Smart Polymers: The Future of Adaptive Materials

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***Abstract*—When exposed to external stimuli like temperature, pH, light, or mechanical stress, smart polymers—also referred to as stimuli-responsive polymers—can reversibly change their mechanical, chemical, or physical characteristics. Because of their distinctive adaptive behaviors, these polymers are especially adaptable for use in medication administration, soft robotics, biomedicine, and environmental sensing. With a focus on the function of molecular structure and environmental interactions, this research investigates the fundamental processes of stimulus responsiveness. The design and synthesis methods for smart polymers, including as functional group modification, self-assembly, and reversible crosslinking, are covered in depth. Key application areas are discussed, including the use of smart polymers in the development of controlled release systems, shape-memory materials, and responsive hydrogels. Along with potential future paths for maximizing polymer responsiveness and multifunctionality, the difficulties associated with stability, scalability, and biocompatibility are also examined. Smart polymers have the potential to revolutionize a variety of sectors by combining developments in material engineering, nanotechnology, and polymer science. They will also solve unmet demands for sustainable solutions and adaptable systems. The purpose of this article is to inspire ideas that close the gap between lab research and practical applications by offering a thorough review of the most recent advancements in smart polymers.**

***Index Terms*— Smart polymers, Stimuli-responsive polymer, Adaptive materials, Drug Delivery, Responsive hydrogels, Shape-memory materials.**

I. INTRODUCTION

The innovative uses of smart polymers in pharmaceutical sciences, particularly in innovative drug delivery methods. These intelligent materials, which are inspired by the adaptability of nature, change their structure and properties nonlinearly in response to even the smallest external inputs. Smart polymers increase drug targeting, bioavailability, patient compliance, and gene therapy.

Characterized by their stimuli-responsive behavior, these materials respond to a variety of physical, chemical, and biological inputs, such as temperature, electric or magnetic fields, deformation and pH enzymes, by going through significant changes that can include disintegration, swelling, or contraction.

Smart polymers are a class of polymers that can respond to environmental stimuli and change their properties. Other names for them include intelligent polymers and stimuli-responsive polymers. The complex materials known as polymers, or macromolecules, are made up of repeated micro molecule subunits (Aguilar MR, Smart polymers and their applications. Woodhead publishing, 2019). Originating from the Greek terms & poly, which means “many” and metros which means “part” or unit, polymers have been used. Therefore, using their advantageous qualities, like mechanical strength and biocompatibility, since ancient times (Fattah-alhosseini A, A review of smart polymeric materials: Recent developments and prospects for medicine applications, 2024).

By creating customized biomaterials for particular requirements, the invention of synthetic polymers transformed medicine. Polymer science breakthroughs in recent years have opened up new medical uses (Mahajan A, Smart polymers: innovations in novel drug delivery, 2011). Significant research has been paid to stimuli-responsive polymers, sometimes known as smart polymers. Developed by materials react to stimuli such as pH, temperature, and light to adjust to changes in their surroundings (Almeida H, Temperature and pH stimuli-responsive polymers and their applications in controlled and selfregulated drug delivery, 2012).

Smart polymers are made to react to certain stimuli by undergoing sudden, reversible phase or property changes as a result of structural modifications, according to IUPAC (Priya James H, 2014). In response to external stimuli such as temperature, stress, or magnetic fields, these polymers can alter their chemical or physical properties. These reversible changes can be seen in macroscopic properties like conductivity, form, or solubility.

Intelligent polymers exhibit characteristics such as instantaneous viscosity changes in reaction to electrical currents, allowing them to sense and adjust to their surroundings (Aguilar MR, Smart polymers and their applications, 2019). Among the main benefits of smart polymers are increased medication stability, therapeutic window management, patient compliance, and manufacturing convenience. Smart polymers also have strength, resilience, flexibility, biocompatibility, and ease of coloring and sculpting.

