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Biodegradable and Natural Fiber-Reinforced Polymer Composites for Advanced Controlled Drug Delivery Systems

Patil P. A.[1,*], K. A. Shirbavikar[2], Ram Garg[3]

Abstract

Polymer-gel forms have gained popularity in medicine as means of medication delivery over the skin. This is so since they enable medications pass the skin more readily. These products allow medicine to be administered without surgery and provide continuous active ingredient supply. They are excellent for long-term therapy for managing conditions that keep resurfacing. From tiny synthetic ones to huge biological ones, polymer gels can store a wide spectrum of medications and are flexible. This makes them a perfect delivery tool for medication. Selecting polymers that are safe, suitable for the environment, and occasionally generate stable gels helps you create polymer-gel formulas. These products are aimed to make patients comfortable and ensure they follow the directions while helping medications pass the top layer of skin, stratum corneum. Researchers have investigated several approaches to enhance the way various forms of medications including hormones, painkillers, and anti-inflammatory drugs are delivered. These call for applying hydrogels, organogels, and nanostructured gels. Made to enable medications enter the body more readily and gently depart the body, polymer gels can People could therefore not have to take their medication as often, which would assist the therapy to be more effective. More so for therapy, these instruments may target certain areas of the skin or deeper organs, therefore addressing specific organs. Recent developments in nanotechnology have made it feasible to include small particles into polymer gel construction. Drugs are therefore more stable, simpler to dissolve, and better released from this standpoint.

Keywords: Transdermal drug delivery, polymer-gel formulations, controlled release, biocompatible polymers, nanotechnology

INTRODUCTION

These methods make it possible to give medicine without surgery, which is very helpful in many ways. They help people follow through with their treatment plans, make stomach problems less likely, and keep blood drug levels steady. Polymer-gel devices could be used to get drugs into the body through the skin. They can make it easier for drugs to pass through the skin, keep the drug from running out, and ease skin pain. People like these polymer-gel mixes because they can safely deliver a lot of different meds and stay stable and work well. The skin helps keep bad things out and is the body's largest organ. Drugs also have a harder time getting through this layer of defence. This is a problem for cutaneous medicine delivery because the stratum corneum (the top layer of skin) blocks some substances from passing through. To solve this problem, people have come up with different plans. One of the best is to use polymer-gel mixes. The

***Author for Correspondence**
Patil P. A.

[1]Assistant Professor, Department of Pharmaceutics, Krishna Vishwa Vidyapeeth (Deemed to be University), Krishna Institute of Pharmacy, Karad, Maharashtra, India
[2]Assistant Professor, Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India.
[3]Assistant Professor, Department of Pharmacy, Arya College of Pharmacy, Jaipur, Rajasthan, India

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safe, reusable materials used to make these items work like a cushion to hold drugs and get them to the skin. Polymer oils can assist medications that do not dissolve well in water dissolve more readily, remain stable longer, and be more readily absorbed by the body. Applying them to the skin makes them more successful. Various medical applications call for different types of polymer-gel formulations, which can be created to meet their particular requirements. These systems mostly come in two flavours: organogels and hydrogels. Hydrogels are those with a lot of water content. They can create a rather flexible and connected structure and store a lot of water. These creams are perfect for delivering medications that dissolve in water and moisten the skin, therefore facilitating comfortable application of medication on it.

Organogels are gels formed using oil-based coolants rather than water. Usually used when you need to mix in bigger medicine dosages, they go great with medications that cause weight gain. Including nanoparticles improves both kinds of polymer-gel systems [1]. This is because the nanoparticles improve how well the gels breakdown drugs, how quickly they release them, and how well they can get through the skin. How well polymer-gel skin patches can control the release of medicine determines how well they work. When you take medicine by mouth, it moves quickly through your body. Transdermal drug delivery methods, on the other hand, let the medicine work slowly over a longer period of time. Because of this, you need to take the medicine less often, it works better, and there are fewer side effects. There are some polymer creams that are made to slowly release medicine over time, so one use can treat for hours or even days [2]. People who need steady amounts of medicine, like those with long-term conditions like diabetes, high blood pressure, or pain, will find this feature very useful. In Figure 1, you can see polymer-gel mixes that are used to send drugs through the skin. The focus is on how quickly the drugs can pass through and be released at a controlled rate.

One of the best things about devices made of polymer gel is that they can target certain organs or skin areas. This is especially important for treatments like hormone therapy that need to get the drug straight to a certain place in order to work. We can make formulas that release the drug at a certain speed by changing the polymer gel mix. This clarifies for us the dosage and the result of the treatment. Some polymer creams can help treat the tissues under for greater benefits and penetrate deeper into the skin to assist. New approaches to enhance skin absorption of medications have resulted from nanotechnology used in polymer-gel formulations.

