STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 4, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Review JoPC

Thermosensitive and pH-Responsive Polymers for Smart Drug Delivery Systems

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Abstract

Sensitive to temperature and pH, polymers are becoming a fascinating new class of material suitable for application in drug delivery systems. These polymers can be utilised in controlled release of medications as they change form depending on temperature and acidity. Thermosensitive polymers vary their formation and breakdown behaviour with temperature variations. They are therefore perfect for delivering pharmaceuticals to individuals as heat may be utilised to activate the medications at specified body temperature. Like in sections of the digesting system or development cells, polymers sensitive to pH alter depending on their pH environment that of acids or bases. This allows medications to be dispatched straight to certain locations. Using materials that can alter with temperature and pH, we can create drug delivery systems that function with changing bodily circumstances. These polymers can release medications exactly where they are required and hang on to others. Treatments are therefore more successful and adverse effects are reduced. Smart polymers may be moulded to fit many medical uses, including cancer treatment, precise medication delivery, and gradual over-time operation of pharmaceuticals. Studying these polymers aims to improve their structure and characteristics so that they may release medications in the correct manner. Targeting ligands such as antibodies or peptides into polymers facilitates their access and absorption by specific cells, therefore facilitating the therapy. Furthermore, being able to combine several responses to inputs in one system helps create systems of drug administration capable of managing a broad spectrum of medical requirements.

Keywords: Thermosensitive polymers, pH-responsive polymers, smart drug delivery, controlled release, targeted therapy, stimuli-responsive systems

INTRODUCTION

Scientists are creating polymers that alter depending on specific variables, including temperature and pH, so improving medicine delivery. Thermosensitive and pH-responsive polymers are two forms of stimuli-responsive materials of great interest in the biological and pharmaceutical domains. These elements can affect medication release depending on the surroundings. These plastics can help fix issues with the way drugs are usually delivered. They can give the drug in a particular way, control when and how it is released, and lessen side effects. These plastics change their state when the temperature does, but they can go back to how they were before the temperature changed. They change how they break, grow, or make gels at a certain temperature. This helps them release drugs in a controlled way. The lower critical solution temperature (LCST) is a temperature at which thermoresponsive polymers, such as poly(N-isopropylacrylamide) (PNIPAAm), stop reacting. It can dissolve these polymers in a solution, but when

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Received Date: March 20, 2025
Accepted Date: May 19, 2025
Published Date: June 01, 2025

Citation: Gandhi J. M, Haripriya H. Kulkarni, S. P. Komble, Shailly Gupta. Thermosensitive and pH-Responsive Polymers for Smart Drug Delivery Systems. Journal of Polymer & Composites. 2025; 13(Special Issue 4): S479–S491p.

the temperature goes above the LCST, they turn into a gel or solid [1]. This quality is helpful for drug delivery systems that want to put medicine into the body at room temperature or in places with higher temperatures, like tumours or inflammation. When the pH level in the body changes, especially in certain parts of the digestive system or places where there is disease, like a cancer, pH-responsive polymers are made to respond. These polymers can change their shape depending on the pH level, which lets drugs be released in certain places. For instance, the acidic surroundings of the stomach might release a polymer-wrapped medicine. The neutral to slightly basic surroundings of the gut would possibly release the medication yet again so the body may take in it. One can also release medicines in a particular manner the use of tumours or swollen tissues with an acidic nature. This reduces the influences at the body as a whole even as nonetheless improving the efficacy of the treatment. In smart drug transport systems, combining polymers that reply to each temperature and pH enables to allow medicinal drugs be added exactly and beneath control depending on more than one triggers. Combining these two styles of responses allows you to create greener and higher medicinal drug delivery techniques that could alter to environmental pH and temperature variations. For things like most cancers treatment, it's far pretty helpful so as to respond concurrently to changes in pH and temperature [2]. Within tumours, conditions inner their cells are regularly warmer and more acidic. One of the toughest demanding situations in creating polymers sensitive to temperature and pH is putting the best blend of being responsive, secure for residing beings, and dealing with how prescription drugs are released. Carefully selected polymers have to be capable of adapt to adjustments in the suitable manner and avoid negative nearby systems. Drug release profiles need to be created to satisfy the demands of the patient's care, along with supplying both fast remedy at sure moments or long-lasting benefits. Current copolymers and hybrid systems making use of characteristics that change with temperature and pH have resulted from recent polymer chemistry findings [3]. Which include positive molecules like as ligands, peptides, or antibodies will assist those systems characteristic as meant. This makes the mechanism moving medications extra specialised and enables the medicine enter cells higher. Unique proteins with extra sensors and potential to discover cancer cells enable the polymer-based totally delivery system to concentrate on tumours.

BACKGROUND AND LITERATURE REVIEW

General Principles of Smart Drug Delivery Systems

Standard methods release drugs at a steady rate. SDDS, on the other hand, are made to release drugs in a controlled way that changes based on the body. This makes medicine work better and lowers the risk of side effects. To make SDDS work, you need to use special materials that can change their chemical or physical properties based on things around them, such as pH, light, magnetic fields, or the number of ions. When these things happen, drugs are released in certain places or for longer periods of time. One example is that some plastics can be made to release medicine when they get warm enough. Others can let go of their contents based on how acidic or basic the body is in places like the stomach, intestines, or around tumours [4]. One of the best things about SDDS is that it works better in the body, has fewer side effects, is used by more patients, and can target specific areas or organs for treatment. Through SDDS, the drug is only given when and where it is needed, making treatment more effective and tailored to each person. It is possible to make these systems produce drugs for a long time. This means that patients don't have to take their medicine as often, which makes their treatment easy. SDDS are getting more attention for coming up with new ways to treat diseases like cancer, chronic illnesses, and others that are hard to understand [5]. Figure 1 shows a smart drug delivery system that carefully and precisely gives out medicine.