II. PROPERTIES OF SMART POLYMERS

A. Responsive
Smart polymers can respond to a variety of factors, such as temperature, humidity, pH, chemical compounds, light, and electricity.

B. Reversible
Reversible macroscopic changes in smart polymers allow the system to revert to its initial condition upon removal of the trigger.

C. Biocompatible
Smart polymers are biocompatible, strong, resilient, and flexible.

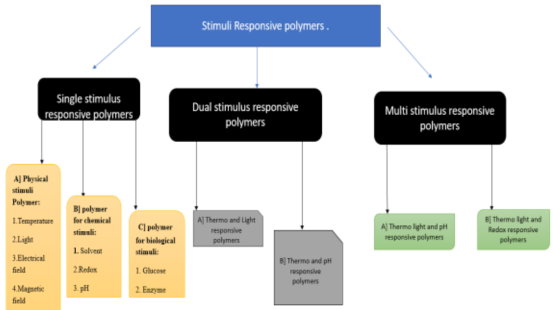
D. Easy to Manufacture
Smart polymers are easy to manufacture.

E. Drug delivery carriers
Smart polymers are a popular choice for drug delivery carriers. Smart polymers are effective at delivering nutrients to cells.

F. Shape Memory
External stimuli can cause shape-memory polymers (SMPs) to change in size, shape, stiffness, and strain.

G. Hydrogels
Large volumes of water can be absorbed by hydrogels, which are three-dimensional polymers that retain their dimensional stability.

III. CLASSIFICATION



1. PHYSICAL STIMULI POLYMER:-

A] Tangible stimuli One type of polymer is temperature-sensitive:

These kinds of polymers are temperature sensitive, changing their microstructure in reaction to variations in temperature. Notably, their solution experiences phase separation and changes from an isotropic to an anisotropic state at a threshold known as the critical solution temperature (CST).

Some polymers exhibit lower critical solution temperatures (LCST), changing from monophasic to biphasic and changing their behaviour from hydrophilic to hydrophobic, while Others exhibit upper critical solution temperatures (UCST), as the temperature increases, transitioning from biphasic to monophasic (Aguilar MR, Smart polymers and their applications, 2019). Because of this characteristic, LCST polymers are frequently used in drug delivery systems.

Three types of temperature-sensitive polymers are:

1) Shape memory content

2) A liquid crystal substance

3) The third and primarily researched kind.

Temperature-sensitive polymer mechanism:

The existence of a lower critical solution temperature (LCST), over which aqueous insolubility takes place, is the cause of the temperature-dependent solubility phenomenon in smart polymers. This behavior is shown by polymers that form hydrogen bonds with water, which makes them useful for DNA sequencing, smart medication delivery, and cell patterning. Customized temperature responsiveness is possible by modification of the monomer’s chemical makeup (Meléndez-Ortiz HI, 2016).

1) Material for shape memory:

Thermoplastic elastomers with a dual-phase structure that includes a hard segment with a high glass transition temperature are known as shape memory materials.

2) Liquid crystal substance:

There are two different phases in this polymer: an isotropic rubbery phase and a liquid crystalline phase. In particular, the nematic liquid crystalline blocks that make up its main chain have an extended shape when in the liquid crystalline phase. The isotropic phase is reached by these blocks when heated.

3) The third and largely researched kinds:

When the temperature varies, thermos responsive polymers experience liquid-liquid phase transitions [13]

These polymers remove the toxicity of organic solvents, making them a useful substitute for conventional systems. The low biocompatibility of thermosensitive polymeric systems is a major disadvantage.

B] Polymer that responds to field:

Field-responsive polymers have an advantage over conventional stimuli-sensitive polymers in that they respond to electric, acoustic, or electromagnetic fields.