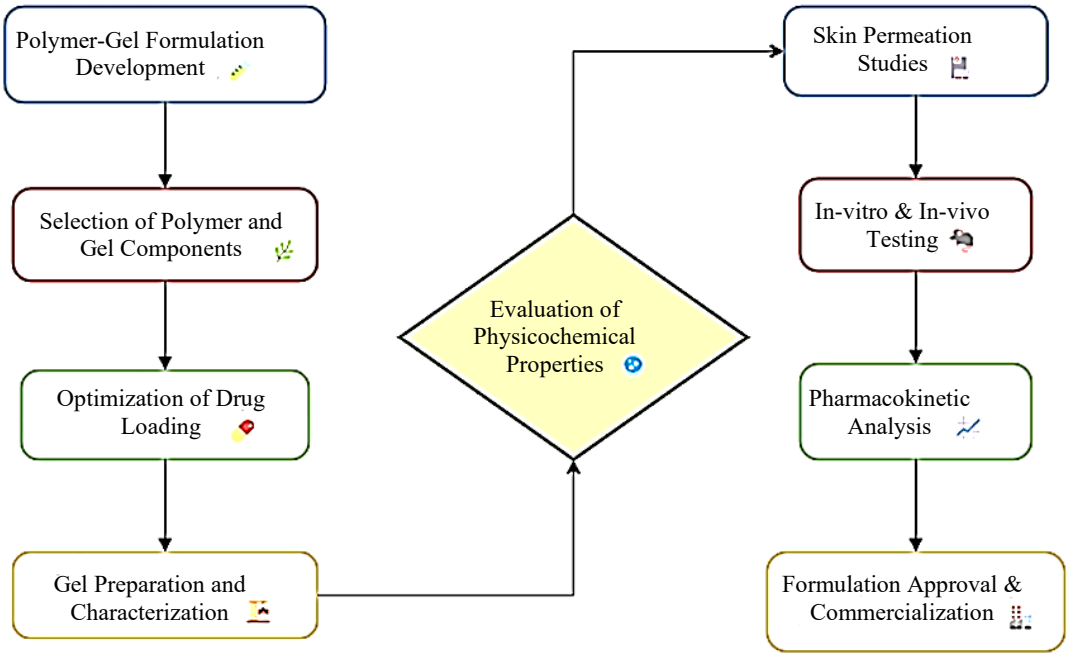

Figure 1. Polymer-gel formulations for transdermal drug delivery.

Addition of nanoparticles to the polymer can enable better breakdown of medications and preservation of their solid form. Moreover, they provide additional surface area for the medications to be absorbed [3]. Scientists have investigated how well various medications may be passed through the skin by means of nanocarriers including liposomes, dendrimers, and solid lipid nanoparticles (SLN). More fast releasing pharmaceuticals made possible by nanotechnology facilitate proper and effective administration of medications. Although transdermal drug delivery systems based on polymer gel offer numerous advantages, certain problems still need to be addressed before they may expand and improve [18-23].

MECHANISM OF TRANSDERMAL DRUG DELIVERY

Skin Anatomy and Permeability

Comprising the most of our body, our skin protects us from toxins, poisons, and mishaps. The dermis sits in the centre; the skin is on the outside; the subcutaneous tissue resides within. Comprising the top layer, the epidermis shields the body from injury. The stratum corneum, a thick layer of dead keratinised cells, is largely responsible for this. Underneath the epidermis is the layer known as the dermis. With blood arteries, nerves, and connective tissue, it maintains skin in place [4]. As a shield and pillow, the hypodermis, which is under the skin, is mostly made up of fat and elastic tissue. It's hard for drugs to get through the stratum corneum because it slows down the flow of things from outside the body into it. What lets things pass through the skin is mostly because of the stratum corneum, a fatty layer on the outside. This layer is a strong defence against things that dissolve in water. The layer corneum is very slippery, which makes it hard for many drugs to get into the skin. Several things can change permeability, such as the state of the skin (for example, how wet it is), active delivery systems, and the method used to make penetration better [5]. There isn't much that the dermis and other inner layers of skin do to keep things out, but they are necessary for drugs to get into the body after they pass through the dermis.

Drug Absorption Through the Skin

Chemicals move from outside the body through the top layer of skin and into the blood. This is how drugs are absorbed through the skin. The process starts when a drug is put on the skin's surface and combines with the stratum corneum, which is the top layer. The drug may be able to move through the top layer of skin on its own, or it may need to be moved through certain channels. After going through the top layer of skin, the drug can enter the dermis, which is below, and be taken up into the bloodstream by small blood vessels or lymph vessels [6]. Drugs have to get through the layer corneum in order to be taken. It depends on the drug's size, how well it breaks in fat, and how well it sticks to fat. Lipophilic drugs are better at getting through the skin because they mix well with the fats on the skin's surface. But hydrophilic drugs have a hard time getting through because the skin doesn't like water. The drug goes through the top layer of skin and into the live part of the epidermis. The cells in this part of the skin are wet, making it easier for the drug to move through them. The medicine is absorbed more slowly than when taken by mouth, but it lasts longer [7]. This is helpful because it skips the liver's first-pass absorption. There are other ways besides passive spread that drugs can get into the body through the skin. Some of these are micro-needle methods, iontophoresis (which uses electricity), and sonophoresis (which uses ultrasound). Being able to get around the skin's defences in these ways makes it easier to apply a wider range of drugs. More and more, these methods are being used to make better ways to send drugs through the skin [8].

Factors Influencing Drug Delivery (e.g., Molecular Size, Lipophilicity)

Many things can affect how well drugs are delivered through the skin. The two most important factors are the drug’s molecular size and its lipophilicity. Molecules that are smaller in size tend to spread more easily through the skin, as they can pass through the intercellular fatty tissue of the stratum corneum more readily. Drugs that weigh less than 500 Daltons are usually better at getting through the skin. Big molecules like proteins and peptides have a hard time getting through the skin unless special ways like microneedles or chemical helpers are used. Lipophilicity is an important factor that influences how well

a drug is absorbed. Lipophilic (fat-soluble) drugs are more likely to pass through the lipid-rich stratum corneum, which contains of fatty acids, cholesterol, and ceramides [9]. The hydrophobic nature of the stratum corneum allows lipophilic drugs to split into the skin layers and slowly spread through. On the other hand, water-soluble drugs have a harder time getting through the skin because they do not bond well with the fatty layer of the outer skin. To help hydrophilic drugs get through the skin better, formulations may use surfactants, solvents, or chemical boosters that briefly break down the skin's protective layer [10].

Table 1 summarizes the mechanism of transdermal drug delivery, highlighting key findings, benefits, and limitations. Other things that can influence how well a drug is delivered through the skin are skin moisture, temperature, and any skin problems.

Table 1. Summary of mechanism of transdermal drug delivery.

