

Hydrogel-Based Drug Delivery Systems: Fabrication and Performance

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ABSTRACT

Hydrogel-based drug delivery systems (HDDS) have attracted a lot of attention in biomedical engineering as they can continuously, locally, and under control release medications. These systems can store a lot of water without changing their form as they are largely composed of hydrophilic polymers. This allows them to respond from the outside to elements including pH, temperature, and ionic strength. For particular medication delivery, notably in cancer therapy, wound healing, and tissue regeneration, this makes them ideal. Hydrogel-based systems are produced by liquid casting, electrospinning, and 3D printing among other techniques. Each one is meant to raise the dynamic properties and release rate of the hydrogel. The kind of polymer utilised, the density of the crosslinks, and the degree of drug encapsulation all affect how effectively these systems function. Making hydrogels more biocompatible, stable, and capable of holding pharmaceuticals has more recently advanced. Functional groups added to the polymer network will help the medication interact with the hydrogel matrix better. This makes the patterns of release more efficient. To enable medications to be delivered on demand, smart hydrogels—that which react to outside variables—for example, temperature- and pH-sensitive—have also been developed. These approaches could help patients follow their treatment programs and reduce side effects by controlling the dosage of drug entering the body. This paper aims to discuss the most recent approaches to create hydrogel-based drug delivery systems, weigh their advantages and drawbacks, and demonstrate their application in clinical environments. The article will also discuss the issues associated with producing a lot of hydrogels for clinical application, such as ensuring that the drug release rates are always the same and the possibility of damage is always there. Future directions for hydrogel-based drug delivery systems include those of adding fresh materials and techniques. This will enable the design of tailored and successful therapies for many different diseases

Keywords: Hydrogel, drug delivery, controlled release, polymer composition, bio-compatibility, smart hydrogels

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INTRODUCTION

Rapidly rising in popularity in the field of therapeutic treatments and regulated drug administration are hydrogel-based drug delivery systems (HDDS). Made of hydrophilic polymers, which can absorb and retain a lot of water to form a gel-like structure, these systems are. Among the unique features that make hydrogels ideal for many biological applications—especially in drug delivery—are flexibility, biocompatibility, and ability to react to outside cues. Because HDDS enable for regulated and continuous drug release, they are far superior than other methods of administering medications. Other techniques can include quick release, which might cause broad negative effects. This is why hydrogel-based solutions have taken front stage in studies aiming at making pharmaceutical treatments more efficient, safer, and simpler for consumers to follow.

The ability of hydrogel-based drug delivery systems to precisely and under control release medications is its greatest advantage. The physical and chemical characteristics of the hydrogel are altered in order to accomplish this. For instance, the medication packaging techniques, bonding density, and polymer composition alter.

Unlike conventional drug delivery systems that may release medications rapidly into the circulation, hydrogels can be designed to release pharmaceuticals gradually and slowly over a lengthy period of time. This constant release guarantees that suitable levels are maintained over time by lowering the possibility of medication quantity fluctuations. This makes the therapy generally more successful. Furthermore produced in response to certain body variables as pH, temperature, or ionic strength is the medication. This

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facilitates the target of the medication release to the precise area of action. One may create hydrogel-based drug delivery systems using several techniques. Among the most often used techniques is solvent casting. This approach generates a hydrogel matrix by pouring a polymer solution into a mould and allowing it to dry. Another often used technique is electrospinning, which produces nanofibrous hydrogel networks capable of storing medicines and gradually releasing them [1]. 3D printing also piques curiosity among people as it allows one to create bespoke designs with hydrogel-based systems that let one customise the medication release profiles as well as the form and size of the hydrogel.

Depending on the treatment needs, such as the type of drug, the desired release rates, and the target site of action, each of these manufacturing methods has its own unique benefits. Most hydrogels used to transport drugs are made from polymers that come from plants or animals. Chitosan, alginate, and hyaluronic acid are some examples of natural polymers that are very biocompatible and biodegradable. Synthetic polymers, like poly(vinyl alcohol) (PVA) and poly(ethylene glycol) (PEG), let you have more control over the qualities of the material, like how strong it is and how fast the drug releases [2]. The choice of polymer affects how well the hydrogel works generally, including how strong it is, how it swells, and how quickly it breaks down. The bonding of the polymers, which makes a three-dimensional network structure, is a key factor in determining how stable and release-friendly the hydrogel is [3]. Crosslinking can be done chemically or physically, and each has its own benefits in terms of how easy it is to make and how much control you have over the structure of the network. Adding "smart" hydrogels to drug delivery methods built on hydrogels is one of the most interesting new discoveries. Figure 1 displays hydrogel-based drug delivery systems, including how they are made and how well they work for controlled drug release uses.