Key benefits:

Rapid reaction times, anisotropic deformation from directed stimuli, and controlled drug release rates that may be adjusted via signal modulation are some of the main advantages. These characteristics allow for precise control over medication distribution and polymer behaviour. It is made up of two kinds of polymers: a) light-sensitive polymer and b) electric/magnetic-sensitive polymer.

a] Light-sensitive polymer:

Water solubility, biodegradability, and biocompatibility are desirable characteristics of light-sensitive polymers. When stimulated, they facilitate instantaneous sol-gel transformations [16]. Moreover, light can cause polymers applied to the skin or other external body surfaces to undergo phase changes [17]. Interestingly, smart polymers that are responsive to visible light create aqueous two-phase systems that have potential for industrial bio-separation.

Light-sensitive polymer mechanism:

Macromers include:

Hyaluronic acid and other polysaccharides, PEG, PEO-PPO, and poly (vinyl alcohol), or proteins like albumin are examples of at least one water-soluble area. Polylactic acid, polyglycolic acid, poly(anhydrides), poly (amino acids), or poly-lactones are examples of at least one biodegradable region. A minimum of two areas that are susceptible to polymerization by free radicals, such as acrylates, diacrylates, methacrylates, or other biocompatible groups.

Free radical initiation is how polymerization happens under:

- UV light, or ultraviolet light
- Excitation by visible light
- Thermal energy

Ethyl eosin and derivatives of acetophenone are good agents for generating free radicals. Camphor quinones are light-sensitive polymers that are further divided into two categories based on wavelength.

1) ultraviolet light polymer

2) The Polymer of Visible Light

Polymers that are sensitive to visible light and UV light both cause phase changes. In contrast, visible light-sensitive polymers are more commonly used and typically favored than.

1] Ultraviolet light: The polymer that is sensitive: -

UV-sensitive light polymers react to UV radiation by forming polymer gels and displaying phase transition behavior. Osmotic pressure causes these gels to swell intermittently at constant temperature, returning to their initial state when the stimulus is removed. Before being injected into target areas, thermosensitive diarylated Pluronic F21 solutions are specifically exposed to UV light (James HP, Smart polymers for the controlled delivery of drugs– a concise overview., 2014). UV-sensitive light polymers eliminate the requirement for postinjection UV cross-linking equipment and minimize tissue injury by forming stable hydrogels upon injection.

2) Polymer of Visible Lights:

Photosensitive compounds like chromophores are added to hydrogels to create visible light-sensitive hydrogels. Chromophores produce localized heat in response to light absorption, raising the temperature of the hydrogel. It is noteworthy that the temperature increase is directly correlated with the light intensity and chromophore concentration (Fattah-alhosseini A, A review of smart polymeric materials: Recent developments and prospects for medicine applications, 2024).

C] A polymer responsive to electric fields:

Due to their high concentration of ionizable groups, electric field-sensitive polymers change their physical characteristics in response to minute variations in electric current. The electric current causes pH shifts in certain polymers, which break the hydrogen bonds that hold polymer chains together, converting electrical energy into mechanical energy. These polymers change shape in response to an electric field, aligning themselves parallel to the field as voltage and current rise (James HP, Smart polymers for the controlled delivery of drugs–a concise overview., 2014).

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1. Electrically conductive polymers are known as electroactive polymers (EAPs).

2. Ionic electroactive polymers: their functioning requires an electrolyte medium

These polymers, salient features include:

- Elevated susceptibility to electric fields
- Reversible modifications to properties
- Transduction of energy from electrical to mechanical

There are several benefits to using electroactive polymers, sometimes referred to as electrically conductive polymers, and ionic electroactive polymers, which need an electrolyte medium (DHANDAPANI TS, 2023). It is biocompatible, lightweight, and production ready. These polymers require a high electric strength (10-100V) to function. It is possible precisely regulate their response by: - Current magnitude the length of electrical pulses and the time between them (James HP, Smart polymers for the controlled delivery of drugs–a concise overview., 2014). In a variety of applications, this degree of control allows for customized performance.