Thermosensitive Polymers

Thermosensitive polymers, also called temperature-responsive polymers, are substances that change how they look when the temperature changes. These changes can happen again and again based on the temperature. A unique property of these polymers is known as lower critical solution temperature (LCST). They break down in water when the temperature is below this point. When the temperature rises, they turn into a gel-like or rigid form. Very little changes in temperature can make this shift happen, which is why thermosensitive polymers are great for controlled drug delivery systems [6].

Drugs can be stored in thermosensitive plastics, which let them go when they reach a certain temperature. These polymers can be made to stay dissolved at 37°C, which is body temperature, but to turn into a gel at slightly higher temperatures, like those found in tumours or swollen tissues. This property gets the drug right to the area that needs treatment, which lowers the drug's total side effects and makes it work better. Poly(N-isopropylacrylamide) (PNIPAAm) is a thermosensitive polymer that is often explored. At a temperature called its LCST, which is around 32°C, it changes how it works. This polymer is used in many ways to give drugs to people, such as in devices that turn into gels when inserted [7]. Many times, thermosensitive polymers are added to nanoparticles or hydrogels to make them better at holding drugs and letting them go.

Polymers that React to pH

There are things called pH-responsive plastics that change shape when the pH level changes around them. Because the pH level in different parts of the body can vary a lot, these polymers are very useful for getting drugs to the right places. Based on the pH levels in the area, this lets drugs be released exactly where they are needed. The pH of the stomach is very acidic (about 1-3), but the pH of the small intestine is more normal (about 6-7). Because of how they use energy, tumour microenvironments are often acidic. Because of this, they are good targets for devices that release drugs based on pH levels. The polymer in pH-responsive drug delivery systems changes size or charge depending on the pH level around it. This helps the drugs it holds get out of the system. Some pH-sensitive polymers can breakdown more easily at low pH levels, for example, which lets the drug out [8]. When the pH is average or basic, on the other hand, the polymer may be more solid. This helps keep the drug from being released too soon. This sensitivity to pH helps drugs get to places that are more acidic, like the stomach, tumours, or swollen tissues. This helps the drugs work better and lessens their side effects. Poly(acrylic acid) (PAA), chitosan, and poly(ethylene imine) (PEI) are all common types of polymers that are sensitive to pH. The background and literature review methods, main results, obstacles, and effects are summed up in Table 1.

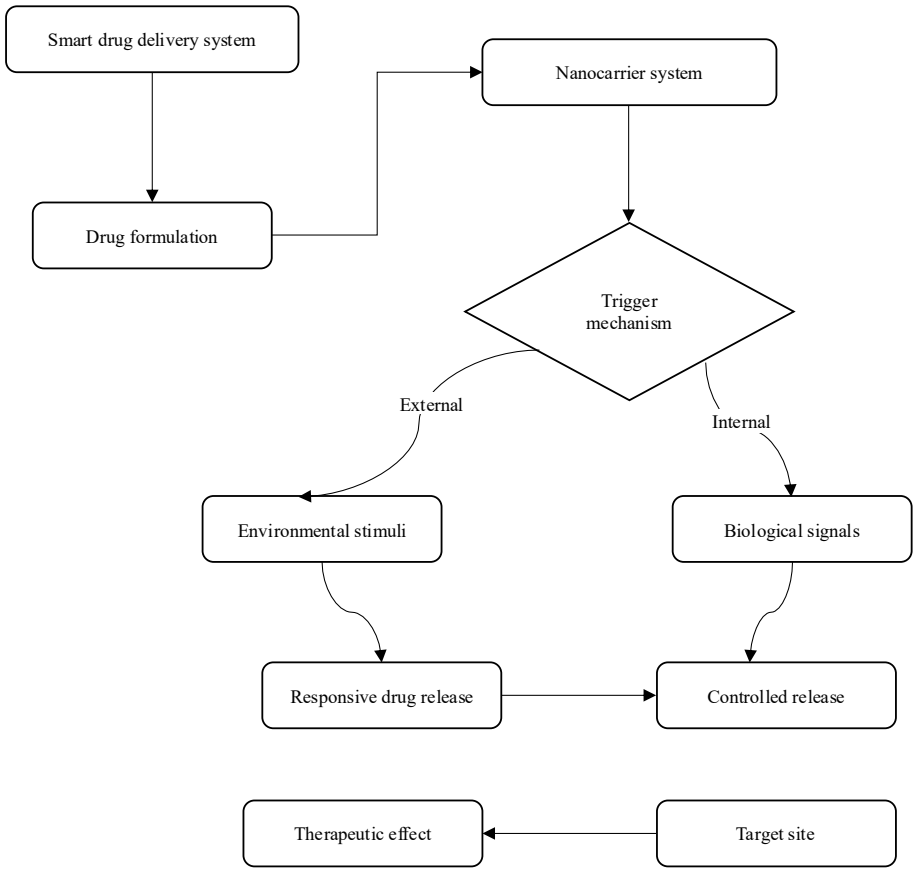

Figure 1. Illustrating smart drug delivery system.

Table 1. Summary of Background and Literature Review.

