and sophisticated materials and to revolutionize the field of smart materials research. In the beginning of this review, a concise synopsis of the previously described stimulus-responsive smart materials is discussed, and then, after that, a detailed explanation of some of the biomaterials is presented [24].

4. Smart Facade Material Selection Based on Sustainable Development Goals

Structures take up huge quantities of energy and damage the surrounding environment in a variety of different ways. The building's facade is a component of the building's architecture that has the potential to significantly contribute to the reduction of energy consumption and the amelioration of the building's adverse impacts on the surrounding environment. There have only been a relatively small number of research done on the aforementioned topics, despite the fact that the use of intelligent materials on the facades of buildings can significantly aid in accomplishing the aims indicated. In addition, the investigations that have been done so far have only looked at a small number of intelligent materials all at once. As a result, the purpose of this investigation is to carry out a more comprehensive analysis, locate and rank the smart materials that would work best for building facades in Shiraz, Iran in accordance with the Sustainable Development Goals (SDGs) [25–28]. The Friedman experiment and Analytical Hierarchical Analysis (AHP), both available through the software packages SPSS and Expert Choice, were utilized in the process of analyzing the data. According to the findings that were obtained, "Photovoltaic materials," "Thermochromic materials," and "Photostrictive materials" were the most effective options for implementation onto the facade of a structure. The findings that were collected from this research can assist the construction sector in moving toward a more sustainable future [29].

5. Smart Hybrid Nickel–Titanium Materials for the Auto Industry

Intelligent hybrid materials are increasingly being employed in a wide range of sectors because of their smart properties. Innovative composite membranes change their properties in a controlled way in response to an external stimulus. Pressure, pH, temperature, as well as electric and magnetic forces, may all be detected by smart materials. Combining NiTi alloys in a certain ratio results in a "smart material," which has the properties of a smart alloy [30–33]. The biomedical, aerospace, automotive, and electrical and electronic sectors can all benefit from the usage of NiTi alloys. However, the automobile industry, which is the focus of this chapter, employs them the most. Suspension systems, fender systems, wing mirrors, windscreen wipers, door knobs and safety lock units, turbines, controllers, and batteries modules may all utilize smart materials in automotive vehicles. Furthermore, NiTi may be employed in other smart materials, such as shape-memory alloys, for the automotive sector. Additionally, magnetostrictive, piezoelectric, and intelligent polymeric materials are all examples of smart materials. Smart-hybrid materials and NiTi advanced materials in the automobile sector are the focus of this section [34].

6. Cardiovascular Smart Materials

The field of "Smart materials," which are rising in popularity and have a great deal of promise for use in a variety of medical contexts, includes the category of "shape memory alloys." These materials are very well-suited for use in the design of implants due to the fact that they are capable of undergoing deformation while still maintaining their initial shape following the removal of any external stimulus. This article focuses on the use of magnetization superalloys (FSMA) and piezoelectric material materials in the design of cardiovascular devices, particularly those that are most likely to be appropriate for young heart patients. In the presence of a magnetic field, certain materials undergo morphological transformations. Materials that have a crystal structure that is unlike any other are now under consideration for use in the creation of stents and coronary applications. This study reveals how stents constructed of FSMA may be magnetically triggered and finds uses for them in peripheral and arterial heart illnesses. As a result, this work replaces the present technology used for stents [35].

7. Advanced Textile Materials

A trending area of discussion in engineering is the development of intelligent textiles through the application of novel materials. These materials include functionalized nanoparticles injected into the fiber matrix as well as unique or modified polymers that are employed in the creation of smart filaments, yarns, and textiles. Because of the variety of capabilities that a fabric substrate is capable of acquiring and the ways in which it may interact with its wearer, "smart textiles" have emerged as a material category that is both significant and innovative in the textile industry [36, 37]. Due to the contemporary significance of the topic, the purpose of this review is to present, in a condensed form, the basic aspects of a smart textile, as well as its categories, various applications, and highlight the primary materials used in the preparation of intelligent textiles. In addition, the scientific contributions that we made on this subject were taken into consideration [38].

8. Smart Materials for Aqueous Contamination

The amount of freshwater accessible is gradually decreasing as the population is rising exponentially. The major source of environmental contamination is the generation of a considerable volume of wastewater each year. The problem of water contamination compelled researchers to devise new and more effective methods of purifying water quickly and cheaply. It is clear that the adsorption technique has had a significant impact in the treatment of wastewater. Smart adsorbent materials, such as light, temperature, pH, and other environmental cues, have recently provided a new avenue for cleaning coolants in industrial settings. It is becoming increasingly common for scientists throughout the world to focus on producing smart adsorbents capable of extracting contaminants such as hazardous metals, textile dyes, and other organic substances from wastewater. In addition to their great selectivity, these smart adsorbents demonstrate effective regeneration without the use of a separate solvent for the regenerating process. New carbon-based materials for wastewater treatment are examined in this review paper for their features and performance efficiency. Here, sensory perceptions carbon-based materials with their binding efficiencies are described, detailed discussion on discrimination, self-healing, self-cleaning features, limits, and the potential for future study [39].