D] Polymer of magnetic field responsiveness:

Magnetic fields cause magnetic-responsive polymers to react (James HP, Smart polymers for the controlled delivery of drugs–a concise overview, 2014). They are made of hydrogels and elastomers as well as magnetic particles, such as nickel powder and iron ferromagnetic particles.

2.CHEMICAL STIMULI POLYMER:

1]A Polymer that has an acid group function:

2] A polymer with pH requirement:

1] A polymer that has an acid group function:

In response to pH variations, pH-sensitive—which are defined by weakly basic or acidic groups—accept or release protons, changing their electrical charge (Almeida H, Temperature and pH stimuli-responsive polymers and their applications in controlled and selfregulated drug delivery., 2012). Known as polyelectrolytes, these polymers have a large number of ionizable groups that ionize at particular pH values (pKa). Solubility is impacted by the structural alterations in the polymeric chain brought about by this ionization. Smart polymers go from soluble to insoluble because of their lower electrical charge. This behavior is best illustrated by the polycationic biopolymer chitosan: Solubility in acidic solutions Phase separation caused by main amino group deprotonation by inorganic ions close to pH impartiality. Hydrophobic interactions and electrostatic attraction between chitosan chains are key components of the gelation mechanism. Polymers can be hydrophobically changed or blended with complimentary polymers to improve structural integrity.

1] Based on the groups, there are two types of pH polymers:

a) A polymer with an acid group that functions:

Polyacids and polyanions, which are pH-responsive polymers, have large concentrations of ionizable acid moieties. Carboxylic and sulphonic acid groups are examples of polyanions that display pH-dependent protonation and deprotonation behavior. Because of the electrostatic repulsion this ionization creates, polymer swelling is triggered, allowing for regulated drug release (Mahajan A, Smart polymers: innovations in novel drug delivery., 2011).

b] Polymer with functional basic group:

Polymer with functional basic group pH-responsive polymers, which include poly-bases and polycations, exhibit ionization and protonation that is dependent on pH. Particularly, PPAA and PEAA show increased hemolytic activity in the pH range of 5–6, while physiological pH (7.4) shows negligible hemolysis, suggesting biocompatibility.

Polymer Mechanism of pH responsive:

Because of changes in their charge state, pH-responsive polymers show electrostatic-driven solubility shifts. Through pH-sensitive reactions, this phenomenon makes it easier to detect glucose in biosensors. Applications in biomedicine that take advantage of the biodegradability of natural pH-responsive polymers for controlled medication release and implanted devices.

2]Ion responsive polymer:

Ion-responsive polymers react to ionic stimuli, such as variations in ionic strength or pH, by changing their chemical and physical characteristics (IY., 1995). These adaptable polymers distinctive rheological characteristics result from the allure of Coulombic interactions between species with opposing charges. Their adaptability makes it easier to create novel materials. As polyelectrolytes, they have the ability to swell and Deswell in response to variations in ionic strength.

Particularly:

Electrolytes protonate at low pH, becoming hydrophobic, which results in the collapse of polymer chains and decreased swelling. Electrolytes deprotonate and become hydrophilic at high pH values, which causes polymer chains to expand and swelling to rise.

3]Redox responsive polymer:

Redox-responsive polymers respond to changes in their environment by undergoing reversible physical and chemical changes the redox status of the environment. These polymers take part in reduction-oxidation reactions by means of electron transfer between species. Redox-active groups are incorporated into their design to facilitate reduction and oxidation reactions. Through alterations to the chemical structure of the monomer, these groups are incorporated into the polymer pendant or backbone, enabling changeable redox potential. Systems that are redox responsive, biodegradable, or bio erodible are created using redox polymers.

3] BIOLOGICAL RESPONSIVE POLYMER: -

Enzyme-responsive polymer:

Targeting certain tissues or areas with high enzyme concentrations causes enzyme-responsive polymers to change in response to the enzymatic activity around them. Due to their selective degradation by related enzymes, these polymers have both therapeutic and diagnostic uses. Nonetheless, careful design considerations are essential. Furthermore, it is crucial to guarantee biocompatibility and reduce toxicity in the drug delivery system.

