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Investigation of the Properties of Smart Polymers and their Application

Abstract

Today's rapidly developing technology, new and interesting materials are emerging. One of these materials is smart polymers. Smart polymers are polymer materials with special molecular structures that respond to different external effects and change shape. These polymers can change in shape, volume, or other properties in response to environmental changes. The most striking feature of smart polymers is their ability to respond directly to environmental stimuli. The shape-changing abilities of smart polymers usually occur depending on environmental factors such as heat, humidity, pH value, light or electricity. This occurs when the bonds within the polymer molecules undergo structural changes. The areas of use of smart polymers are quite wide. They play an important role in many industries such as medicine, textile, automotive, electronics and energy. Interest in smart polymers, which are frequently used in the development of drug delivery systems, biomaterials and smart materials, is increasing. Taking these into account, the presented review provides information on smart polymers, their properties and application areas.

Keywords: *smart polymers, properties, application, drug delivery systems*

Introduction

The ability of materials to sense and respond to changes in their environment has captivated researchers for years, driving the innovation of smart materials. Among these, smart hydrogels with responsive properties and improved mechanical characteristics have become a major area of research and have found applications across numerous fields (Moses et al., 2024).

Research

In order for a material to be classified as a smart material, the material must have the ability to respond to environmental stimuli (heat, temperature, mechanical and magnetic) and change its performance or properties accordingly, the material's responses to stimuli must be explainable, understandable and predictable, it must be able to exchange energy (emitting light, generating electricity and being able to change energy) and it must have reversibility (the change in the quality and phase of the material and this change can be reversed) (Aguilar et al., 2019; Bahl et al., 2020). Smart materials are an attractive class of materials for advanced applications today due to the advantages partially mentioned above (Aguilar, 2007). Materials that can change their properties according to the environment and have sensory capabilities, can automatically repair themselves, can change shape with heat or can instantly change phase when a magnetic field is applied, piezoelectric materials (sensors and actuators), shape memory alloys, magneto-rheological materials and electro-rheostat materials are examples of applications where smart materials are used (Bahl et al., 2020). Although they have many applications, there is no widely accepted classification system for the classification of smart materials that is used academically and commercially. As new areas of use emerge, these materials are included in the smart material class. Today, thermoelectrics, multiferroics, magnetocaloric materials, magnetorheological and electrorheological fluids, shape memory materials, thermo and light sensitive polymers have been added to the smart material class. In addition, polymer gels that can change their volume hundreds of times with a small change in

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external conditions such as temperature, solvent composition, pH are also considered smart materials (Tüylek, 2019). The features that can be given as examples for a polymer to be defined as a smart material are; reacting to environmental stimuli (external factors such as temperature, humidity, pH, light intensity, electrical or magnetic field, etc.), changing its color or transparency, becoming conductive or water permeable, or responding to this reaction by changing its shape. The response rate of smart polymers can be controlled by the intensity of functional stimuli. The change and control of the physicochemical properties of smart polymers are preferred for their use in different applications and for the regulation of desired properties (Meng & Li, 2013; Zhuang et al., 2013; Peng et al., 2011; Derya & Idris, 2023).

There is no standard definition used to describe smart materials. The most widely accepted definition for smart materials is that a material changes one or more of its properties in a predictable and useful way in response to an external stimulus (Chung et al., 2012). The term smart materials, also called intelligent materials or active materials, refers to a group of materials with unique properties (Qiu & Park, 2011). According to Addington and Schodeck (Nakayama et al., 2006) whether a material is a smart material or not:

- Immediacy: Responding to stimuli in real time
- Temporality: Responding to multiple environmental conditions
- Self-activation: Intelligence is not external to the material, but internal to it
- Selectivity: Responses to stimuli are discrete and predictable
- Directness: Local activation of responses to stimuli can be distinguished by examining.

Smart Polymers

Smart polymers have gained increasing attention and have seen significant advancements in recent years. These adaptable materials are capable of changing their properties when exposed to different external stimuli. The foundation of smart polymer research was laid in the late 1950s when J. F. Katchalsky and P. Eisenberg created the first synthetic hydrogel (Kuhn et al., 1950). This hydrogel demonstrated the ability to swell or contract depending on the pH and ionic strength of the surrounding solution. This breakthrough marked the beginning of smart polymer studies, which have since evolved to encompass a wide range of applications.