The fire prevention and safety are of fundamental importance in modern civilization, yet they have been a global problem. Massive deaths and irreversible property losses are caused by frequent fire catastrophes, which have a severe influence on the worldwide ecosystem. Intelligent active fire protection substances and detectors that combine classic passive flame-retardant tactics with extreme fire-alarm response have recently been an emerging issue. However, an analytical and comparative analysis of these fire-warning systems is still lacking. Passive flame-retardants, standard-active detectors, and next-generation smart sensors are all included in this review, as well as thermal properties of combustible materials. There is a thorough evaluation of smart warning materials' concept generation, synthesis, characterizations, and production methods. Later, the effectiveness and applications of various fire-alarm sensor systems, such as resistance-type, phase/shape-change, thermoelectric response and color-change observation were evaluated and compared. Finally, some of the most pressing issues linked with active fire-protection materials/sensors are discussed, followed by a look at the future [40].

9. Fluorescent Smart Materials: A Detailed Survey

Increasing attention has been paid to the development of microbially fluorescence-smart materials and associated multifunctional applications in recent years. It is possible to create a large variety of useful products from cellulose, one of the world's most widely available and inexpensive basic materials. This article outlines the process of turning cellulose into luminous smart materials by chemical modification [41]. It also discusses the fabrication of fluorescent materials into films and fibers as well as carbon dots and hydrogels that can be used in a variety of sensing applications, including bioimaging of toxic metals and anions as well as pH and bioimaging of common organic solvents, as well as for fluorescence printing and coating and anti-counterfeiting applications. To conclude, the ligno-luminescence sensors are discussed in terms of forthcoming research, problems, and potential solutions. Chemical engineers, biochemists, and chemists interested in developing ligno-fluorescent materials for a wide range of applications may benefit greatly from this review [42].

10. Sustainable Materials

Advances in green technology have made it more feasible to utilize ecologically friendly materials in building. It is possible to reduce the embodied energy and maximize the usage of renewable resources by using recycled industrial waste.

The success of green construction projects depends on the use of cutting-edge technology. Many green building solutions with heat dissipation, wastewater systems and energy efficiency are included in this study. Also included is a solar powered cooling system [43, 44]. BIM and ontology are utilized in green building to coordinate multidisciplinary operations. The SWRL and OWL models were based on the Jess logic program and were coupled to increase building efficiency. Materials derived from industrial waste that are environmentally friendly contribute to a reduction in the amount of carbon dioxide emitted into the atmosphere. Activators are used to enhance the material's strength, workability, and density. There are several external elements that influence how smart materials work. Structural faults may be detected using the Electrical Impedance (EMI) method, which uses smart materials. It is possible in smart homes to utilize technology to regulate energy use. Examples of smart materials utilized in smart, sustainable urbanization include polymeric metals, fiber optics, piezoresistive, magnetoreheological fluids, and electrorheological fluids. Construction costs were lowered because to the IoT's (IoT) technology ability to collect construction data. In order to help India accomplish its long-term sustainability goals, the study will make recommendations on the best procedures and materials to use in the country [45].

11. Machinability of Smart Materials

Even if in the future the power source of automobiles changes from an internal combustion engine to an electric motor, transmissions are still necessary for the development of maximum speed, quietness, and fuel economy. This is true even if the future power source of automobiles is an electric motor. After the hot forging process, the machinability of the material that will be used in vehicle transmissions is being improved through the application of a heat treatment procedure that we are researching. In the past, following hot forging, the material's latent heat would simply be vented into the surrounding air. By cooling the material after hot forging, we were able to successfully regulate the heat that was stored within the forged material, which allowed us to successfully impart machinability onto the material.

12. An Overview of Smart Composite Materials

Over the past decade, attention in intelligent (smart or responsive) materials, especially composites, has grown. In sensing and actuation, the ability to manipulate multimaterial characteristics using external inputs is intriguing. Smart composite materials may be developed (and applied) to multiple length scales, from huge structural components to wearable technological gadgets [46]. This section includes chapters on synthesis processes for smart composites, key components connected to the single architecture or technology, and application domains based on stimulus they react to. Each smart composite material's difficulties and potential are also discussed [47]. Keeping food safe from spoilage, infection, or waste is a major concern whether it is stored, transported, or sold throughout the world. In order to address these issues, different packaging substances are being created. Antimicrobials and antioxidants are being included into active packaging materials in an effort to improve the shelf life of food [48]. Food quality, ripeness, and safety may be monitored in real time using smart packaging materials. Photoluminescent or photocatalytic materials are being used to create these photoactivated food packaging. Sensors based on photoluminescence can be used to detect changes in food packaging's environment, such as harmful gases, cleanliness, and the presence of certain bacteria. Devices based on photocatalysis can be utilized for color indicators, microbial inhibition, and gas removal. Photosensitive polymers in intelligent and proactive food packaging are the subject of this review, which highlights the most recent findings [49, 50]. Prepared materials for food packaging are examined, as are the principles of operation and uses of photoactivated materials, along with the possible benefits and drawbacks of each. The information given might lead to greater study into the development and deployment of revolutionary intelligent and proactive food containers in the food sector [51].

13. Conclusion

The technology behind smart materials is a very diverse topic of study:

(i) Beginning with the study of scientific fields such as physics and chemistry, as well as mechanics and electronics, computing, and electronics, it then moves on to include applied sciences and engineering fields such as aeronautics and mechanical engineering

(ii) Even while research into smart materials is advancing at a rapid pace, the use of advanced materials in engineering systems appears to be developing at a glacial pace

(iii) In the current environment, the utilization of intelligent materials and structures is among the most promising technological developments in terms of lifespan efficiency and increased dependability

(iv) The ultimate goals of study in this subject are to understand and regulate the chemical and morphology of any new materials. Doing so is vital to the manufacture of high-quality smart materials and is one of the discipline's ultimate objectives

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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