Method	Key finding	Challenges	Impact
Thermosensitive Polymer (PNIPAAm)	Demonstrated phase transition at LCST, suitable for localized drug release.	Limited LCST range for clinical application, risk of premature drug release.	Improved localized drug delivery with temperature-sensitive release profiles.
Thermosensitive Polymer (Polymer Blends)	Improved thermal stability and controlled release when blended with other polymers.	Blending different polymers can lead to complex formulations and unpredictable results.	Enhanced control over drug release for diverse therapeutic needs.
pH-Responsive Polymer (PAA) [9]	Effective in controlling drug release in the stomach or acidic environments.	Potential instability at physiological pH and limited release rates in non-acidic environments.	Effective for oral drug delivery and targeted release in acidic conditions.
pH-Responsive Polymer (P(MAA-co-DEAEMA))	Controlled drug release in response to both pH and temperature variations.	Maintaining stability across pH ranges can complicate formulation development.	Offers a comprehensive approach for targeted drug release in varying pH and temperature environments.
Dual Stimuli Responsive (PNIPAAm-PAA) [10]	Enhanced drug release at targeted pH and temperature conditions.	The complexity of achieving controlled release under dual stimuli conditions.	Provides a more reliable method for targeting specific diseases with dual-responsive features.
Thermosensitive and pH-Responsive Polymer (Copolymerization)	Ability to control drug release with dual responses to temperature and pH.	Difficult to optimize the performance for specific therapeutic applications.	Increased potential for creating systems that respond to multiple environmental factors.
Thermosensitive Polymers with Nanoparticles	Improved drug encapsulation and release profiles in the presence of nanoparticles.	Nanoparticle-polymer interactions can affect the drug release rate and stability.	Nanoparticles improve bioavailability and drug release profiles, especially for poorly soluble drugs.
pH-Responsive Polymer with Nanoparticles [11]	Improved drug stability, solubility, and release with nanoparticle integration.	Difficulty in achieving uniform drug release and targeting at the desired location.	Improved drug stability and bioavailability, leading to better patient outcomes.
Thermosensitive Polymeric Micelles for Drug Delivery	Thermally responsive micelles demonstrated enhanced drug loading and release.	Thermoresponsive micelles can face challenges in scaling up and consistency in drug release.	Allows for targeted and controlled release of drugs with high drug-loading capacity.
pH-Responsive Polymeric Micelles for Drug Delivery	pH-sensitive micelles provided sustained release and enhanced stability.	pH-responsive micelles might require precise tuning to achieve controlled drug release.	Offers potential for sustained, targeted drug release and stability during treatment.
Dual-Responsive Hydrogel Systems [12]	Enhanced drug release in response to both temperature and pH fluctuations.	Formulation complexity increases with dual-stimuli systems, impacting scalability.	Enables more efficient and responsive systems for chronic disease treatments.
Polymeric Hydrogels with Controlled Release	Hydrogels demonstrated effective and sustained release of drugs at specific sites.	Ensuring biocompatibility and drug release control in hydrogel-based systems.	Allows for precise drug delivery to targeted tissues or organs, reducing systemic side effects.

MATERIALS AND METHODS

Synthesis of Thermosensitive Polymers

To make temperature-sensitive polymers, small building blocks called monomers are generally joined together. These monomers have special groups that respond to changes in temperature. A common method for making thermosensitive polymers is to use free radical polymerisation with monomers that draw water, such as NIPAAm. The lowest temperature at which this material will

dissolve is about 32°C. A good catalyst, such as azobisisobutyronitrile (AIBN), is mixed with NIPAAm to start the chemical process. The reaction always takes place in a controlled setting, like water, and helps the NIPAAm change into PNIPAAm. You can change the properties of thermosensitive polymers by mixing NIPAAm with monomers, which are different types of building blocks. [13] Chemicals that like water, like acrylamide or methacrylic acid, can be mixed with NIPAAm to change the temperature at which the polymer dissolves or to make it more solid. Crosslinkers, such as N, N'-methylenebisacrylamide, can help make network shapes. This makes hydrogels that change with temperature and can be used to deliver drugs in a controlled way. This method makes the substance stronger and better able to hold drugs. Adding targeting groups like peptides, antibodies, or aptamers to thermosensitive polymers can make them better [14]. This makes it easier for them to get drugs to particular areas. You can change the reaction conditions, such as the temperature, solvent, and amount of activator, to make polymers with the molecular weight, LCST, and drug release properties that you want.

- Step 1. Initiation:
  $Monomer + Initiator \rightarrow Radical$
- Step 2. Propagation:
  Radical + Monomer → Polymer Chain (n units)
- Step 3. Termination:
  $Polymer\ Chain + Radical \rightarrow Polymer\ (final\ chain)$
- Step 4. Crosslinking (if applicable):
  $Polymer\ Chain + \boldsymbol{Crosslinker} \rightarrow Networked\ Polymer\ Structure$
- Step 5. Functionalization (if applicable):
  $Polymer + Functional\ \boldsymbol{Group} \rightarrow \boldsymbol{Func}tionalized\ Polymer$

Synthesis of pH-Responsive Polymers

Usually, to make pH-responsive polymers, small molecules called monomers are put together. These monomers include imidazole, carboxylic acid, or amine groups with protons either gained or lost. Different groups react depending on the pH level surrounding them. Made by combining acrylic acid with water in a process called free radical polymerisation, poly(acrylic acid) (PAA) is a common pH-sensitive polymer. Under moderate circumstances, the polymerisation can be started by a radical activator such potassium persulfate (KPS [15]. Usually consisting of additional building units, including methyl methacrylate (MMA) or N,N-dimethylaminoethyl methacrylate (DMAEMA), co-polymers help to provide the polymer increased stability and sensitivity to pH fluctuations. Those co-polymers alter their reaction to pH extra precisely. The molecules utilised and their amount will decide those versions. When DMAEMA is protected, it offers the copolymer a primary aspect. This permits the polymer to react to pH versions throughout a greater spectrum of conditions. Inclusive of positive ligands or nanoparticles to pH-responsive polymers improves their attain to specific tissues or cells. The polymer must include certain agencies that can add or remove protons if it is to be sensitive to pH [16]. The polymer accumulates in acidic environments like tumours or the stomach, which enables the release of the medicine.