Application	Key Finding	Benefits	Limitations
Pain Management	Sustained release of analgesics, reducing the need for frequent dosing.	Non-invasive and easy to use.	Skin irritation and allergic reactions in sensitive individuals.
Hormone Replacement Therapy	Consistent hormone levels with reduced side effects compared to oral administration.	Reduced risk of side effects and drug fluctuations.	Difficult to achieve precise dosing for certain hormones.
Acne Treatment	Increased drug retention on the skin, leading to better therapeutic outcomes.	Improved patient compliance due to fewer applications.	Potential for skin irritation or dryness due to active ingredients.
Psoriasis Treatment [11]	Improved drug penetration and efficacy in reducing inflammation and skin lesions.	Enhanced therapeutic effects with reduced systemic exposure.	Limited penetration depth of the drug for some conditions.
Skin Infections	Efficient delivery of antibiotics directly to the site of infection.	Localized treatment with reduced risk of resistance development.	Not suitable for systemic infections requiring high drug concentrations.
Chronic Disease Management	Polymer gels help maintain therapeutic drug levels for prolonged periods.	Reduced side effects by avoiding first-pass metabolism.	Slow release for drugs that require rapid action.
Topical Analgesics	Efficient penetration of analgesics for fast relief, especially in localized areas.	Faster onset of action and controlled release.	Limited effectiveness for large-molecule drugs without penetration enhancers.
Antibiotic Delivery [12]	Targeted delivery to infection sites with minimal systemic absorption.	Minimized side effects due to localized antibiotic action.	Risk of incomplete drug release, affecting efficacy.
Anti-inflammatory Drugs	Reduced irritation and enhanced localized anti-inflammatory effects.	Less irritation and prolonged anti-inflammatory effects.	Possible side effects on sensitive skin areas.
Vaccination	Improved drug stability and immune response in targeted regions.	Better immune response with targeted vaccine delivery.	Limited by skin penetration and immune system interactions.
Cancer Therapy	Targeted delivery of chemotherapeutic agents to tumor sites, minimizing systemic toxicity.	Localized treatment with reduced damage to healthy tissues.	Possible resistance development over time in cancer cells.
Gene Therapy	Efficient drug delivery to the site of action, reducing side effects associated with conventional methods.	Reduced adverse reactions and better targeting of drugs.	Challenges in maintaining drug stability over time.
Wound Healing [13]	Enhanced wound healing through localized delivery of growth factors and antimicrobial agents.	Accelerated tissue repair and infection control.	Wound healing may be slower in chronic or severe wounds.

POLYMER-GEL FORMULATIONS

Types of Polymers used in Transdermal Gels

Polymer gels are important in skin drug delivery systems because they provide a flexible and effective way to release medicine through the skin. The kind of polymer employed in gel influences drug release, system performance, and stability of the system. Two primary forms of polymers are synthetic and natural, used in transdermal creams. Often preferred for their biocompatibility and biodegradability, natural polymers alginates, chitosan, and cellulose products are derived from natural sources. Usually employed in gels, alginates derived from seaweed may produce stiff shapes when combined with water. Taken from the shells of crabs, chitosan is a protein prized for its antibacterial properties and capacity to increase medication absorption [14]. Commonly found in gel products are cellulose replacements such methylcellulose (MC) and hydroxypropyl cellulose (HPC). They produce thick, transparent gels that adhere to skin really nicely. Transdermal gel formulations frequently call for synthetic polymers such polyacrylic acid, polyethylene glycol (PEG), and polyvinyl alcohol (PVA). Extremely friendly with skin, PVA is a water-soluble material that may create a film. Good for water-soluble medications, PEG is a water-loving polymer that helps increase drug absorption and maintains moisture, therefore preventing dryness. Commonly utilised in hydrogels is polyacrylic acid as it may produce extensively growing gels. This regulates the release speed of medicines.

Properties of Ideal Polymers for Transdermal Delivery

An optimal substance for passing medications via the skin must possess certain characteristics to guarantee system safety and efficiency. Important characteristics of a good polymer should include bodily safety, regulated medication release, and skin permeability of allowing substances pass through. The content first of all must be safe. This implies that, applied on the skin, it shouldn't produce any adverse effects, allergic responses, or irritation. The polymer must be non-immunogenic that is, it shouldn't set off an immunological response when it comes into touch with skin over an extended period of time. One of the main traits of an excellent polymer is its capacity to release medicines consistently and slowly [15]. The polymer should be able to produce a gel that traps the medication and gradually releases it, therefore maintaining the correct dosage of medicine in the blood over time. Medications like hormones or painkillers that must be administered gradually over an extended period of time depend mainly on this regulated release. Good permeability of the material will also enable effective medication diffusion over the stratum corneum. The polymer must complement the characteristics of the medication, such as its size and behaviour with regard to lipids. By including compounds that assist with penetration or by ensuring the polymer is appropriate for particular kinds of medications, the polymer can increase drug absorption [16]. The polymer should cling nicely so that the gel remains on the skin for a long period without causing any discomfort.

Gel Formulation Techniques

Different techniques are used in building polymer-gel systems for drug release via the skin to ensure the gel performs well, maintains stability, and releases the drug at the proper rate. While keeping patients safe and comfortable, these techniques seek to produce the optimal gel structure, add the correct dosage of medication, and regulate how the drug is administered. Gelation is a common technique whereby polymerisation or bonding produces a gel structure. Reactions between the polymer chains either chemically or physically allow this. Usually using temperature, pH, or ionic strength, physical gelation forms a gel. Chemical gelation, on the other hand, ties polymer chains together using bonding agents [17]. The type of polymer and the desired gel properties will determine the gel-making technique you decide upon. Drug integration where the active pharmaceutical ingredient (API) is entwined with the polymer framework is another crucial approach. Either distributing the drug pieces in the gel or combining the drug with the liquid and the polymer will help you. Medication interaction with the polymer determines both loading and release methods of a medication. These interactions help to determine the speed of medication release. Particularly for medications that don't dissolve well in water, gel-based solutions are created by emulsification. This approach mixes a medicine with a fatty material using an emulsifying agent, producing a combination stabilised by a polymer structure. This can enable

lipophilic medications to breakdown more readily and be absorbed via the skin. Modern approaches to enhance medication delivery are the use of microspheres and nanoparticles.