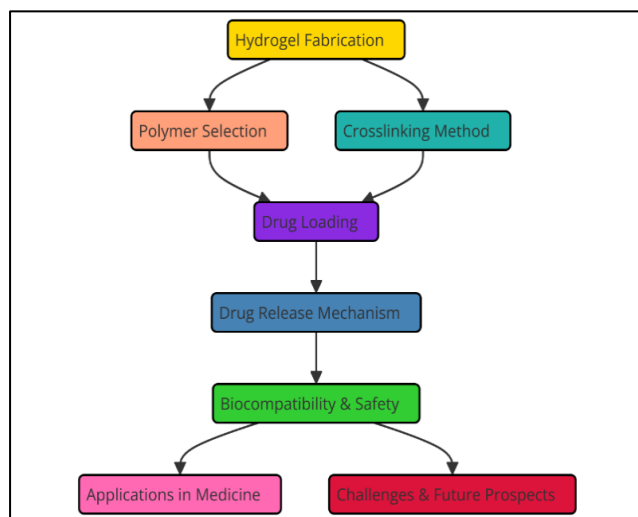


Figure 1: Hydrogel-Based Drug Delivery Systems: Fabrication and Performance:

These hydrogels are made to react to certain things in their surroundings, like changes in pH, temperature, light, or even the presence of certain enzymes or ions. Smart hydrogels can be set up to release drugs when needed or in reaction to certain triggers at the site of the disease [4]. This makes drug administration much more precise. Being able to send drugs only when and where they are needed lowers the chance of side effects and improves the effectiveness of treatment.

RELATED WORK

Over the past few years, hydrogel-based drug delivery systems (HDDS) have been extensively investigated since they might be able to release pharmaceuticals in a regulated, localised, continuous manner. Many research have sought to identify the best strategies to improve the performance of these systems in many biological environments. Mostly, researchers have been focused on enhancing the loading, release, and interacting with living entities of medications [5]. They have also been investigating fresh approaches to enable better functioning of systems. Important research has been done on the development of natural polymer-based hydrogels, which are better biocompatible and biodegradable. For instance, several research have examined base polymers for hydrogel drug delivery systems including chitosan, alginate, and hyaluronic acid. These hydrogels hold much promise in fields like tissue engineering, cancer therapy, and wound healing [6]. To improve their ability to encapsulate medications and release them more rapidly, scientists have been altering the structure and bonding techniques of these natural hydrogels. For instance, various compounds have been added to chitosan-based hydrogels to enhance their mechanical properties and drug release patterns. This has proven that regulated release of chemotherapeutic medicines performs effectively [7]. Made hydrogels have attracted a lot of attention along with natural polymers because of their ability to vary their properties. Manufactured polymers such as poly(vinyl alcohol) (PVA) and poly(ethylene glycol) (PEG) are widely employed in hydrogel forms.

Research on the degree of crosslinks and molecular weight of these polymers has revealed that one may adjust them to satisfy medical demands for medication release. PEG-based hydrogels, for example, can release pharmaceuticals depending on temperature, pH, or ionic strength variations. This makes them ideal for delivering medications exclusively to the proper location. Smart hydrogels that react to outside stimulus have drawn a lot of attention lately. To make drug release on demand, researchers have made hydrogels that are sensitive to pH, temperature, and ions [8]. For example, pH-sensitive hydrogels have been used to send chemotherapy drugs to specific areas of a tumour during treatment. The acidic environment around the tumour causes the drug to be released. Table 1 summarizes related work: applications, future trends, benefits, and limitations in relevant fields. Similarly, temperature-sensitive hydrogels have been looked at for drug delivery in