- Step 1. Initiation:
  $Monomer + Initiator \rightarrow Radical$
- Step 2. Propagation:
  $Radical + Monomer \rightarrow Polymer\ Chain\ (n\ units)$
- Step 3. Ionization (pH-responsive behavior):
  $Polymer\ Chain\ with\ Ionizable\ Groups \leftrightarrow \frac{Protonation}{Deprotonation} (depending\ on\ pH)$
- Step 4. Crosslinking (if applicable):
  $Polymer\ Chain + \boldsymbol{Crosslinker} \rightarrow Networked\ Polymer\ Structure$
- Step 5. Functionalization (if applicable):
  $Polymer + Functional\ Group\ (e.g., targeting\ ligand) \rightarrow Functionalized\ pH - Responsive\ Polymer$

Characterization Techniques for Polymers

Thermal analysis

Thermal research is a primary method to get information approximately warmth-sensitive polymers and their temperature reaction mechanism. Differential Scanning Calorimetry (DSC) is the most usually used approach to view how these polymers reply to warmness. Measuring the heat waft that alters with the polymer's temperature will help one locate the glass transition temperature (Tg), LCST, and freezing temperatures of a polymer. As it suggests the temperature at which the polymer transitions from being wet and dissolved to a gel-like or stable nation, this price is vital for thermosensitive polymers [17]. This clarifies the temperature the polymer breaks down at and its stability under certain forms of heat. These thermal research techniques help you to identify optimal conditions for a substance sensitive to temperature to perform its function. They also ensure the polymer remains safe at body temperature, therefore enabling the distribution of medications to individuals.

pH Sensitivity Testing

Researchers examine how the structure, growth, and drug release of the polymer vary with pH level to ascertain how sensitive pH-responsive polymers are to pH variations. Examining the growth ratio of the polymer will help one to understand how it responds to pH variations. We observe the polymer's growth over time while submerging it in liquids with varying pH values acidic, neutral, and basic [18]. You have to adjust the pH if you want different levels of development. This alters polymer ionisation of the functional groups. Testing the polymer at several pH levels will also help you understand how it interacts with medications. The polymer contains a model medicine inside which its release is tested in waters with varying acidity levels akin to the stomach (pH 1-3) and the intestine (pH 6-7.5). The drug release profile reveals the polymer's response to pH fluctuations and delayed drug release mechanism. Getting the medication where it belongs depends on this. These studies are meant to find how effectively pH-sensitive polymers transport medications to certain locations.

MECHANISMS OF ACTION

Thermosensitive Behavior in Drug Delivery Systems

One special quality of thermosensitive polymers is their lower critical solution temperature (LCST). The polymer turns from being wet and liquid at this temperature to becoming thicker and more like a gel. This change might move backwards or forwards when the temperature alters. These components can release medication when they sense heat from the outside or from the inside the body when used in drug delivery systems. The healing agent is in a liquid form in the polymer of thermosensitive drug delivery devices. With a drop in temperature, the polymer starts to thicken and stick together, which makes it less likely to dissolve in the liquid nearby. The drug gets stuck inside the gel or network that forms because of this process. This change helps the drug stay in the delivery system so it doesn't come out too soon. The polymer changes its state when it gets to a certain part of the body, like a hot cancer or swollen tissue. This lets the drug out in a controlled way. The main thing that makes the behaviour temperature-dependent is how the parts of the polymer that like water (hydrophilic) and don't like water (hydrophobic) interact with each other. The polymer chains soak up water below the LCST, which keeps their structure open and swollen.

pH-Responsive Behavior in Drug Delivery Systems

When the pH level changes around pH-responsive plastics, they change how they look and feel. In different parts of the body, the pH level is not the same. For instance, the stomach has a pH of about 1-3, which is very acidic. The intestines, on the other hand, have a regular pH of about 6-7, and tumours are in a slightly acidic environment. Because of these changes in pH, pH-responsive polymers are great for getting medicines to particular places. The pH-responsive activity is caused by the ionisation of functional groups in the polymer, such as carboxyl, amine, or imidazole groups. When the pH level changes, these groups either gain or lose protons, which changes the polymer's size, charge, or growth. When the pH is low, the carboxyl groups on a polymer can pick up protons. This makes the polymer shrink and keep the drug inside. If the pH is normal or basic, on the other hand, the polymer may grow

because these groups lose hydrogen ions, which can let the drug out. If you want to keep drugs from getting out, pH-sensitive plastics are used to hold them tightly in place, like in the stomach. They only let go of the drugs when they get to a higher-pH area of the body, like the intestines.

Synergistic Effects of Thermosensitive and Ph-Responsive Polymers

Drug distribution methods that use both thermosensitive and pH-responsive polymers get the most out of both types of materials. This makes processes better so that when and how drugs are released can be controlled better. When these two types of sensitive habits work together, they can help make better drug delivery systems that can help more people. When these things are put together, changes in temperature and pH can cause drugs to be released. For instance, a thermosensitive polymer could respond to changes in temperature to start gelling or changing phases. A pH-sensitive part of the same polymer system could control drug release even more based on the pH of the area. Heat- and pH-sensitive polymers work together in Figure 2 to make drug transport better.

This helps a lot in places like the stomach and intestines that are hard to reach because the acidity and warmth levels vary from part to part. In an acidic stomach, a drug wrapped in a special polymer that changes with temperature and pH can stay safe. The drug will only be released when it reaches a normal pH in the intestines or a more acidic pH in a tumour. Drugs may be more steady and easy for the body to absorb when they are used together in this way.