Step 1: Selection of Polymer and Solvent

- Choose the appropriate polymer (natural, synthetic, or hybrid) based on the desired properties of the gel (e.g., viscosity, drug loading, release profile).
- Select a solvent (water or organic solvent) that is compatible with both the polymer and the drug.

Equation:

$$- Polymer\ Concentration\ = \left(\frac{Amount\ of\ Polymer}{Total\ Volume}\right) * 100$$

This equation calculates the percentage concentration of the polymer in the gel matrix based on the weight of polymer used and the final volume of the formulation.

Step 2: Polymer Dissolution or Dispersal

- Dissolve the polymer in the solvent under constant stirring at a suitable temperature until a homogeneous solution or dispersion is obtained.
- For hydrogels, water may be used as the solvent, while organic solvents may be used for organogels.

Mathematical Concept

Time to dissolve can be estimated using the diffusion equation:

$$C(t) = C0 * \left(1 - e^{-kt}\right)$$

Where:

- C(t) = concentration of the polymer in the solution at time t
- C0 = initial concentration
- k = rate constant
- t = time of dissolution

Step 3: Drug Incorporation

- Gradually add the drug into the polymer solution and stir to ensure uniform dispersion.
- The drug can either be dissolved in the solvent before adding the polymer or mixed directly into the polymer matrix, depending on the solubility of the drug.

Equation:

$$- Drug\ Loading\ Percentage\ = \left(\frac{Weight\ of\ Drug}{Total\ Weight\ of\ Gel}\right) * 100$$

Step 4: Gelation and Crosslinking

- After the drug is incorporated, induce gel formation by either physical or chemical crosslinking (e.g., cooling, pH adjustment, or adding a crosslinking agent).
- For hydrogels, cooling may cause the polymer to form a network, while for chemically crosslinked gels, a chemical crosslinking agent (e.g., glutaraldehyde) may be used to link the polymer chains.

Mathematical Concept

Crosslink Density: The number of crosslink points per unit volume can be estimated by:

$$\rho\ = \left(\frac{Number\ of\ Crosslinks}{Volume\ of\ Gel}\right)$$

This step-wise algorithm ensures the creation of polymer-gel formulations with optimized properties for transdermal drug delivery.

CHARACTERIZATION OF POLYMER-GEL FORMULATIONS

Physicochemical Characterization Techniques

Analysing the characteristics of polymer-gel mixtures helps one to ensure that the drug delivery system performs well for cutaneous application of medicine. Gel physical and chemical properties are checked using several techniques. These features determine the gels' stability, medication release capacity, and skin penetration ease among other things. Viscosity testing which gauges the resistance of the gel to flow is one of the main physical tests. Because it affects how quickly the medicine is delivered, how readily the gel spreads, and how simple it is to administer, viscosity is vital. The gel should be smooth enough to apply readily yet thick enough to remain on the skin without running off. Further understanding of the stability of the gel and how it responds to shear forces that is, when applied to the skincomes from rheological tests including flow behaviour index, thixotropy, and yield stress. Drug content analysis which gauges the active ingredient (API) concentration in the gel is another crucial technique. Accurate medicine dosage measurement is frequently accomplished with high-performance liquid chromatography (HPLC). Important for consistent drug release, this ensures that the medication is uniformly distributed throughout the gel and blended in at the correct dosage.

Rheological Properties of Gels

Rheological properties define material movement and change of form. They help one to grasp the behaviour of polymer-gel combinations in usage and manufacture. Important factors include how readily gels disperse, their structure, and how medications are released depend on their behaviour. Among the most critical rheological considerations is viscosity. Finding the proper thickness of a gel will help to ensure that the drug releases steadily and can be administered readily. A gel that is too thick can be hard to apply and uncomfortable, while a gel that is too thin might not stick to the skin properly, resulting in poor medicine delivery. Viscosity can be tested with tools like a Brookfield viscometer or a spinning rheometer. These instruments show how much the gel resists flowing when different forces are applied. Thixotropy is a feature of gels that makes them thinner when stirred or shaken, and thicker again when they sit still. This trait helps to understand how easy it is to apply the gel. A thixotropic gel is good for skin applications because it spreads quickly but stays in place, helping it stick to the skin effectively. Figure 2 shows the features of gels, focussing on how thick they are (viscosity), how much they can stretch (elasticity), and how they move.