localised heat treatments, where high temperatures cause drugs to be released

Table 1: Summary of Related Work

Application	Future Trend	Benefits	Limitation
Anticancer and antimicrobial drug delivery	Integration with nanotechnology for enhanced drug loading	Biocompatibility, biodegradability, ease of synthesis	Limited mechanical strength, slower drug release
Wound healing and tissue regeneration	Use of biodegradable and bioactive polymers for better healing	Effective tissue regeneration and reduced infection risk	Difficulty in maintaining mechanical properties over time
Sustained release of hydrophilic drugs [9]	Development of multi-functional hydrogels for different drugs	Sustained drug release, improved therapeutic outcomes	Limited drug loading for hydrophobic drugs
Targeted drug delivery to specific tissues	Advancements in stimuli-responsive hydrogels for personalized therapy	Targeted therapy, minimized side effects	Potential toxicity of some polymeric materials
Localized delivery of anticancer drugs	Enhanced targeting and controlled release for cancer therapy	Localized delivery, better tumor targeting	Complex fabrication process, high cost
Encapsulation of hydrophobic and hydrophilic drugs	Development of scalable electrospinning techniques for industrial production	Enhanced drug loading and release control	Need for optimization of drug release profiles
On-demand drug release triggered by external stimuli [10]	Progress in self-healing and adaptive hydrogels for drug delivery	Precise, controllable drug release on-demand	Challenges in scalability and reproducibility
Personalized drug delivery with precise control over release	Incorporation of biomaterials in 3D printing for complex drug delivery systems	Customization for personalized treatment plans	Challenges in manufacturing high-quality 3D printed hydrogels
Release of drugs at tumor sites in response to temperature changes	Utilization of external temperature control for precise drug release	Localized treatment with minimal systemic side effects	Temperature sensitivity may affect stability
Delivery of drugs in acidic tumor microenvironments [11]	Design of hydrogels that respond to tumor-specific environmental cues	Effective drug delivery in tumor microenvironments	Difficulty in targeting only tumor tissues
Controlled release of proteins and peptides for therapeutic use	Innovative strategies for improving protein stability in hydrogels	Safe and controlled delivery of sensitive proteins and peptides	Protein degradation or instability during encapsulation and release

FABRICATION TECHNIQUES OF HYDROGEL-BASED DRUG DELIVERY SYSTEMS

A. Methods of hydrogel synthesis

1. Physical methods

When you use physical ways to make hydrogels, you can make networks of hydrogels without using chemical processes or binding agents. To make a stable gel structure, these ways mostly use physical interactions like hydrogen bonding, van der Waals forces, or ionic interactions. The solvent casting method is a popular physical method. It involves pouring a polymer solution into a mould and then letting the solvent evaporate. [12] This lets the polymer

chains stick together to form a gel. This process is easy, doesn't cost much, and works with many types of polymers. Freeze-thaw cycling is another common physical method. It includes regularly freezing and melting a polymer solution, which makes solid areas form inside the hydrogel. This method works especially well for making hydrogels from natural polymers that don't need binding agents, like gelatin or agarose. By putting a high-voltage electric field on a polymer solution and turning it, another advanced physical way makes nanofibrous hydrogel networks [13]. When electrospinning, fibres are made that can hold drugs and have a lot of surface area for the drugs to release. Additionally, cryogelation, a method of polymerising a

hydrogel at very low temperatures, has become famous because it can create structures with a lot of holes, which makes it useful for tissue engineering and drug delivery.

Step 1: Swelling Ratio Calculation

The swelling ratio (Q) of a hydrogel is the ratio of the swollen weight (Ws) to the dry weight (Wd) of the hydrogel.

$$Q = \frac{W_s}{W_d}$$

Where:

- Ws = weight of the swollen hydrogel after immersion in a solvent (g)

- Wd = weight of the dry hydrogel (g)

Step 2: Degree of Swelling as a Function of Time

The degree of swelling (ΔW) of the hydrogel over time is given by:

$$\Delta W = W_s(t) - W_d$$

Where:

- Ws(t) = weight of the hydrogel at time t after immersion

Step 3: Diffusion-Controlled Swelling

For hydrogels that swell due to solvent diffusion, the rate of swelling (rs) can be described using Fick's law of diffusion:

$$r_s = D * \left(\frac{\partial C}{\partial x} \right)$$

Where:

- D = diffusion coefficient (cm²/s)

- C = concentration of the solvent within the hydrogel at position x

Step 4: Kinetics of Swelling (First-Order Kinetics)

The swelling behavior is often described by first-order kinetics, where the change in weight (ΔW) is proportional to the time (t):

$$\Delta W(t) = \Delta W_{\infty} * (1 - e^{-kt})$$

Where:

- ΔW_{∞} = final swelling weight after equilibrium (g)

- k = swelling rate constant (s⁻¹)

- t = time (s)

Step 5: Polymer Network Crosslinking

The equilibrium swelling ratio (Qeq) is influenced by the crosslinking density of the polymer network, which is related to the Flory-Rehner equation:

$$\ln(1 - \phi) + \phi + \chi\phi^2 = \nu f * \left(\frac{1}{R} \right)$$

Where:

- ϕ = volume fraction of polymer in the hydrogel

- χ = Flory-Huggins interaction parameter

- νf = molar volume of the solvent (cm³/mol)

- R = gas constant (8.314 J/mol·K)

2. Chemical methods

Usually, hydrogels are produced in chemical terms via covalent connections. Among polymer chains, these linkages create a solid three-dimensional network. These techniques provide us more control over general hydrogel performance, drug release rates, and material properties. Among the most often used chemical processes is free radical polymerisation. It generates hydrogels [14] by starting polymerisation processes between monomers using a chemical initiator. Because it allows you exact control over the polymerisation process, this technique is quite

effective in producing hydrogels from man-made polymers such poly(vinyl alcohol) (PVA) and poly(ethylene glycol) (PEG). Another frequent method is crosslinking with chemical agents. Covalent bonds between polymer chains are formed by crosslinks agents such as glutaraldehyde or genipin. This allows hydrogels with appropriate mechanical strength and regulated rates of breakdown [15]. Moreover, click chemistry has evolved into a rather helpful technique for hydrogel production. This approach links monomers or polymers by very efficient and targeted chemical procedures. This provides exact control over the manufactured hydrogel's structure and purpose.

B. Crosslinking mechanisms

It is very important to crosslink the hydrogel before making a drug delivery system out of it because it affects the structure, stability, and drug release qualities of the system. Crosslinking is when covalent or non-covalent links are made between polymer chains. This makes a network that is three-dimensional. Physical crosslinking and chemical crosslinking are the two main types of crosslinking processes. Physical crosslinking relies on non-covalent interactions, such as hydrogen bonds, van der Waals forces, or ionic interactions, to form a stable network. This kind of crosslinking doesn't use chemical processes and can usually be undone [16]. As an example, polyelectrolytes such as alginate or chitosan work with metal ions (for example, calcium ions) to create structures that look like gels. These hydrogels are often used to deliver drugs where behaviour that responds to inputs is needed.

Physical crosslinking is better than chemical crosslinking because it is easier to do and less harmful. However, the dynamic features of these hydrogels are usually not as good as chemically crosslinked ones. When you use chemicals like glutaraldehyde, genipin, or even light to start processes (photopolymerization), you can make covalent bonds between polymer chains. This is called chemical crosslinking. This method makes hydrogels that are more solid, last longer, and have higher tensile strength. You can change the amount of crosslinking by changing the concentration of the crosslinking agent. This also changes how the substance swells and how fast the drug is released. Chemical crosslinking lets you finetune the hydrogel's qualities, which makes it perfect for uses that need to release drugs slowly over time. However, the chemical agents used in this process may make it more poisonous, so it needs to be carefully optimised to make sure it is biocompatible.

C. Influence of fabrication methods on drug release

The way that hydrogel-based drug delivery systems are made has a big impact on the way the drugs are released because it changes the physical and chemical qualities of the hydrogel, like how porous it is, how it swells, and how densely it crosslinks. These features have a direct effect on how the hydrogel reacts with the drug and how quickly the drug is released. For example, liquid casting, which is a popular way to make things, makes hydrogels with controlled porosity, which can change how fast the drug moves out of the matrix. A high level of porosity can lead to a faster release because it makes it easier for the drug

molecules to move around. Electrospinning, on the other hand, makes nanofibrous hydrogels, which have a lot more surface area for drugs to stick to, which could increase their filling capacity. The linked fibre network in electrospun hydrogels often makes the drug release last longer because it slows down the rate at which drugs spread.