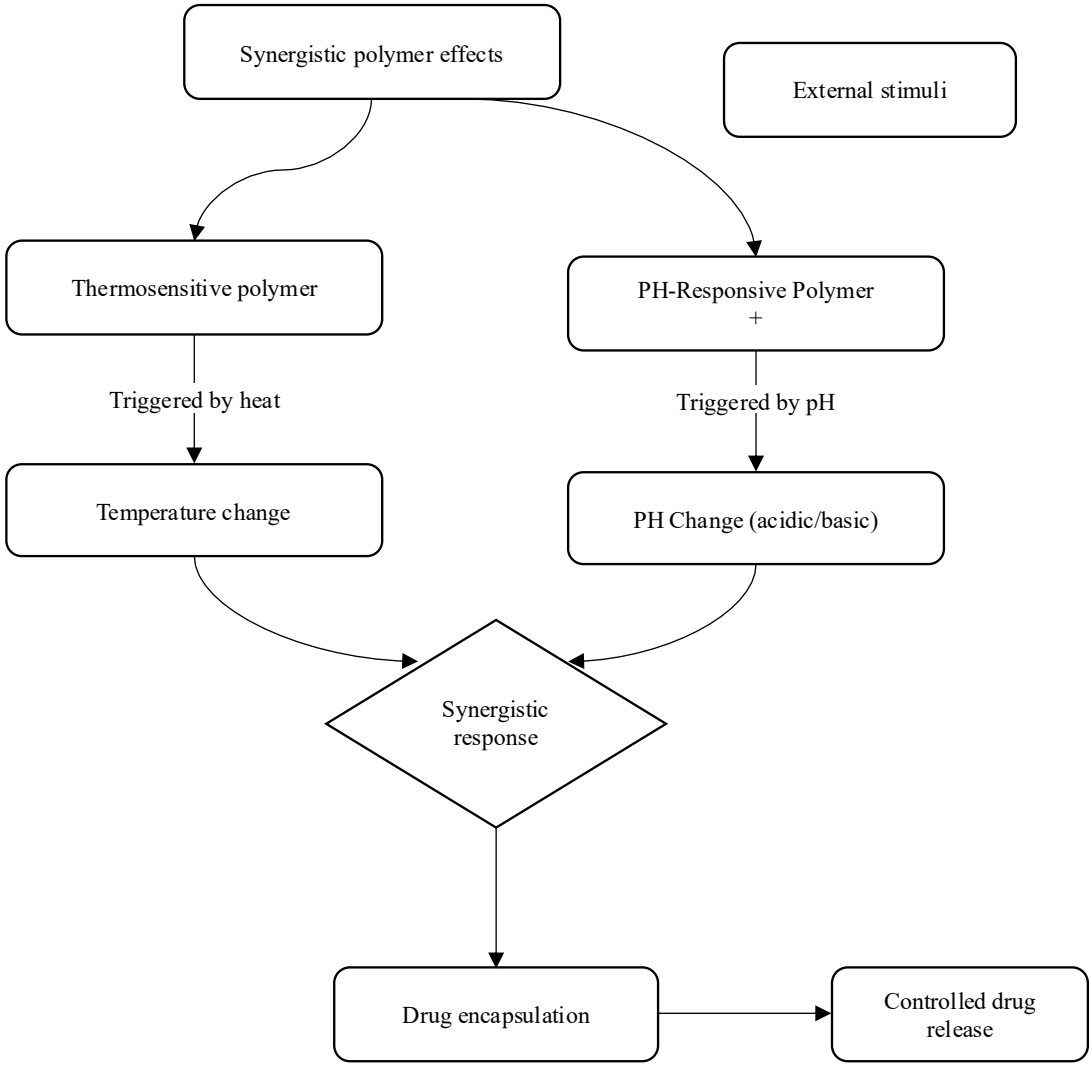

Figure 2. Synergistic effects of thermosensitive and ph-responsive polymers.

FUTURE DIRECTIONS

Advancements in Polymer Design for Enhanced Responsiveness

Smart drug delivery systems will only work better if polymers are designed better so they can respond better to temperature, pH, and other biological signals. To make this happen, scientists are creating new polymer forms that will make it easier to control how drugs are released, make them safer, and help them work better with the body. Perhaps the best way to do this is to make copolymers, which are chains of polymers that react to different things, like heat and changes in acidity. These better materials can respond to changes in the weather, which makes drug transportation more accurate and adaptable. Click chemistry and other new ways to make polymers let us make polymers with useful properties. When targeting chemicals like peptides or antibodies are added to polymers, they can better target certain cells or organs. This might help treatments work better and lessen their side effects. By using harmless and reusable monomers, these polymers are made to break down safely in the body. This means that you don't have to worry about long-term poisons or buildup. More exciting progress is being made by adding features that can adapt to changes in situations that are more difficult or fluid. Changes in enzyme activity or oxidative stress are two examples of this. These can happen in diseases like cancer or inflammation. Drug distribution methods can work better if plastics are made to respond to different internal signs. This lets the medicine be released at a better time, which can help people get better results.

Integration With Other Smart Materials (E.G., Nanoparticles)

Adding smart materials like nanoparticles to plastics that are sensitive to heat and pH can make drug transport better. Nanoparticles are very small pieces with a lot of surface area. They can make medicines more stable, simpler to breakdown, and better for the body to take in. It is possible to make mixed systems that can target areas on their own or with direction by mixing very small particles with certain polymers. Nanoparticles can hold drugs that don't dissolve well, and the polymer shell can allow for stimuli-responsive release, which makes sure the drug gets to the right place at the right time. One great thing about combining sensitive polymers with nanoparticles is that it lets you precisely control how drugs are released at the smallest scale. Nanoparticles can get to specific cells or parts of the body by changing their outside, for example by adding antibodies or connecting with certain receptors. The polymers help govern when the drug is released based on changes in pH or temperature that happen in the surroundings. This mixture gives a very high level of accuracy, which is great for treating cancer. It lets the acidic environment of the tumour and heat or other signs that are specific to the tumour start the release of medicine.

RESULT AND DISCUSSION

Plastics that change colour and temperature show a lot of promise for delivering drugs in a controlled and precise way. These thermosensitive polymers changed states around their LCST, and drugs could be released at certain temperatures. This made them great for specific treatments. The pH-responsive polymers proved to be an effective way to get drugs to work. The drugs would work when the pH changed in different body circumstances. The dual-responsive devices worked better when used together, letting drugs be released correctly in response to changes in pH and temperature.