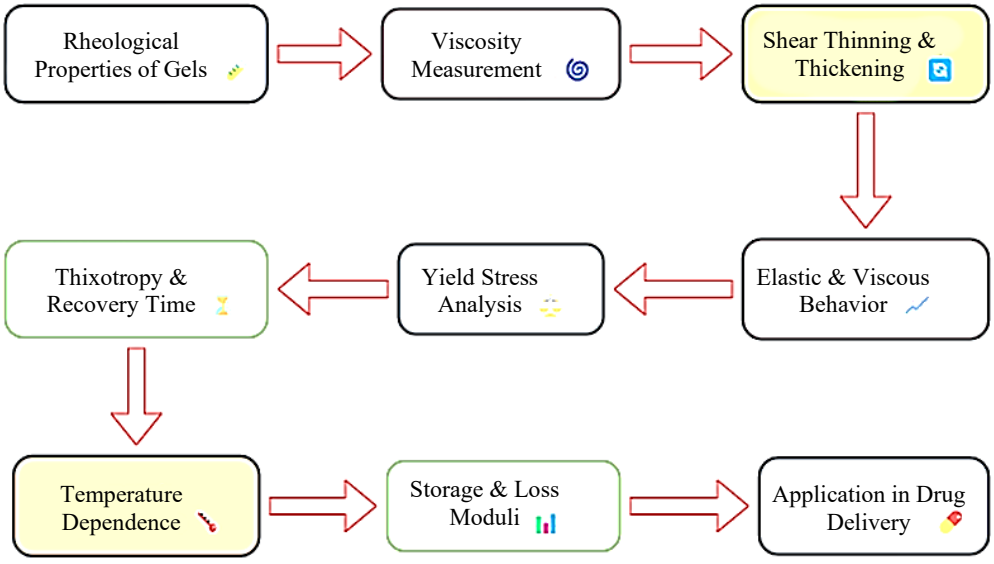

Figure 2. Illustrating rheological properties of gels.

The yield stress shows how much force is needed to start the flow in a gel. Gels with a higher yield stress tend to stay on the skin better, which helps prevent early release of the drug. The gel's flexibility, or its ability to go back to its original shape after being changed, is another important feature. This is very important for transdermal devices, where the gel needs to fit smoothly on the skin without breaking or coming apart. Storage modulus (G') and loss modulus (G") readings help evaluate the elastic and viscous parts of the gel, giving important information about how well it works.

In Vitro and in Vivo Evaluation of Formulations

Lab tests and research on live animals are conducted to assess polymer-gel forms in terms of how well they release drug, how well they permeate into the skin, and therapeutic efficacy. These tests help to guarantee that the combination safely and effectively provides the medicine. Mostly, in vitro study focusses on the release of the medication from the polymer-gel combination. Usually using unique equipment known as diffusion cells or Franz diffusion chambers, in vitro drug release investigations These instruments detect how fast a medicine passes through a membrane modelled by human skin and assist to replicate the skin barrier. These investigations provide crucial information on the mode of release of the medication, indicating whether it is delivered steadily and under control or if it is administered either too rapidly or too slowly. By altering the polymer matrix or adding penetration enhancers to attain the appropriate drug release profile, the in vitro data is also used to maximise the gel combination. Another crucial in vitro study is skin permeability testing, which gauge the drug's capacity to pass through skin. Techniques such as tape stripping or utilising bits of animal or human skin enable one to estimate the dosage of drugs entering the skin. These tests reveal how well the goo passes the skin and reaches the desired locations. In vivo review is the process of testing the gel on live entities such as animals or humans to observe how well it performs in actual life. Not only are the pharmacokinetics of the drug such as absorption, distribution, metabolism, and clearance but also the therapeutic efficacy and product safety evaluated using in vivo research. To assess the safety and efficacy of the medication, we examine its levels in the blood over time, any skin pain, and further local side effects. These investigations are crucial to ensure the gel can be safely applied in medical environments and functions well in the body.

CLINICAL APPLICATIONS

Treatment of Chronic Diseases (e.g., Pain Management, Hormone Replacement)

Formulas made of polymer-gel can help treat long-term illnesses, especially pain and hormone replacement treatment. Transdermal drug delivery devices slowly release painkillers to help people who are in pain. Lidocaine, fentanyl, and diclofenac are some of the drugs that are now used in polymer-gel devices. These devices release the drugs slowly during a long time. This method works really well for people who need long-term pain relief. As a result, the drug stays steady in the blood, stomach problems are less likely, and the liver doesn't break it down before it works. Polymer-gel solutions are now often used in hormone replacement therapy (HRT) to put hormones like testosterone and oestrogen under the skin. Compared to taking pills or getting shots, this is an easy way to do it. Transdermal HRT has a lot of advantages. It helps people stay on their medicine, keeps hormone levels fixed, and lowers the risk of side effects like stomach problems. Rather than taking pills, polymer creams can be made to slowly release the hormone. This helps keep hormone levels steady. If you have trouble swallowing pills or stomach issues, hormone replacement gels are a good choice for you.

Dermatological Applications (e.g., Acne, Skin Infections)

Dermatologists often use polymer-gel products to treat skin problems like acne and rashes as well as skin illnesses. To treat acne, medicines like benzoyl peroxide, retinoids, and antibiotics (like clindamycin) are often put together in polymer-gel devices that allow for focused, controlled release. This makes the medicine stay on the skin longer, which means you don't have to put it on as often. Active ingredients can get deep into the skin with polymer creams. This lets the medicine reach hair shafts and oil glands, which are where acne starts. People with acne often have redness and swelling on their skin. Polymer gels help reduce this inflammation, which is one of their main benefits. Polymer-

based creams leave behind a smooth, non-greasy layer on the skin that can help reduce the redness and pain that normal skin products cause. These are great for people with sensitive skin who might feel pain from normal acne treatments because they don't hurt as much. When someone has a skin problem, polymer-gel items can be used to put antibiotics or antifungal drugs right where they need to be. The medicine stays useful for longer because these forms give a steady flow of it. This is very important when healing skin diseases that don't go away. Drugs that don't mix well with water can be mixed better with polymer gels. This helps the drugs get through the skin and work better.

Novel Applications and Advancements in Polymer-Gels for Targeted Drug Delivery

Scientists are very interested in how polymer gels can be used to deliver drugs in a specific way. This method helps get medicine to the right places in the body, which improves treatments and lowers the risk of side effects. Newer polymer gel recipes have made it possible for "smart" gels to release drugs when they sense changes in acidity, temperature, or light. More advanced and individualised treatments can be made with these sensitive solutions, especially for cancer treatment, pain relief, and taking care of cuts that don't heal. Using tiny particles or carriers in polymer gel mixes is a big step forward because it helps drugs breakdown better, stay steady, and does their job better. These very small particles can get a drug to the right place without hurting healthy cells, which means fewer side effects. In the treatment of cancer, special gels made from polymers and tiny particles can be made to send chemotherapy right to areas with tumours. This helps keep good cells safe and makes the medicine work better. Polymer gels are being studied by researchers as a way to send genes straight to certain places and treat brain diseases.