Smart polymers are specialized materials with unique molecular structures that react to various external influences by altering their shape. These polymers can adjust their shape, size, or other properties in response to environmental changes. Their most remarkable characteristic is their capacity to respond directly to stimuli from their surroundings. The ability of smart polymers to change shape is typically triggered by environmental factors such as temperature, humidity, pH levels, light, or electrical signals. This behavior occurs due to structural changes in the bonds within the polymer molecules. For instance, a smart polymer subjected to heat may expand or contract as the temperature rises (Arash Fattah-alhosseini et al., 2024).

Smart Polymers Types

Considering the different usage and application areas and polymer types, it is quite difficult to classify smart polymers. However, considering the scientific studies and usage areas conducted to date, it is possible to examine smart polymers under four basic headings as shown in Figure 1. Accordingly, smart polymers can be classified as smart polymeric gels, shape memory polymers, self-healing polymers and stimuli-responsive polymers. Although such a classification method was chosen to make the subject more understandable, smart polymers are actually materials that have very strong interactions with each other and some similar properties.

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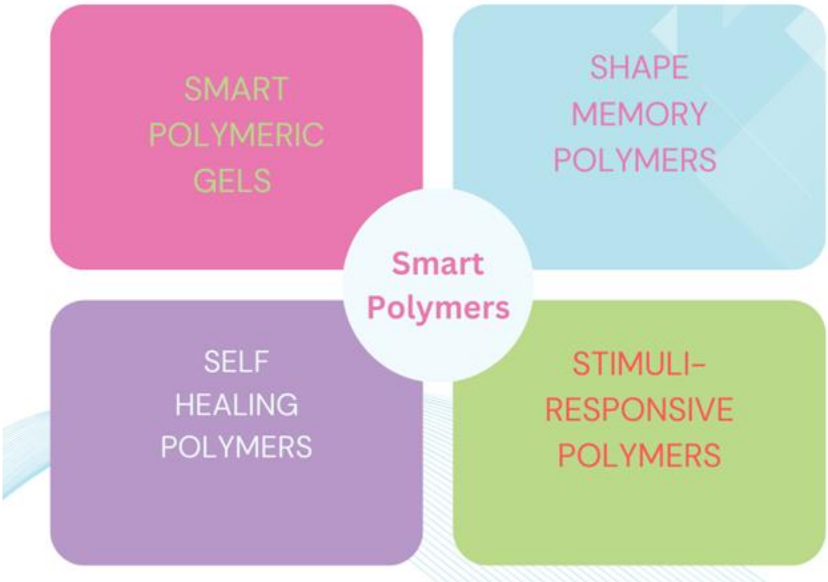
Figure 1
Smart Polymers Types



Smart Polymeric Gels

Hydrogels are polymers with a three-dimensional network structure that can be physically or chemically cross-linked. Hydrogels can also be defined as three-dimensional (3D) natural or synthetic polymeric networks that absorb large amounts of water, up to thousands of times their dry weight in water, without dissolving the polymer due to their hydrophilic but cross-linked structures (Yang et al., 2013). In order for a gel to be defined as a hydrogel, it must be able to absorb a t least 20 % of its own weight in water (Priya et al., 2014). In general, hydrogels do not dissolve when they interact with water and swell by taking in the solvent. This is due to the presence of hydrophilic groups in the polymer chain and the porous structure in the form of a network (Ganesh et al., 2014). With their water retention capacity, soft and flexible structures, hydrogels are similar to living tissues. The most important advantages of hydrogels are that they are permeable to water-soluble substances, compatible with the human body, soft and have low friction when swollen with water, can be used in drug delivery systems, and have high water retention capacities. In addition, the weak mechanical strength of hydrogels restricts their use in areas requiring strength (such as bone tissue) (Shalla & Bhat, 2021). The areas of use of hydrogels can be listed as contact lenses, artificial tendon materials, biosensors, surface coating materials, artificial muscle, artificial skin, drug delivery systems, aesthetic surgery, smart irrigation systems in agriculture, heavy metal removal, etc. (Yang et al., 2013; Bauri et al., 2018; Arash Fattah-alhosseini et al., 2024). Smart hydrogels are defined as hydrogels that undergo sudden reversible volume phase transitions or sol-gel phase transitions in response to small external changes (stimuli) in environmental conditions. Compared to traditional hydrogels, smart hydrogels respond faster to these reactions. There are many different classification methods for smart hydrogels in the literature. Polymers with responsive systems exhibit significant property changes when exposed to specific stimuli. These stimuli can impact the polymer chains by altering attributes like hydrophilicity, shape, solubility, degradation, or even triggering bond cleavage (Aguilar & San Rom, 2019). Such transformations directly affect the structural behavior of the polymers. The stimuli can be classified as chemical, physical, or biological. Physical stimuli, such as temperature, light, or electrical signals, often influence the motion of polymer chains. In contrast, chemical stimuli like pH, ionic strength, or redox conditions modify the interactions between polymers and solvents or other polymeric structures. Biological stimuli, including enzyme activity and glucose response, involve molecular processes such as enzyme catalysis or receptor-mediated molecule recognition (Shalla et al., 2021; Aguilar & San Rom, 2019; Bauri et al., 2018; Arash Fattah-alhosseini et al., 2024; Wei et al., 2017).