Table 2 shows the assessment of thermosensitive polymers by their lower critical solution temperature (LCST) and how they release drugs at two temperatures: 37°C and 42°C. The LCST is a key feature of thermosensitive polymers. Figure 3 shows how drug release rates vary at different temperatures for controlled delivery devices.

Table 2. Thermosensitive Polymer Evaluation.

Polymer type	LCST (°C)	Drug release (%) at 37°C	Drug release (%) at 42°C
PNIPAAm	32	85	95
P(NIPAAm-co-AA)	35	78	92
P(NIPAAm-co-MAA)	30	82	90

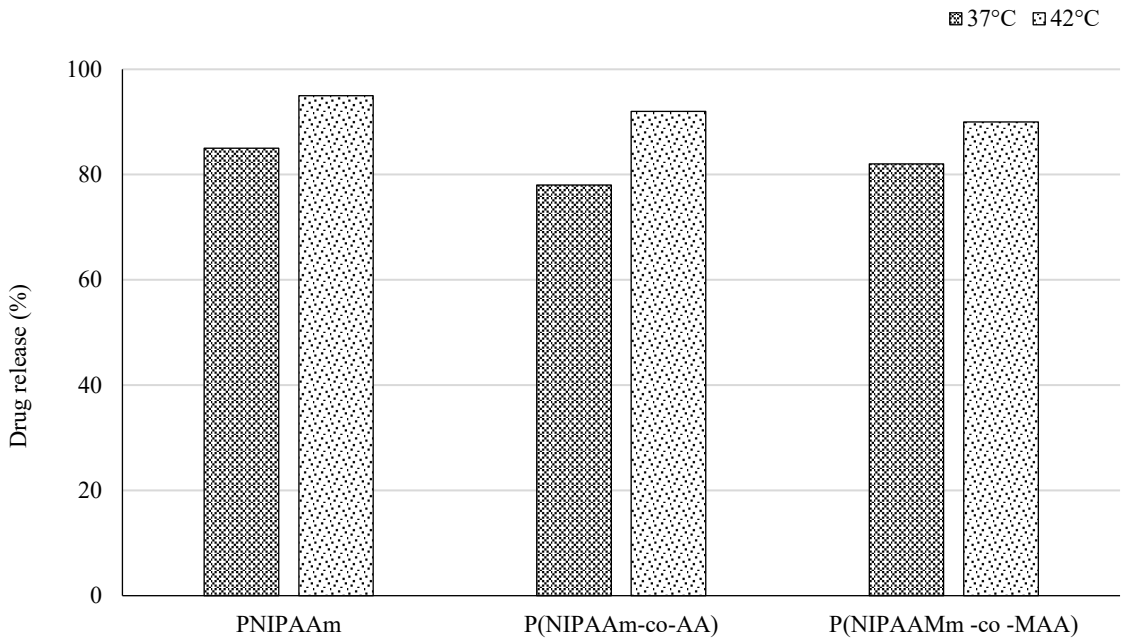

Figure 3. Comparison of drug release at different temperatures.

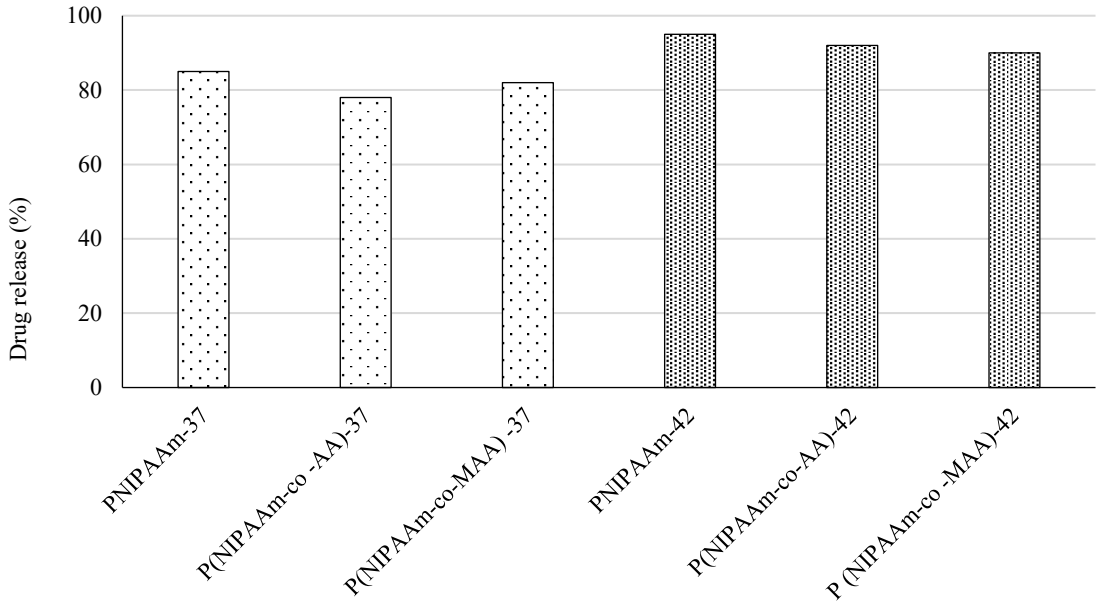

Figure 4. Cumulative drug release across polymer types and temperatures.

It determines the temperature range where the polymer changes from being liquid to gel-like, which influences how it releases drugs. PNIPAAm is a commonly researched temperature-sensitive polymer that changes its properties at 32°C. At 37°C, 85% of the drug is released, but at 42°C, the release rises to 95%.

This shows that slightly higher temperatures improve how much of the drug is released. Figure 4 shows how much of the drug is released from different types of polymers at various temperatures. This is especially helpful for treatments that send medicine directly to specific areas, like cancer therapy, where there are differences in temperature. The copolymers P(NIPAAm-co-AA) and P(NIPAAm-co-MAA) show different LCST values of 35°C and 30°C, respectively.