RESULT AND DISCUSSION

Polymer-gel mixes showed they can effectively deliver drugs through the skin, allowing better absorption and controlled release of the medicine. In vitro studies showed that gels containing hydrophobic polymers displayed extended release, making them ideal for drugs needing longer treatment effects, such as pain control and hormone replacement. Rheological research found that gels with thixotropic traits spread easily and are comfortable for patients. Tests on living organisms showed that the gels effectively carry drugs while causing little discomfort and improving skin absorption. These results show that polymer gels could be a good option for delivering medicine without any invasive methods.

Table 2 shows the evaluation results of different polymer-gel formulas for drug release in vitro, focussing on key factors such as viscosity, drug release rate, total drug release, and skin entry efficiency. Formulations with hydrogel bases (Hydrogel A and B) showed higher drug release rates and total release percentages compared to organogels. Hydrogel B released the most medicine, reaching 90% in 24 hours. This is because it has a smaller thickness (450 cP), which helps the medicine move out more quickly. Hydrogel A, which has a thickness of 500 cP, released 85% of the drug, which is a bit lower than expected. Figure 3 displays how different composition qualities add up to affect drug delivery performance.

However, it still performed well overall, with 88% total drug release and 78% ability to penetrate the skin. In comparison, organogel formulas have a similar thickness but release the drug more slowly. Figure 4 shows the changes in release rate and stability of the formulations.

Table 2. Evaluation of Polymer-Gel Formulations for Drug Release (In Vitro).

Formulation Type	Viscosity (cP)	Drug Release Rate (%) after 24 hrs	Cumulative Drug Release (%)	Skin Penetration Efficiency (%)
Hydrogel (A)	500	85	88	78
Hydrogel (B)	450	90	93	82
Organogel (A)	600	75	78	70
Organogel (B)	550	80	82	74

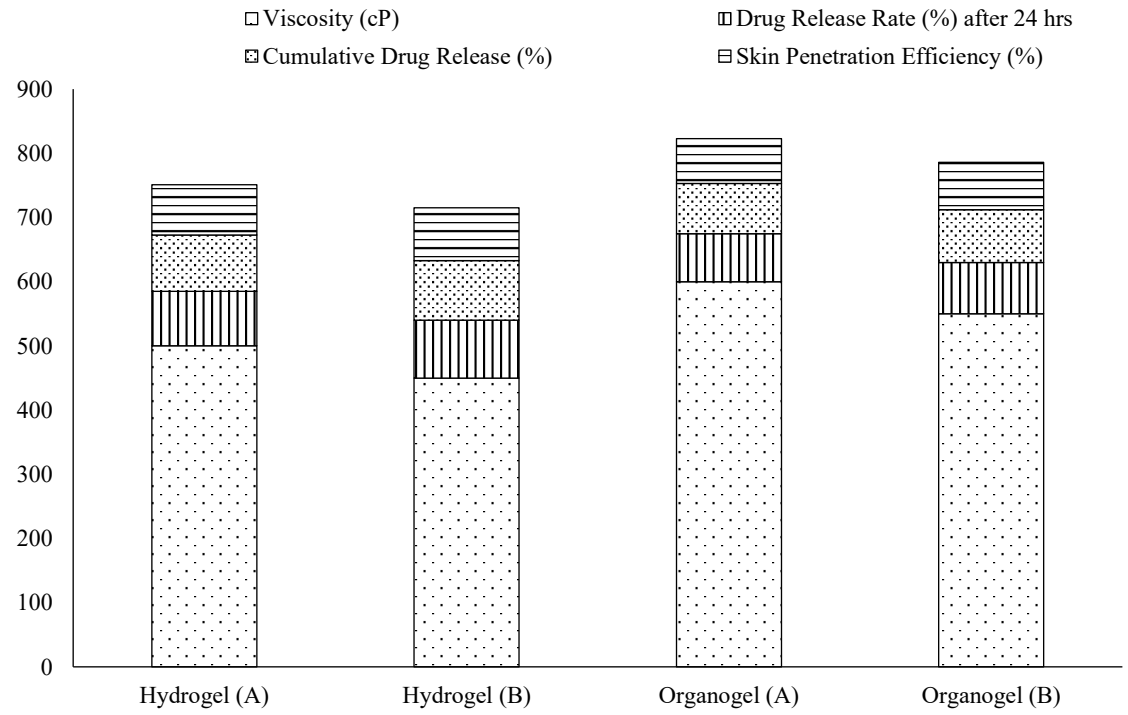

Figure 3. Cumulative Contribution of Formulation Properties.