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Polymers that respond to more than one type of stimulus simultaneously are referred to as dual stimuli-responsive polymers. Stimuli-sensitive smart hydrogels Stimuli-responsive polymers are smart polymers that respond to external parameters such as temperature mechanical stress magnetic/electric field humidity fluctuations, pH some small molecules (CO_2 etc.) and some biomolecules (glucose etc.). The response to external stimuli can be a physical or chemical change in the shape, color and solubility of the polymer. Such smart polymers have potential applications in many fields of biology and medicine. For example; they are widely used as sensors and biosensors in controlled drug delivery in environmental remediation and in chemo-mechanical actuators (Derya & Idris, 2023). Light sensitive smart hydrogels Apart from temperature, studies are also being conducted on light and pH sensitive types of stimuli responsive polymers. For example; pH sensitive polymers with ionizable functional groups have the ability to donate or accept protons depending on environmental pH changes. Some common examples are acrylic acid (AAc) (Connal et al., 2008; Kim et al., 2004) and N,N-dimethylaminoethyl methacrylate (DMAEMA) (Liu et al., 2008; Zhang et al., 2017). Light sensitive monomers can also be used to produce materials that exhibit both temperature and light sensitivity. A common example is azobenzene (Gohy & Zhao, 2013; Jochum & Theato, 2013). In most cases, the response of these polymers occurs by light-induced isomerization or light-induced ionization of the light-sensitive molecules incorporated into the polymer. Similarly; Bioresponsive systems can also be used to produce polymers that have the ability to respond to stimuli naturally present in biological structures, such as enzymes and glucose (Derya & Idris, 2023). pH-sensitive smart hydrogels pH-sensitive polymers are polyelectrolyte structures containing ionizable groups in their backbone structures. They have the ability to change their volume in response to a change in the pH of the environment they are in. They can accept or release protons in response to environmental pH changes. They can detect very small pH changes (up to 10-5 pH) within minutes and swell significantly with high sensitivity (Riaz et al., 2019; Zhao et al., 2018). The degree of ionization (pKa or pKb) of a pH-sensitive hydrogel changes with changes in pH. This change in the net charge of the polymer chain causes the hydrogel to undergo volume deformation due to electrostatic repulsive forces, which creates a large osmotic swelling force. The main phenomenon governing the process is the ability to dissociate and associate hydrogen ions due to pH changes in the aqueous environment. Since this protonation–deprotonation is reversible, the hydrogel swelling–shrinkage can be easily reversed by changing the pH of the ambient solution (Derya & Idris, 2023). Natural pH-responsive polymers, as well as multi-responsive polymers, have garnered significant attention in recent years (Dai et al., 2008).

Application of Smart Polymers

Smart polymers are a type of material that has developed rapidly in recent years and provides many advantages. These polymers can behave in a special way by reacting to environmental conditions or external effects. With these features, smart polymers used in many areas have many advantages. One of the primary advantages is that smart polymers have a shape memory feature. In other words, they can return to their original shape if they are deformed. This feature is very useful in many industrial applications. For example, smart polymers used in the healthcare sector are used in the production of prostheses or orthoses, providing patients with a better quality of life. Another advantage of smart polymers is their ability to respond to various stimuli. They can perform the desired function by responding to various stimuli such as heat, pH, electrical stimulior chemical substances. Thanks to these features, smart polymers can be used in many areas such as drug delivery systems, controllable coatings or sensors. Another advantage of smart polymers is their diversity in areas of use. These polymers are used in many sectors from the textile industry to electronics, from the automotive sector to energy storage systems. For example, smart polymers used in the automotive sector can increase fuel efficiency and save energy by improving the aerodynamic properties of vehicles.