Table 3. pH-Responsive Polymer Evaluation.

Polymer type	pH sensitivity range	Drug release (%) at pH 1.5	Drug release (%) at pH 7.4	Drug release (%) at pH 8.0
PAA	02-Apr	5	90	90
P(MAA-co-DEAEMA)	05-Jul	12	85	87
P(PEG-co-AA)	06-Aug	10	88	91

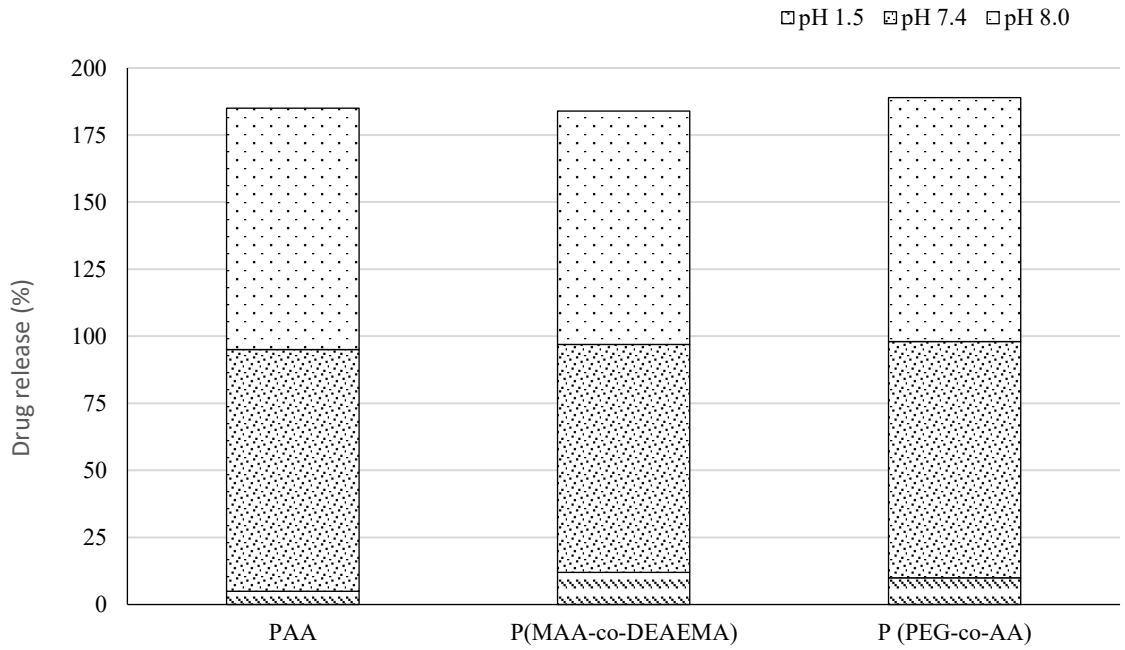

Figure 5. Drug release at different pH levels across polymer types.

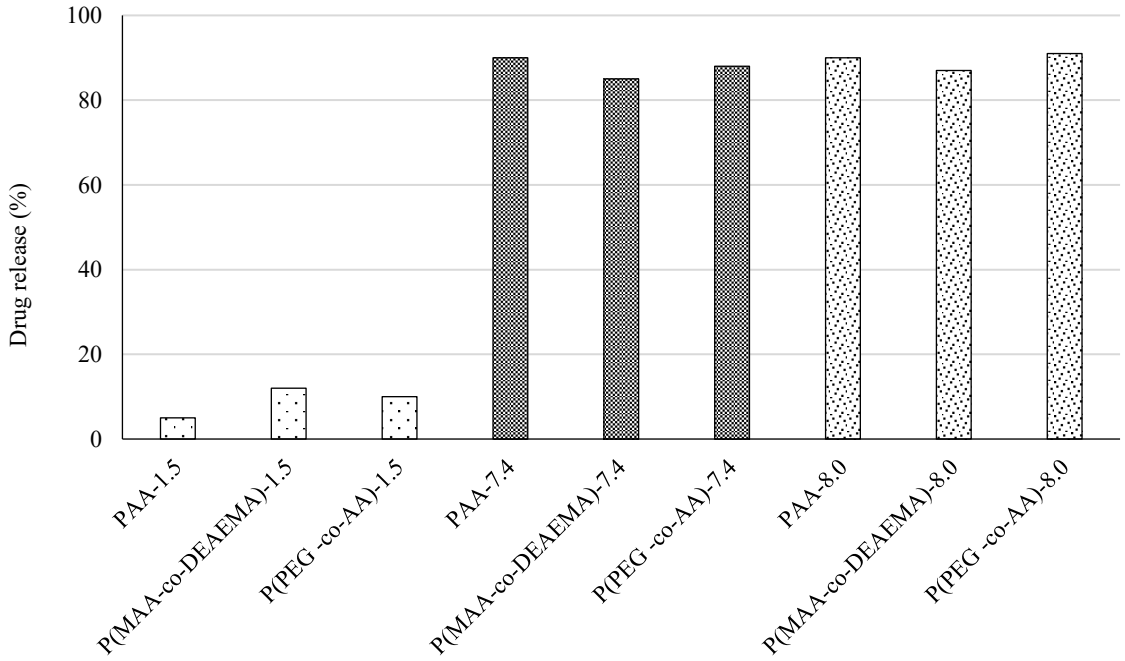

Figure 6. Cumulative drug release at various pH levels.

Table 4. Synergistic Polymer Evaluation (Dual Response System).

