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A Comprehensive review on "Polymer-based gels: Properties, evaluation and emerging applications of Hydrogels, Organogels and Xerogels

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A B S T R A C T :

Polymer-based gels are promising systems for drug delivery, cosmetics, and biomedical use. This review covers key properties, classifications, and preparation methods of hydrogels, organogels, and xerogels. Hydrogels offer high water retention and biocompatibility for drug release and tissue engineering. Organogels, with lipid-based structures, support transdermal delivery and stability. Xerogels, formed by drying hydrogels, offer strong mechanical properties and are used in packaging, sensors, and drug delivery. The review also highlights pros, cons, and testing methods, focusing on recent innovations and future directions.

KEYWORDS: Gels, Hydrogels, Polymers, Organogels, Xerogels, Evaluation

1.INTRODUCTION:

1.1. Structure of gels:

A gel is a substance that is soft, stable, or solid-like that is made up of at least two components, one of which is a liquid, and is present in significant amounts. Gels are a condition of transitional matter that contains dependable substances (semi-liquids or semi-solids) as well as liquid. The cohesive qualities of solids and the diffusive transport capabilities of fluids are combined in gels. It is made up of a safe, reliable, three-dimensional component network. The polymer network in gels is created when polymer chains are cross-linked, either by the creation of non-covalent (physical cross-linking) or covalent (chemical) links . Gels are classified into two categories based on their nature: physical and chemical. Chemical gels contain a permanent covalent bonding that binds the particles together, whereas physical topical gels include weaker and reversible secondary intermolecular forces such hydrogen bonds, electrostatic interactions, hydrophobic contacts, and Vander Waal forces. (Sharma G, Anusha L, Kiran R, Geetha K, Rao T, 2022)

1.2. Ideal Properties of gels:

- The gel should be translucent and homogeneous.
- The gel should break easily when shear or force is applied while the container is shaking.
- The composition of the gel should be inert.
- The gel shouldn't stick.
- The gel must never come into touch with another formulation ingredient.
- The gel ought to be trustworthy.
- Avoid irritating the skin or any other area where the gel is applied. (Karande P, Mitragotri S,2009)

1.3. Advantages:

- Gels are easy to make in comparison to other formulations
- Gel is an elegant, non-greasy formula.
- Gels have excellent adherence to the area of application.
- Gels are biocompatible and environmentally benign.
- Have extraordinary ability in dealing with of adverse conditions.(Sharma M, Arjariya S, Chouksey R, Sharma N. A,2022)

1.4. Disadvantages:

- Gels work more slowly and persistently.
- The gelators or additives may cause skin irritation.
- The gel's water content increases the possibility of fungal or microbial assault.
- When the gel dries, the formulation loses its solvent.
- Some gels become unstable due to flocculation .(Muhammad sheraz,2016)

Classification of gels : Based on the solvent, gels are divided into three categories: hydrogels, organogels, and xerogels.(Gupta S, Archana, Niranjan.AK,2022)

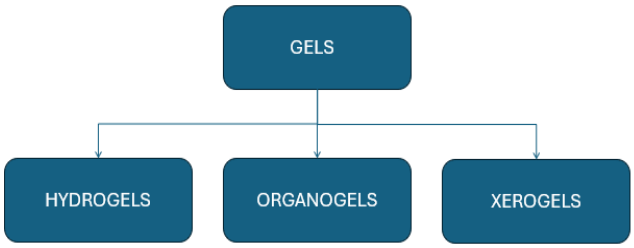

Figure 1: Classification of gels , Based on the solvent: hydrogels, organogels, and xerogels.

2. HYDROGELS:

Applications for hydrogels can be found in a variety of fields, including biotechnology, medicine, food, agriculture, and environmental science. Hydrogels are a class of materials that can retain a significant amount of water in their structure without dissolving. They are composed of hydrophilic polymer chains, which have an affinity for water and can absorb and retain large amounts of water or aqueous solutions.
Because of the crosslinking between the polymer chains, hydrogels maintain their solid structure even though they have the capacity to expand in water. They are especially suitable for controlled medication delivery systems, wound care, tissue engineering, and sensors because of their ability to respond to a variety of stimuli, including changes in pH, temperature, light, or ionic strength (Peppas, N. A., &Bures, P ,2000).