The rate at which the drug is released is also affected by the degree of crosslinking. Higher crosslinking density hydrogels release drugs more slowly because the tightly bound polymer chains make it harder for the drug molecules inside to move around. Hydrogels with weaker crosslinks or lower crosslinking density, on the other hand, tend to release drugs more quickly.

PERFORMANCE OF HYDROGEL DRUG DELIVERY SYSTEMS

A. Drug release mechanisms

Different ways allow drugs to be released from hydrogel-based drug delivery systems, which rely on the structure of the hydrogel, how the polymers interact with each other, and the outside environments. Diffusion, swelling-controlled release, and external trigger release are the main ways that drugs are released. Each method can be changed to get a certain drug release rate, whether it's for long-term, managed, or on-demand delivery. The most common way is diffusion-controlled release, in which the drug molecules slowly move out of the hydrogel network and into the medium around it. This is often affected by how porous the hydrogel is, how densely the molecules are crosslinked, and how big the molecules are. These factors can be changed to control the rate of drug spread, which lets the drug stay in the body for a long time. Swelling-controlled release happens when the hydrogel takes in water and grows, making holes that make it easier for the drug to be released. Figure 2 shows drug release mechanisms, which are the different ways and processes that drugs can be delivered safely.

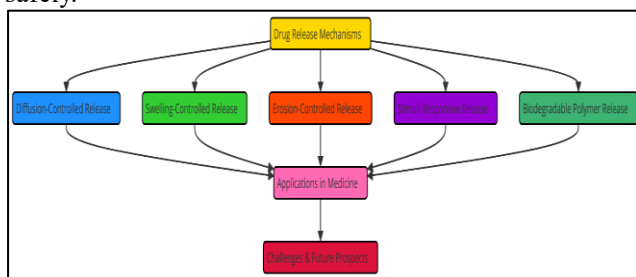


Figure 2: Illustrating Drug Release Mechanisms

This method works especially well with hydrogels made from highly hydrophilic polymers. Growing up in response to pH or temperature changes causes the hydrogel to release more drugs. Under more complicated processes known as "stimulus-responsive release," the hydrogel's structure alters in response to certain outside stimuli include pH, temperature, light, or ionic strength. Drugs are delivered to certain locations, such as tumours or the digestive system, where the pH level is different than in the rest of the body using pH-sensitive hydrogels. Temperature-sensitive hydrogels can similarly release medications when they

become very heated. These systems improve treatment outcomes by allowing medications to be sent to certain areas or on-demand, therefore lowering systemic side effects.

B. Biocompatibility and biodegradability

Two of the most crucial factors determining how safe and effective hydrogel-based drug delivery techniques are their biocompatibility and biodegradability in clinical environments. Biocompatibility is the ability of the hydrogel to coexist with the surrounding live cells without generating an immunological reaction or damage. Not only should biocompatible hydrogels not produce harmful breakdown products or cause the body to swell, itch, or react negatively in any other manner. The kind of material chosen determines a lot of how biocompatible something is. Because they are biocompatible—that is, derived from natural sources and often well-tolerated by the body—people frequently pick natural polymers such as alginate, chitosan, and gelatin. It is also possible to make synthetic polymers like PEG and PVA nontoxic, especially when they are modified to make them less likely to cause immune reactions.

Being biodegradable, on the other hand, means that the hydrogel can break down into harmless leftovers that the body can safely get rid of. Biodegradable hydrogels are very important for controlled drug delivery methods because they keep the hydrogel from building up in tissues over time. You can change the rate of biodegradation by changing the bonding density, the makeup of the polymers, and external factors like pH and temperature. Biodegradable hydrogels, like chitosan and alginate, break down through chemical or hydrolytic processes. Synthetic hydrogels, on the other hand, can be made to break down at specific rates to meet medicinal needs.