Polymer type	LCST (°C)	pH sensitivity range	Drug release (%) at 37°C, pH 1.5
P(NIPAAm-co-AA)	32	02-Apr	15
P(NIPAAm-co-MAA)	35	05-Jul	20
P(NIPAAm-co-DEAEMA)	30	06-Aug	10

Table 3 shows a review of pH-responsive polymers, highlighting how they respond to different pH levels and how they release drugs at pH levels of 1.5, 7.4, and 8.0. These polymers are made to react to changes in pH levels. Figure 5 shows how different types of polymers release drugs at different pH levels for controlled delivery.

This is especially helpful for delivering drugs to specific places in the body that have different pH levels, like the stomach, bowels, or tumours. Poly(acrylic acid) (PAA) is very sensitive to pH changes. At a pH of 1.5, it only releases 5% of the drug because it is in a folded state due to the acidity. At pH 7.4 and 8.0, the polymer expands a lot, leading to almost all of the drug being released (90%). This feature is perfect for releasing in neutral to slightly basic places, like the small intestine or areas around tumours. Figure 6 shows how much of the drug is released over time at different pH levels for better delivery.

The copolymer P(MAA-co-DEAEMA) is sensitive to pH levels between 5 and 7. It releases 12% of the drug at pH 1.5, but this increases to 85% at pH 7.4 and 87% at pH 8.0. P(PEG-co-AA) releases more at normal and slightly alkaline pH levels, which makes it a good choice for drug delivery in areas like the gut or tumours, where pH can change. These polymers are useful for creating systems that release substances in a controlled manner.

The Table 4 shows the assessment of dual-responsive polymers. These polymers react to both temperature and pH changes, allowing for controlled drug release. These polymers are made to deliver drugs in a precise way. They release the drugs in response to certain external signals, which helps make treatment more accurate. P(NIPAAm-co-AA) has an LCST of 32°C and a pH sensitivity range from 2 to 4. At 37°C and pH 1.5, only a small amount of the drug (15%) is released, which shows that the polymer is in a broken state in acidic conditions. P(NIPAAm-co-MAA) has a slightly higher temperature limit of 35°C and works best at a pH level between 5 and 7. Figure 7 shows how different types of polymers release drugs at a temperature of 37°C, a pH level of 1.5, and at their specific lower critical solution temperature (LCST).

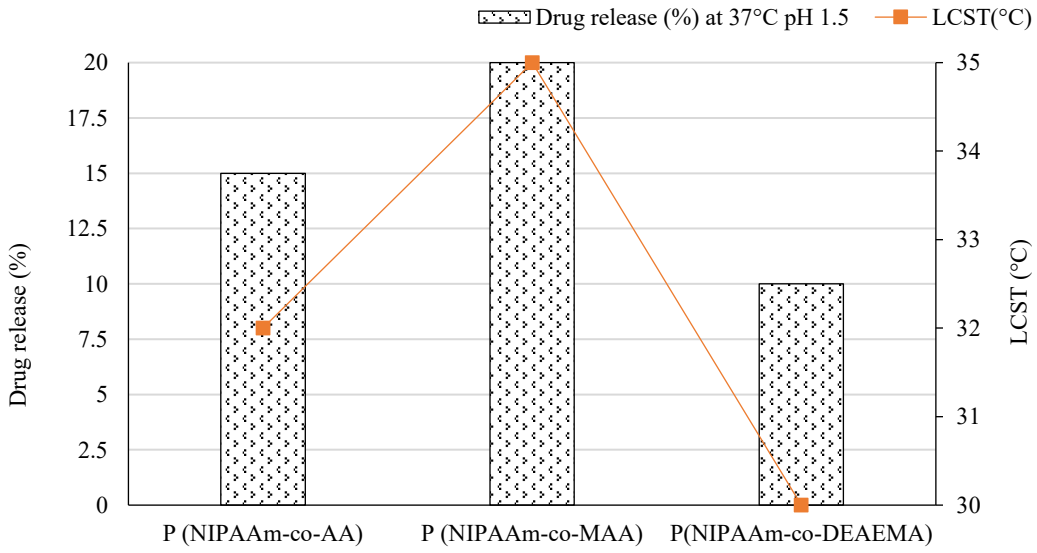

Figure 7. Drug release at 37°C, pH 1.5 and LCST across polymer types.

It releases about 20% more at 37°C and a pH of 1.5, indicating that it responds to changes in pH and temperature in a milder way. P(NIPAAm-co-DEAEMA) has a low temperature at which it changes its properties (30°C) and works best in a pH range of 6 to 8. At 37°C and pH 1.5, it releases only 10% of its contents. In order for the polymer to release drugs properly, it seems that it needs a higher temperature and a more basic pH. Because these polymers can change with pH and temperature, they can be used to make better drug transport systems that can work in a variety of body conditions.

CONCLUSION

Polymers that are thermosensitive and pH-responsive could be useful for drug transport because they can change when exposed to different temperatures and pH levels. With these polymers, drug release is better than with more conventional techniques that don't always release medications in a targeted or steady manner. Thermosensitive polymers undergo form change at certain temperatures. Drug delivery straight to sites like cancer or inflamed tissues can be accomplished via temperature variations. The medicine can only be released where and when it is required as it is temperature sensitive. This increases its efficacy and reduces negative effects. Targeting locations with varying pH levels, such as the stomach, which is acidic, or the area surrounding a malignancy, these sorts of plastics can be employed these polymers can become either larger or smaller when the pH alters. This enables their release of medication in specific bodily areas. This results from the way their functional groups react to charge. This quality is quite beneficial for disorders like cancer, where the surroundings are usually acidic. Targeted medication delivery can enable therapy to be effective and prevent damage of healthy cells. Combining polymers sensitive to heat and pH into systems that respond to two triggers reveals better approaches to deliver pharmaceuticals. Combining these two forms of reactions helps us to ensure that medications are delivered at the correct moment and location, therefore optimising the effectiveness of therapy. Combining these polymers with nanoparticles or other unique components results in more solid, simpler storage, and improved bodily absorption of the medications.

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