2.1. Properties of Hydrogels:

- **High Water Content:** Because hydrogels may expand and absorb water, they frequently retain a high amount of water, ranging from 20% to more than 90% of their weight.
- **Biocompatibility**: A lot of hydrogels, particularly natural ones like chitosan and alginate, are biocompatible, meaning the body can handle them well. This makes them perfect for use in pharmaceutical and medical applications.
- **Softness and Flexibility:** Because hydrogels include a lot of water, they are usually soft, flexible, and mechanically comparable to real tissues. Because of this, they can be used in soft tissue implants and wound dressings.
- **Swelling Behavior:** When hydrogels are exposed to water, they show special swelling characteristics. The hydrogel's chemical makeup and the surrounding conditions, including pH, determine how much swelling occurs.
- **Responsive Behavior**: Many hydrogels can respond to external stimuli (e.g., pH-responsive hydrogels, temperature-sensitive hydrogels). These smart hydrogels are used in controlled release systems, such as drug delivery.
- **Porosity**: Hydrogels can have a porous structure, which can facilitate the exchange of fluids, making them useful for tissue engineering and wound healing.
- **Biodegradability**: Some hydrogels are biodegradable, meaning they break down over time in the body, reducing the need for surgical removal. This property is important in medical and environmental applications.
- **Viscoelasticity**: Many hydrogels exhibit both viscous and elastic behavior, which allows them to absorb shocks and stresses, useful in drug delivery or as cushioning materials.

2.2. Preparation of Hydrogels:

The preparation of hydrogels involves several methods that allow the formation of cross-linked polymer networks capable of absorbing water. These methods can be broadly categorized into **chemical crosslinking**, **physical crosslinking**, and **solvent-based methods**.

2.2.1. Chemical Crosslinking

Chemical crosslinking involves the use of crosslinking agents to covalently bond polymer chains, forming a stable network structure. This method is used primarily for synthetic hydrogels, although some natural polymers can also be cross-linked chemically.

➢ **Free Radical Polymerization**

This is one of the most common methods for synthesizing synthetic hydrogels. Monomers with reactive functional groups are polymerized using free radical initiators. The radicals generated lead to the formation of covalent bonds between the monomers, resulting in a three-dimensional crosslinked network.

- **Example**: Polyacrylamide (PAM) hydrogels are often prepared using free radical polymerization of acrylamide monomers, in the presence of a crosslinking agent (e.g., N,N'-methylenebisacrylamide) and a free radical initiator like ammonium persulfate.
  Procedure:
  a) Water is used to dissolve the acrylamide crosslinker and monomer.
  b) .A free radical initiator (e.g., ammonium persulfate) is added.
  c) The polymerization is initiated, and the hydrogel forms in the solution.(Roy Chowdhury ,Santanu, Hussan SD, Rajesh G, Masih Daljit, 2013)

➢ **Polyaddition or Polycondensation**

Polyaddition or polycondensation methods involve the use of bifunctional monomers that react to form crosslinked polymers without the need for a free radical initiator. This method is often used for the preparation of hydrogels with functional groups that can participate in specific interactions or responses.

- **Example**: Hydrogels can be synthesized by polycondensation reactions, such as the reaction between diols and diisocyanates to form polyurethanes, or the reaction between diamines and dianhydrides.

2.2.3. Physical Crosslinking

Physical crosslinking relies on non-covalent interactions such as hydrogen bonding, ionic interactions, or van der Waals forces to form the hydrogel network. These hydrogels can often be "reversed" by changing the environmental conditions, such as temperature, ionic strength, or pH.

➢ **Ionic Crosslinking**

This method is particularly useful for hydrogels made from natural polymers like alginate or chitosan, which can be crosslinked in the presence of ions (typically divalent cations such as calcium ions).