MATERIALS AND METHODS

A. Materials

1. Hydrogel polymers used

How well hydrogel-based drug delivery methods work depends a lot on the choice of hydrogel polymers that are used. Hydrogels are mostly made up of natural or man-made polymers that can soak up a lot of water and turn into a gel-like structure. There are two main types of these polymers: natural polymers and manufactured polymers. Each has its own benefits when used for drug transport. Polymers found in nature, like chitosan, alginate, hyaluronic acid, gelatin, and pectin, are often used to make hydrogels because they are biocompatible, biodegradable, and easy to change. Many people choose chitosan, which is made from chitin, because it is good at adhering to biological surfaces, killing microbes, and encasing both water-loving and water-hating drugs. Alginate is a polysaccharide that is taken from kelp. It is very safe and forms gels when it comes in contact with divalent cations like calcium. This makes it perfect for controlled drug release, especially in mouth and wound healing uses. Hyaluronic acid, a biopolymer that occurs naturally, is another favourite choice for hydrogels because it helps cells grow and tissues heal. A lot of people like these natural

plastics because they are not harmful to the body and work well with it. But manmade polymers, such as poly(vinyl alcohol) (PVA), poly(ethylene glycol) (PEG), polyacrylamide, and poly(lactic-co-glycolic acid) (PLGA), have qualities that are easier to predict, like how strong they are, how they will swell, and how quickly drugs will be released. People really like PVA and PEG because they dissolve easily in water and can be changed to give specific drug release rates. Because it biodegrades easily and can be changed to break down at different rates, PLGA is often used in controlled drug release uses. It is important to be able to control the mechanical and release qualities of these manmade polymers in order to make custom drug delivery systems.

2. Drug model(s) selected

Choosing the right drug models for hydrogel-based drug delivery systems is an important part of figuring out how well the system works. It is important that the drug model you choose matches the molecular size, solubility, stability, and release behaviour of the actual medicinal agents you want to use. Researchers and developers of hydrogel-based systems often use both hydrophilic and hydrophobic drugs, as well as protein-based drugs and small-molecule drugs. When it comes to hydrogels made from natural polymers like chitosan or alginate, they work best with hydrophilic drugs like antibiotics (like gentamicin and amoxicillin) and pain relievers (like diclofenac). It's easy for these drugs to breakdown in water, and putting them into hydrogels often leads to long-lasting effects. Researchers have shown that by changing the polymer makeup and bonding density of hydrogels, the release of these drugs can be controlled. Most of the time, diffusion through the hydrogel matrix controls how much of the drug is released in these systems. Hydrophobic drugs, on the other hand, like paclitaxel (an anticancer drug) or curcumin (a natural anti-inflammatory substance), are hard to work with because they don't dissolve well in water.

C. Characterization Methods

1. Physicochemical characterization

To ensure they satisfy stability, performance, and drug release behaviour, physicochemical characterisation on hydrogel-based drug delivery systems is crucial. This kind of study employs several techniques to identify the mechanical, chemical, and physical characteristics of hydrogels, therefore influencing their performance in certain contexts. Important physical characteristics of a substance include its swell behaviour, strength, capacity for drug storage, and rate of breakdown. One of the most often used methods to explain the physical characteristics of a material is swelling analysis. It investigates the water capacity of the hydrogel as well as its size change with time in various physiological settings like pH, temperature, or ionic strength. This is crucial because swelling alters the drug's release rate. Lower swelling ratio hydrogels release medications more slowly; greater swelling ratio hydrogels release pharmaceuticals more rapidly.

Fourier Transform Infrared Spectroscopy (FTIR), which clarifies the chemical structure and functional groups of the hydrogel, is yet another crucial technique. FTIR spectra

reveal molecular interactions between the medication contained inside and the hydrogel polymer. This can assist determine whether interactions might influence medication release and how effectively the drug is encapsulated. Mechanical tests including compression tests and tensile strength readings are also employed to verify the stability and capacity to retain form under stress of the hydrogel, which is vital for its drug delivery purpose. Differential scanning calorimetry (DSC) and thermal gravimetric analysis (TGA) are also used to understand more about how stable they are and how hydrogels respond to heat.