Glucose responsive polymer:

Glucose-responsive polymers control the release of bioactive compounds, simulating natural insulin and reducing the difficulties associated with diabetes. Boronic acid and other glucose-responsive moieties are included into these sugar-sensitive polymers to mimic the natural release of insulin. Byproducts of enzymatic oxidation cause the polymer to react, which results in glucose sensitivity. Three monitoring systems are made possible by glucose oxidase:

1. Enzymatic sensing: this process provides gluconic acid from glucose.

2. Interactions between lectin and proteins: glucose-binding characteristics make sensing easier.

3. Shape/size changes that rely on pH: the polymer contracts, stretches, or swells.

One multivalent protein that improves glucose response is lectin. Gel density decreases with increasing glucose concentrations. The glucose-responsive qualities of these sophisticated polymers are optimum.

IV. SYNTHESIS

1)Synthesis of Hydrogels:

Natural polymers can be used to create smart hydrogels, which react to external stimuli such as temperature, pH, ionic strength, and electrical and magnetic fields. Chitosan and other natural polymers.

polymers can Three-dimensional networks of polymeric chains known as hydrogels expand in water or biological fluids without disintegrating.

Their characteristics and structure can be modified for certain uses and are dependent on the procedures used for preparation.

Because of their high-water content, mechanical qualities, and biocompatibility, hydrogels can be used in biomedical applications.

Synthetic be used to create smart hydrogels, which react to external stimuli such as temperature, biocompatible and have low toxicity, whereas synthetic polymers offer specific degradability and well-defined structures.

Prepared using techniques such as inverse mini-emulsion, microfluidics, or inversenano-precipitation, micro- and nano-gels have applications in drug delivery, tissue engineering, DNA delivery, bioimaging, and antifouling.

2) Graft Polymer Synthesis:

Graft copolymers can be customized for medical purposes, such as temperature/pH-responsive surfaces. Graft polymers are segmented copolymers where the branches of another polymer or polymers are dispersed randomly and have a linear backbone.

Their distinctive shapes and uses in nanoscience and biology have garnered interest. Among the synthesis techniques are

Grafting-onto: coupling reactions that join side chains to a backbone.

Grafting-from: side chains are grown from a primary chain that has already been polymerized. Grafting-through: the process of using a macromonomer to polymerize monomers.

Gamma radiation can create active spots on the backbone of smart graft polymers, facilitating monomer reactivity.

- Some techniques are:

1. Direct: using monomer to irradiate polymer.

2. Pre-irradiation oxidative: peroxides and hydroperoxides are formed, followed by heating with monomer. Using relatively inert materials like polypropylene, cotton, silicone rubber, and polyethylene.

V. ADVANTAGES AND DISADVANTAGES

Advantages of smart polymers:

1.Smart polymers are ideal materials because of their remarkable qualities, which include

resistance, biocompatibility, robustness, flexibility, resilience, and non-thrombogenicity. They are also easily moldable and colored to fit a variety of uses.

2. More patient compliance leads to more effective treatment.

3. Maintain ideal dosage levels within the therapeutic range and guarantee consistent pharmaceutical efficacy.

4. Direct contact with blood is one of its uses.

5. Intelligent polymers efficiently supply cells with nutrients and stimulate growth.

6. Among the main advantages of smart polymer-based drug delivery systems are lower dosage frequency, easier handling, and longer-lasting therapeutic levels with a single dosage.

7. Extended release of the medicine in the capsule, which leads to less adverse effects.

Disadvantages of smart polymers:

1.Their mechanical strength is generally low.

2. In vitro delivery of drugs and cells may encounter issues with pre-loaded matrices.

3. It can be difficult to sterilize these materials.

VI. APPLICATIONS

1] Tissue engineering:

Smart biopolymers are used in the field of tissue engineering to repair or regenerate organs or tissues that have been harmed or afflicted by biological causes. In tissue engineering, the goal is to create a scaffold framework that permits cells to enter and develop tissue in three dimensions by having the proper chemical, physical, and mechanical properties.