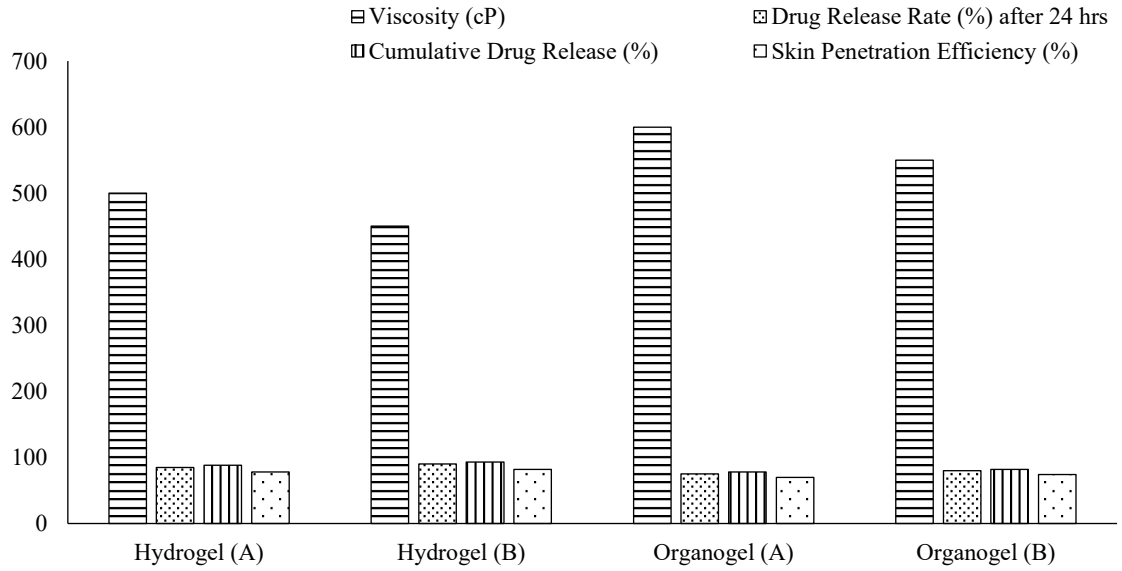

Figure 4. Comparison of formulation properties.

Organogel A, which is thick and has a thickness of 600 cP, released 75% of its content after 24 hours. Figure 5 shows changes in formulation qualities, focussing on gains in stability, release, and effectiveness. Organogel B, which is a bit less thick at 550 cP, did a little better, releasing 80% in the same time. The ability of the organogel forms to penetrate the skin was lower, especially in Organogel A (70%). This shows that they are less effective at getting the drug through the skin compared to hydrogel-based products. Table 3 shows the flow features of different polymer-gel mixtures, highlighting yield stress, thixotropy, and elastic and loss moduli. These qualities are key to knowing how the gel feels, how stable it is, and how well it works for delivering drugs through the skin. Nanogel formulations A and B had the highest yield stress values. Nanogel A was measured at 0.2 Pa, while Nanogel B was a bit lower at

0.18 Pa. The higher yield stress values show that the nanogels are better at resisting flow and can keep their shape when force is applied. Figure 6 shows the changes in stickiness and flexibility among the various formulas.

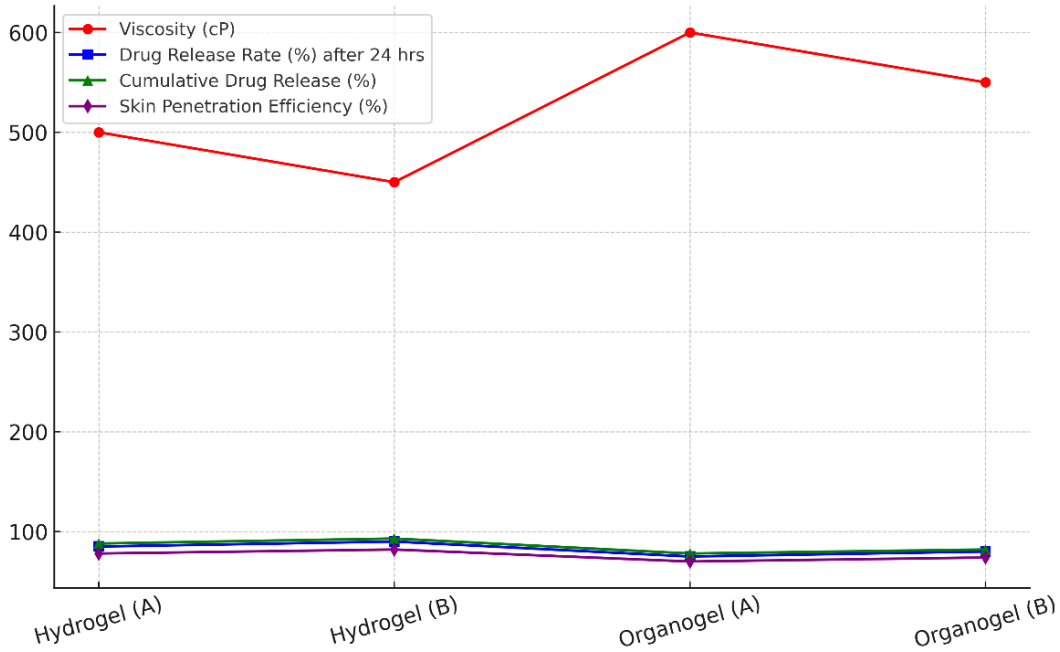

Figure 5. Trends in formulation properties.