2. Morphological analysis

Understanding how hydrogel-based drug delivery devices are physically assembled depends in great part on morphological study. It clarifies the internal and surface structure of hydrogels, which directly affects their capacity to store medications and release those ones. The form of hydrogels is investigated using several imaging techniques, therefore providing valuable information on their surface characteristics, hole size, and overall structure. Scanning electron microscopy (SEM) is among the most often used techniques for surface shape analysis of hydrogels. Very crisp images produced by SEM reveal minute surface features like holes, hardness, and any microstructures influencing the drug diffusion. Additionally showing the density of the crosslinks in the hydrogel, SEM images can affect the swelling and strength of the material. By means of SEM, one may also investigate the degree of drug mixing into the hydrogel matrix, therefore guiding our understanding of the drug distribution at the smallest level.

RESULT AND DISCUSSION

Drug delivery methods based on hydrogels showed a lot of promise for controlled and long-lasting drug release. The ability to encapsulate drugs and the amount of drug that could be loaded changed depending on the type of polymer used. Natural polymers like chitosan and alginate were better at loading drugs that don't dissolve in water, while manmade polymers like PLGA were better at encapsulating drugs that do dissolve in water. It was the crosslinking density that changed the release patterns. Lower crosslinking led to faster drug release, while higher crosslinking led to longer release. Also, pH- and temperature-sensitive hydrogels let drugs out when needed, which shows that they could be used for focused and controlled treatments

Table 2: Drug Loading Capacity and Release Profile

Polymer Type	Drug Loading Capacity (%)	Cumulative Drug Release (%) at 24h	Cumulative Drug Release (%) at 48h
Chitosan	85	65	85
Alginate	90	60	80
PVA	75	50	70
PEG	80	55	75

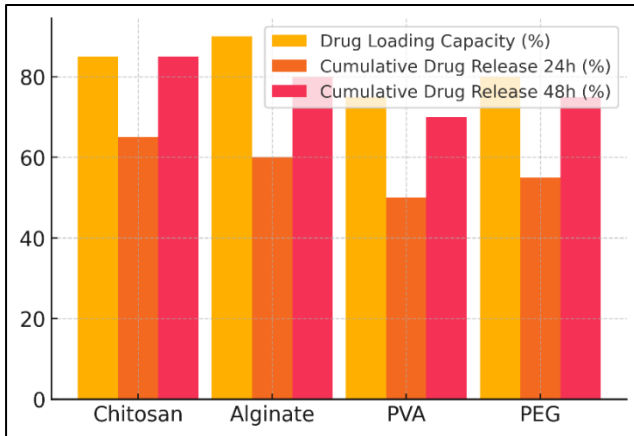


Figure 3: Comparison of Drug Loading Capacity and Cumulative Drug Release (%) for Different Polymers

This might be because of its natural qualities, such as being biocompatible and able to strongly combine with different drug molecules. Alginate can also hold a lot of drugs (90%), but it releases them a little more slowly than chitosan at 24 hours (60%), and 48 hours (80%).

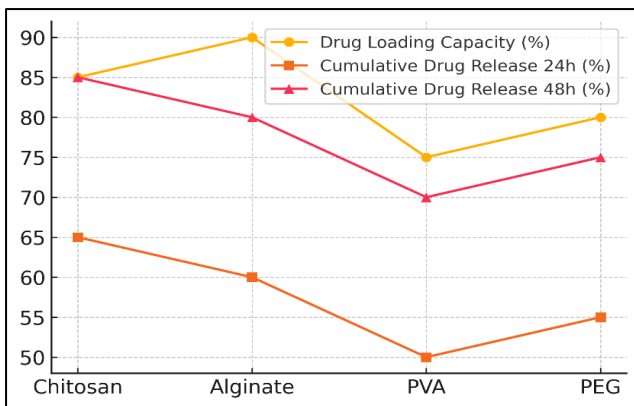


Figure 4: Trends in Drug Loading Capacity and Cumulative Drug Release (%) over 24h and 48h for Different Polymers

This means that hydrogels made from alginate can be made better for uses that need slower, more controlled release rates. It can hold more drugs and release them more slowly over 24 and 48 hours, as shown in Figure 4. Even though PVA and PEG can only hold 75% and 80% of their weight in drugs, respectively, they still have good release rates. The drug release from PVA at 48 hours (70% of the time) and PEG at 48 hours (75% of the time) are both moderate prolonged releases. This means that these materials can be used in situations that need moderate drug release overtime. Overall, the type of polymer used affects both the loading capacity and the rate of release, which lets specific medicinal uses be made