The scaffold aids in tissue regeneration and will go on its own once the tissue has healed, eliminating the necessity for removal later on and preventing issues from leaving objects in the body.

In tissue engineering, temperature-responsive polymers are essential because they have two primary uses: as surfaces that allow cells to adhesion and proliferation, as well as as injectable gels that build internal scaffolds. By altering the temperature, the polymers in the first application might cause the cells to adhere or detach from them. In the second fashion, the cells are situated within the body's three-dimensional form. The body can build the scaffold by adding the required cells, nutrients, as well as growth drivers. With this technique, the scaffold can take on any shapeless damaging than external construction, which includes combining the polymer prior to being administered to the body, with cells at room temperature. When the temperature increases to 37 °C, it surpasses the threshold that causes the polymer to change and solidify into a gel. Consequently, the cells are enclosed by the gel's three-dimensional structure.

2) Gene delivery:

Targeting defective genes that cause genetic illnesses is a treatment strategy known as gene therapy. Effectively delivering therapeutic DNA into cells to replace, fix, or regulate the faulty gene is a crucial stage in this process. Nevertheless, the negatively charged and hydrophobic cell membrane prevents DNA from passing through due to its hydrophilic and negative charge.

Vectors, or gene delivery vehicles, have been created to get around this problem. Because naturally existing viruses have the innate capacity to carry genetic material, they were first used for gene delivery. However, there are serious disadvantages to viral vectors, especially with regard to immunological reactions. Since polymers are more affordable, safe, and versatile than other gene delivery technologies like liposomes, they have become the primary non-viral carrier.

3) Micelles:

The most well-known example of self-assembled structures in solution is micelles, which are created when hydrophilic and hydrophobic monomers combine to form block copolymers. Pharmaceuticals and other hydrophobic substances can be encapsulated and solubilized by these micelles in aqueous settings, improving their bioavailability and dispersion.

4) Cross linked micelles:

In solution, hydrophilic and hydrophobic monomers can be combined to form block copolymers, of which micelles are the most common, to form structured assemblies. As a result, hydrophobic medications can be encapsulated and dispersed in water.

5) Films:

Copolymer films of poly(N-butyl-acrylamide) provide long-term, consistent drug release. Hydrophobic monomer content has an inverse relationship with release rates at 37°C. The PNIPA Am/PA Am copolymers have been investigated as smart membranes for controlled permeability in drug delivery and other applications promise: temperature-controlled folding and release are demonstrated using thermo responsive PVCL/PNI PA Am sheets containing magnetic nanoparticles.

6) Biosensing:

Devices called biosensors, which identify and translate environmental signals into usable data, are essential in a number of domains, such as environmental monitoring and medical diagnosis. Biosensors are essential in many domains, such as environmental monitoring and medical diagnostics, since they transform environmental signals into useful information. Specialized biomolecules, such medications or illness signs, can be recognized and responded to by advanced polymers.

These sensitive materials support research into polymeric sensors by detecting even the smallest changes in chemical, physical, and biological environments. These sensors improve the environment by addressing urgent industrial issues. Biosensors for clinical and forensic purposes detect biological factors continuously by keeping an eye on minute variations in physical variables and analyst concentrations.

7] Drug delivery:

The method of giving pharmaceutical compounds to humans or animals to cure illnesses or ailments is known as drug delivery, with the main goals of delivering medications to the right location, making sure the dosage is right, and efficiently scheduling the administration.

Drug delivery is the process of giving medications to humans or animals in order to cure illnesses or disorders. The goal is to target the appropriate location, optimize dosage, and regulate time. This is accomplished using smart polymeric carriers, which react to stimuli and release medications in a precise and regulated way. These materials are created by polymer scientists to adjust to temperature or pH changes, allowing for precise drug delivery. Targeted delivery and controlled release are only two of the many medicinal uses for smart polymers.