Smart polymers are a special class of polymers that can respond to chemical or physical stimuli. The working principle of these polymers is due to changes in their molecular structure. Side chains, which are usually attached to natural or synthetic polymer chains, undergo conformational changes

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when exposed to various effects. As a result of these changes, polymer molecules respond in a specific way and perform the desired function. The working mechanisms of smart polymers include various stimuli such as thermal, pH, light, electrochemical and magnetic interactions. For example, thermal stimulation occurs when polymers respond to heat. In this case, polymer molecules undergo conformational changes and change shape in a specific way when heated. Similarly, polymers can expand or shrink by undergoing proton exchange reactions with pH stimulation (Derya & Idris, 2023).

Smart polymers are capable of delivering drugs to targeted cells or tissues within the body. Similarly, pH-responsive polymers can be utilized to develop pH-sensitive hydrogels that release drugs at predetermined pH conditions. Smart polymers enable the development of targeted drug delivery systems, allowing medications to be delivered directly to the specific cells or tissues in need. This approach enhances treatment efficacy while minimizing drug side effects. Furthermore, smart polymers can be utilized to design implantable devices that respond to physiological changes, such as variations in temperature or pH (Derya & Idris, 2023).

Drug Delivery Systems – When an enzyme is immobilized with smart hydrogels, the products of the enzymatic reaction can trigger the phase transition of the gel. Thus, in the presence of the substrate, it is possible to convert the chemical signal into an environmental signal (e.g. pH change) and then into a mechanical signal called swelling or shrinkage of the smart gel. Such systems are used in biomimetic actuators on the one hand and contribute to the development of drug delivery systems on the other. The development of a glucose-sensitive, insulin-secreting system for the treatment of diabetes has long been a problem for biomedical engineers. To solve this problem, smart polymer systems are used. An example of such systems is the development of drug delivery systems where drug distribution is free in response to a chemical signal (insulin release in response to increasing glucose concentration). Since the diffusion of the drug through the polymer varies according to the state of the gel, the swelling or shrinkage behavior of smart polymers in response to small changes in pH or temperature can be successfully used to control drug release (Bengi Ozkahraman, 2014).

Smart polymer-based materials, by intelligently responding to external stimuli, offer various applications and enable their use in modern pharmaceutical research (Avinash Kumar et al., 2024). The intelligent behavior of these polymers enables their application in many fields, including drug delivery, tissue engineering, tissue repair, and various sensors (Deepti Bharti et al., 2023). The stimulus-responsive properties, shape memory behavior, and self-healing capabilities of smart polymeric materials are crucial characteristics for applications in tissue engineering, medical devices, and cell therapy. Smart polymeric materials offer significant potential for advancing precision medicine by addressing the “temporal,” “spatial,” and “personal” dimensions. To meet the temporal aspect, these materials enable the creation of innovative biodegradable or biocompatible scaffolds. Their design also supports the development of injectable self-healing hydrogels and controlled-release drug delivery systems, which are essential for achieving spatial precision. Moreover, 3D printing with bioinks containing a patient’s stem cells serves as a key fabrication method, integrating smart polymeric materials with cell therapy to fulfill the personal dimension. Overall, the advancement of smart polymeric materials is pivotal in uniting these three aspects to support cell therapy and precision medicine (Hung-Jin Huang et al., 2019).

The evolving needs of society call for innovative products that enhance daily life. In polymer chemistry, this demand is met by smart materials. Advancing this area of polymer science enables better alignment with societal requirements. The demonstrated applications of these materials highlight their potential to revolutionize numerous industries. The growing interest among scientific communities in this field has been evident for many years (Alicja Balcerak et al., 2024).

Conclusion

Recently, smart polymers have been widely applied in many fields, including drug delivery, tissue engineering, tissue repair, and various sensors. In particular, smart polymers in drug delivery systems show exceptional potential in achieving controlled and targeted profiles, ensuring drug delivery to specific receptors, and minimizing off-target effects. Smart polymers are a class that differs from ordinary polymers by their rapid change in their physico-chemical state in response to the external environment. The main issue here is their tunable structural and functional potential. The classification of these polymers is based on different environmental effects. This includes temperature, pH, light, enzymatic reaction, pressure, electric/magnetic field, etc. İncludes. Note that the properties of these polymers can be changed during polymer synthesis by changing the chain structure, and at the same time, smart polymers have the ability to strongly react to relatively weak external influences.

Thus, the synthesis of smart polymers depending on various factors and their wide application in industry have been studied.

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