Table 3: Mechanical Properties and Swelling Behavior

Polymer Type	Tensile Strength (MPa)	Young's Modulus (MPa)	Swelling Ratio (24h)
Alginate	14.8	3.2	3.5

PVA	16.3	4	2.8
PEG	17.5	4.5	3.2
PLGA	19	5	2.5

Table 3 shows the dynamic qualities and how they grow of different polymer-based hydrogels. Alginate has a Young's value of 3.2 MPa and a tensile strength of 14.8 MPa. This means that it is a fairly soft and flexible material. When measured after 24 hours, alginate has a growth ratio of 3.5, which means it is very hydrated. This is good for uses that need to absorb a lot of water, like wound healing or tissue engineering. PVA and PEG have higher Young's moduli (4 MPa and 4.5 MPa) and tensile strengths (16.3 MPa and 17.5 MPa, respectively). Figure 5 shows how the performance of different plastics is compared by their tensile strength, Young's modulus, and swelling ratio

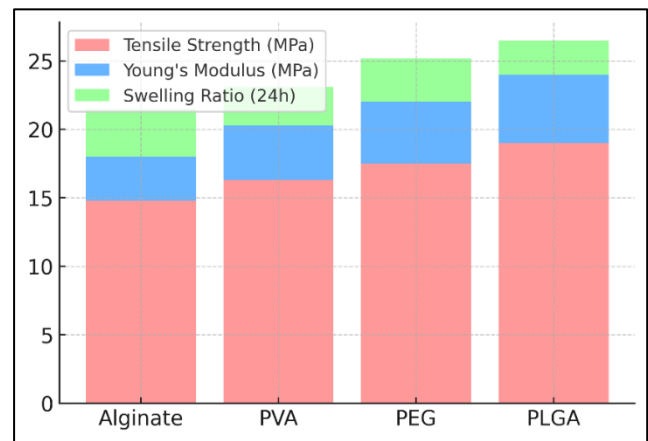


Figure 5: Comparison of Tensile Strength, Young's Modulus, and Swelling Ratio for Different Polymers

This means that they are stronger and less likely to bend than alginate. This makes them better for uses where the structure needs to stay strong even when it's under a lot of stress, like in controlled drug release systems where stability is very important. Their growth ratios, 2.8 and 3.2, are smaller than alginate's, which means they absorb water more slowly. With a swelling ratio of 2.5, PLGA is the stiffest material. It has the highest tensile strength (19 MPa) and Young's modulus (5 MPa), which means it is the best choice for long-term drug delivery systems that need low swelling and high mechanical stability.

CONCLUSION

Hydrogel-based drug delivery methods are a new and interesting way to give drugs in a controlled and focused way. Solvent casting, electrospinning, and 3D printing are some of the ways that hydrogel properties can be precisely changed. These properties include porosity, dynamic strength, and drug release kinetics. Natural and synthetic polymers each have their own benefits. Natural polymers are biocompatible and biodegradable, while synthetic polymers give you more control over the hydrogel qualities. The type of drug model—whether it's hydrophilic, hydrophobic, or protein-based—has a big effect on how well the drug is encapsulated and how it releases. When

smart hydrogels are added that react to changes in pH or temperature, they make it easier to get drugs to where they're needed. This lowers side effects and improves treatment results. Physicochemical characterisation tools, such as swelling analysis, FTIR, and DSC, give important information about the stability, drug loading capacity, and release rates of the hydrogel. Morphological study with SEM and AFM helps improve the structure of the hydrogel even more, ensuring even drug release and controlled release rates. Some problems still need to be fixed, like how to make the hydrogel production more efficient, how to make sure the drug release rates are always the same, and how to make sure the biocompatibility lasts for a long time. To make hydrogel-based drug delivery methods work better in the future, researchers should work on these problems and look into new materials, such as bioactive and biodegradable polymers. As manufacturing methods keep getting better and new technologies like 3D printing and nanotechnology are added, it will be possible to make drug delivery systems that are more effective, personalised, and flexible for a wider range of therapeutic uses.

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