- **Example**: **Alginate hydrogels** are formed by dissolving sodium alginate in water and then adding calcium chloride ($CaCl_2$) solution. The calcium ions bind to the carboxyl groups in alginate, creating crosslinks that form the hydrogel.
  Procedure:

  a) Dissolve sodium alginate in water to form a homogeneous solution.
  b) Dropwise addition of calcium chloride solution leads to the gelation of alginate through ionic crosslinking.(Roy Chowdhury,Santanu, Hussan SD, Rajesh G, Masih Daljit, 2013)

➢ **Thermoreversible Gelation**

Certain polymers exhibit the ability to undergo reversible gelation upon heating or cooling. The thermoresponsive property is typically attributed to the formation of physical networks through hydrophobic interactions, hydrogen bonding, or the self-assembly of polymer chains.

- **Example**: **Poly(N-isopropylacrylamide) (PNIPAM)** forms a gel at temperatures above its lower critical solution temperature (LCST), around 32°C. Below this temperature, the polymer is soluble in water, but above the LCST, it forms a gel due to hydrophobic interactions between the polymer chains.
  Procedure:

  a) Prepare a solution of PNIPAM in water.
  b) The solution will gel when the temperature rises above 32°C due to the polymer's transition from hydrophilic to hydrophobic behavior. (Karande P, Mitragotri S, 2009)

➢ **Hydrogen Bonding**

Hydrogels can also be formed through the formation of hydrogen bonds between polymer chains. This is commonly used with natural polymers like gelatin or agarose, which have functional groups capable of hydrogen bonding.

- **Example**: **Gelatin hydrogels** are formed by dissolving gelatin in hot water, followed by cooling. Upon cooling, the gelatin chains self-assemble into a network through hydrogen bonding. (Ribeiro, A. I., et al ,2014)

2.2.4. Solvent-Based Methods

Solvent-based methods involve the use of a solvent to dissolve the polymer and form a gel once the solvent is removed or the conditions change.

➢ **Solvent Evaporation**

In this method, a polymer solution is cast into a mold, and the solvent is evaporated, causing the polymer to self-assemble into a network and form a

hydrogel.

- **Example**: **Polyvinyl alcohol (PVA)** hydrogels can be formed by dissolving PVA in water, casting the solution into molds, and then allowing the solvent to evaporate, leaving behind the hydrogel network.
  Procedure:

a) Dissolve PVA in water at a high temperature.
b) Pour the solution into a mold and allow it to cool.
c) The water evaporates, leaving behind a hydrogel. (Soppimath, K. S., et al,2001)

- **Freeze-Thaw Method**

This method involves dissolving a polymer in water and then subjecting the solution to freezing and thawing cycles. This process induces the formation of physical crosslinks through the crystallization of water, which helps in the formation of the hydrogel.

- **Example**: **PVA-based hydrogels** can be prepared by freezing the PVA solution at sub-zero temperatures and then thawing it, which results in the formation of a gel due to crystallization and physical crosslinking. (Nair, L. S., & Laurencin, C. T, 2007).

2.2.5. Electrospinning

Electro spinning is a method for producing fibrous hydrogels by applying a high voltage to a polymer solution. This causes the polymer to form fine fibers that can then be crosslinked to form a network of hydrogel fibers. This technique is particularly useful for creating hydrogels with nanostructured, porous networks.

- **Example**: **Gelatin and chitosan electrospun fibers** can be crosslinked with glutaraldehyde to form fibrous hydrogels suitable for tissue engineering applications.
  Procedure:

a) Prepare a polymer solution in a suitable solvent.
b) Apply a high voltage to the solution to form nanofibers.
c) Crosslink the fibers with a chemical agent (e.g., glutaraldehyde). (Tan, Y. Q, et al, 2014)