VII. CONCLUSION

As new drug delivery technologies are developed, smart polymeric drug delivery systems offer a connection between medication delivery and therapeutic need. In addition to discussing the theory, mechanics, and applications of smart polymers in biomaterials, this article sought to gather the most recent developments in the field. More complex features including stimuli-responsive behavior, multi-drug delivery systems, and real-time monitoring capabilities could be added in the future. Furthermore, using smart polymers in conjunction with other cutting-edge technologies like bioinformatics and nanotechnology has great promise for advancing the medical industry. As a result of enabling more precise, efficient, and targeted therapeutic interventions, smart polymeric materials are expected to significantly influence healthcare in the future.

REFERENCES

[1] Aguilar MR, S. R. (2019). Smart polymers and their applications. Woodhead publishing.

[2] Aguilar MR, S. R. (2019). Smart polymers and their applications. Woodhead publishing.

[3] Aguilar MR, S. R. (2019). Smart polymers and their applications. Woodhead publishing.

[4] Aguilar MR, S. R. (2019). Smart polymers and their applications. Woodhead publishing.

[5] Almeida H, A. M. (2012). Temperature and pH stimuli-responsive polymers and their applications in controlled and selfregulated drug delivery. Journal of Applied Pharmaceutical Science., 1-10.

[6] Almeida H, A. M. (2012). Temperature and pH stimuli-responsive polymers and their applications in controlled and selfregulated drug delivery. Journal of Applied Pharmaceutical Science., 1-10.

[7] DHANDAPANI TS, K. V. (2023). EMERGING TRENDS IN STIMULI-SENSITIVE DRUG DELIVERY SYSTEM: A COMPREHENSIVE REVIEW OF CLINICAL APPLICATIONS AND RECENT ADVANCEMENTS. Int J App Pharm, 15(6), 38-44.

[8] Fattah-alhosseini A, C. R. (2024). A review of smart polymeric materials: Recent developments and prospects for medicine applications. Hybrid Advances.

[9] Fattah-alhosseini A, C. R. (2024). A review of smart polymeric materials: Recent developments and prospects for medicine applications. Hybrid Advances.

[10] Fattah-alhosseini A, C. R. (2024). A review of smart polymeric materials: Recent developments and prospects for medicine applications. Hybrid Advances. .

[11] IY., G. (1995). 'Smart'polymers in biotechnology and medicine. Russian Chemical Reviews, 64(5), 471.

[12] James HP, J. R. (2014). Smart polymers for the controlled delivery of drugs–a concise overview. Acta Pharmaceutica Sinica, 4(2), 120-127.

[13] James HP, J. R. (2014). Smart polymers for the controlled delivery of drugs–a concise overview. Acta Pharmaceutica Sinica B. , 4(2), 120-127.

[14] James HP, J. R. (2014). Smart polymers for the controlled delivery of drugs–a concise overview. Acta Pharmaceutica Sinica B. , 4(2), 120-127.

[15] James HP, J. R. (2014). Smart polymers for the controlled delivery of drugs–a concise overview. Acta Pharmaceutica Sinica B., 4(2), 120-127.

[16] Mahajan A, A. G. (2011). Smart polymers: innovations in novel drug delivery. Int. J. Drug Dev. Res. , 3(3), 16-30.

[17] Mahajan A, A. G. (2011). Smart polymers: innovations in novel drug delivery. Int. J. Drug Dev. Res. , 3(3), 16-30.

[18] Meléndez-Ortiz HI, V. G.-L. (2016). State of the art of smart polymers: From fundamentals to final applications. Polymer Science: Research Advances, Practical Applications and Educational Aspects;. Formatex Research Center: Badajoz,, 476-487.

[19] Priya James H, J. R. (2014). Smart polymers for the controlled delivery of drugs - a concise overview. Acta Pharm Sin B., 4(2), 120-127.