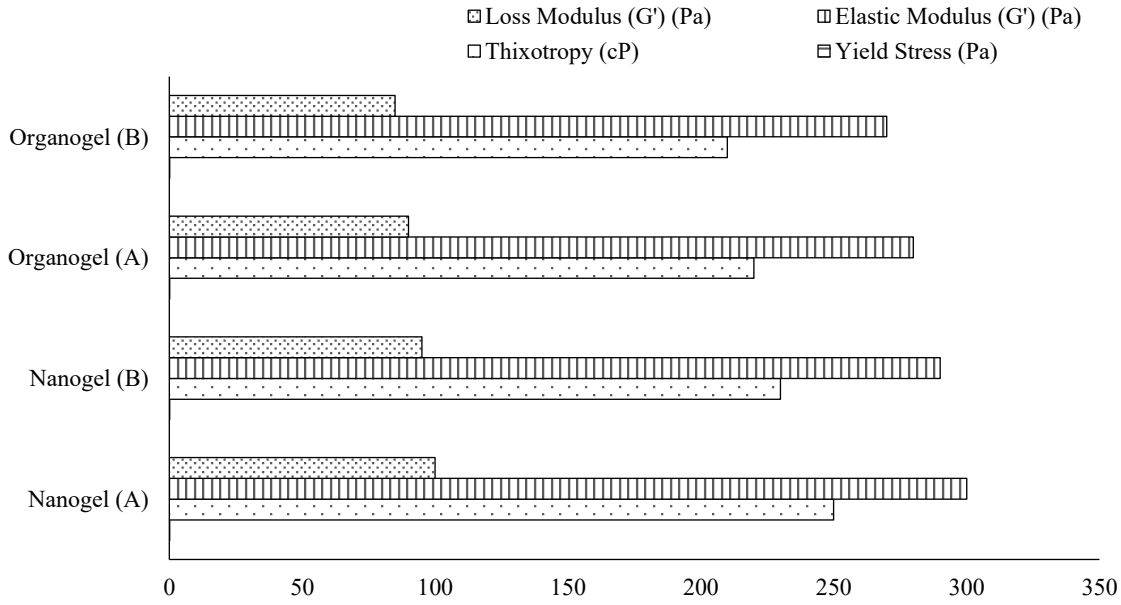

Figure 6. Comparison of rheological properties of formulations.

Table 3. Rheological Properties of Polymer-Gel Formulations.

Formulation Type	Yield Stress (Pa)	Thixotropy (cP)	Elastic Modulus (G') (Pa)	Loss Modulus (G') (Pa)
Nanogel (A)	0.2	250	300	100
Nanogel (B)	0.18	230	290	95
Organogel (A)	0.18	220	280	90
Organogel (B)	0.16	210	270	85

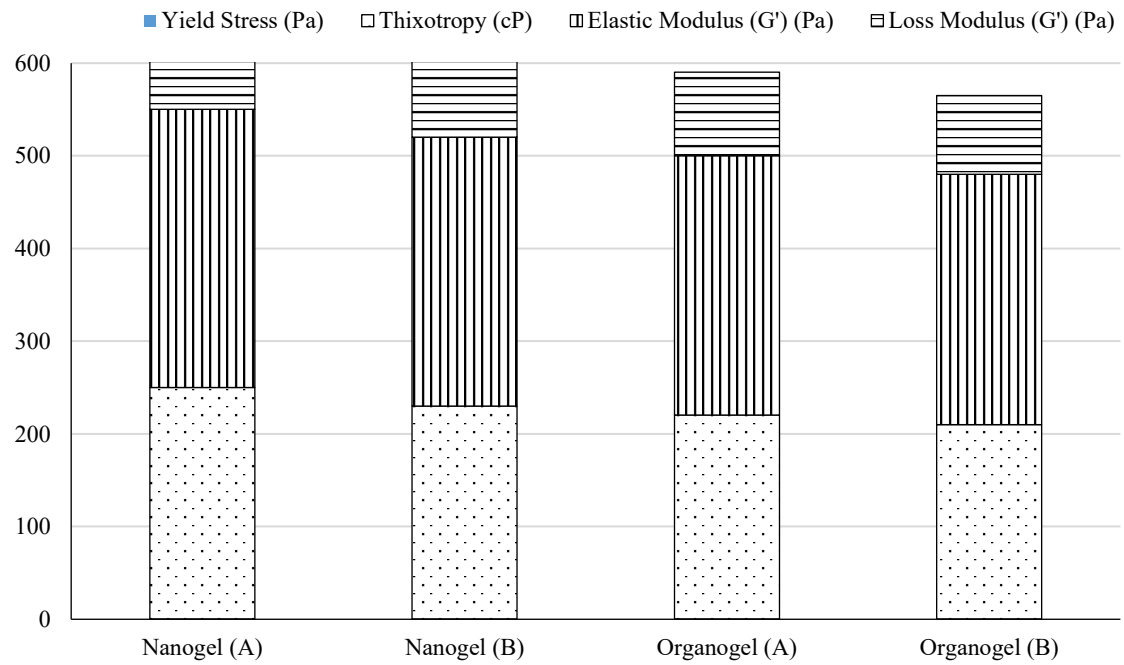

Figure 7. Cumulative rheological properties across formulations.

The thixotropy values of 250 cP for Nanogel A and 230 cP for Nanogel B show that these gels have the ability to return to their original viscosity after shear stress, which is helpful for ease of application and stability on the skin. Figure 7 shows how the qualities of different mixtures add up. It focusses on viscosity, flexibility, and how the mixture flows.

Nanogels were more flexible. Nanogel A had a load of 300 Pa and Nanogel B had a load of 290 Pa. This shows that Nanogels have a stronger network structure, which helps them keep their shape better on the skin. Nanogel A had a higher loss modulus (100 Pa), which shows how viscous the gel is under stress. This means that Nanogel A is more durable when bent.

CONCLUSION

Polymer-gel solutions are a flexible and effective way to get medicine into the body through the skin. They let different drugs be released slowly and steadily. These creams can help drugs break down better and go through the skin more easily. Because of this, they can be used to make drugs that like both water and fat. By using different natural and man-made polymers, the gel's qualities can be changed to meet the needs of different medical applications. Hydrogels, organogels, and nanostructured gels have all been used successfully to make it easier for pain killers, hormones, and skin products to get into the body through the skin. Instead of pills or shots, these choices are easier to use and work better. Nanoparticles and flexible polymers are examples of new technologies that have made polymer-gel recipes more promising for delivering specific drugs. Medicine can be sent through these systems at a steady rate, which can help people stick with their treatment and lower side effects generally. Polymer gels have a lot of advantages. They keep medicine levels fixed in the body, cut down on how often you need to take it, and stop the body from breaking down the medicine before it works, which is especially helpful for people with long-term illnesses. It's still not easy to make polymer-gel systems better at releasing substances, especially biological materials or molecules that are bigger or more complicated. We could get better and more customised treatments if we learn more about "smart" gels that change based on their surroundings. To make sure these goods work well over time, we also need to carefully check how stable they are and how long they last.

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