2.3. Examples of Hydrogels:

- **Polyacrylamide Hydrogel**:
  A synthetic hydrogel widely used in applications like electrophoresis, drug delivery, and tissue engineering. Polyacrylamide can absorb large amounts of water and has good mechanical properties when crosslinked. (Peppas, N. A., &Bures, P,2000)
- **Alginate Hydrogel**:
  Derived from seaweed, alginate forms a gel in the presence of calcium ions. It is biocompatible, biodegradable, and widely used in drug delivery, wound care, and tissue engineering. (Lee, K. Y, & Mooney, D. J,2012)
- **Chitosan Hydrogel**:
  Chitosan is a biopolymer derived from chitin (found in shells of crustaceans). It is biodegradable, biocompatible, and antimicrobial, making it suitable for wound healing and drug delivery. (Shalumon, K. T, et al,2012)
- **Poly(N-isopropylacrylamide) (PNIPAM) Hydrogel**:
  PNIPAM is a thermoresponsive hydrogel that undergoes a phase transition at a specific temperature (around 32°C). It is used in drug delivery, tissue engineering, and biosensors. (Tan, Y. Q, et al.,2014)
- **Gelatin Hydrogel**:
  Gelatin is a natural hydrogel derived from collagen, which is widely used in biomedical applications such as wound healing, tissue engineering, and drug delivery systems. (Ribeiro, A. I., et al. ,2014)
- **Agarose Hydrogel**:
  Derived from agar, this natural polymer forms a gel in the presence of water. It is widely used in molecular biology, including as a matrix for gel electrophoresis and in tissue culture.(Morrison, C. A., & Phelan, M. ,2009).

3.ORGANOGELS:

Organogels have viscoelastic qualities and are non-glassy, thermoplastic, non-crystalline solids. They are semi-solid preparations with limited external apolar phase mobility. Movement in the apolar phase is limited because of physical interactions between structures of substances referred to as gelators. (Budumuru, Padmasri & Nagaraju, Ravouru & Damarasingu, Prasanth. ,2020).

Lecithin, cholesterol, cholesteryl anthraquinone derivatives, sorbitan monostearate, and other substances are examples of gelators. Because of their free fibrous structure genesis, which allows them to exist in low energy states, organogels are thermodynamically stable. Lecithin organogels' unique characteristics include their insensitivity to moisture, resistance to microbial contamination, viscoelastic activities, thermodynamic stability, and many more. Organogels provide a number of benefits. These include its ease of preparation, avoidance of first-pass metabolism, improved medication penetration through the skin, affordability, lack of moisture sensitivity, and decreased frequency of drug use. However, there are disadvantages as well,

like the need for appropriate storage conditions, the fact that impurities prevent gelling, the potential for skin irritation.(Das, Jisu & Bhattacharjee, Bedanta & Dutta, Jagya & Paul, Tirna. ,2021)

3.1 Preparation of organogel:

Fluid-filled fiber mechanism

A solution made up of an apolar solvent and a surfactant, such lecithin molecules, undergoes the gelation process when a tiny quantity of water is introduced. Before water is added, the surfactant is first distributed throughout the organic substrate. The molecules of the surfactant group together to create micelles when a tiny amount of water is added. These micellar structures grow into brief tubular or cylindrical aggregates when additional water is supplied. The hydrophilic ends of the surfactant molecules are where the water molecules stoichiometrically bind. When water is added, flexible, worm-shaped tubular micelles are created that come together to form a three-dimensional gel network with viscoelastic and thermo-reversible properties.Organic solvents are encapsulated within these reverse micelles.(Kirilov, Plamen & Le, Cong Anh Khanh & Rabehi, Halima & Rum, Silvia & Villa, Carla & Haftek, Marek & Pirot, Fabrice. ,2015)(Sushil Raut, Santosh Singh Bhadoriya, Vaibhav Uplanchiwar, Vijay Mishra, Avinash Gahane, Sunil Kumar Jain, 2012)

Solid fiber mechanism

The solid fiber mechanism entails dispersing the solid organogelator into an apolar solvent through a process of hot emulsification, resulting in an apolar liquid mixture containing the organogelator. Upon cooling to ambient temperature, the organogelator molecules begin to precipitate as fibrils, which interact with one another through non-covalent physical forces, creating a three-dimensional fibrous network structure. Consequently, the gelator fibers trap the apolar solvent, leading to the formation of a semi-solid organogel. (Tarun Garg,Ajay Bilandi,Bhawana Kapoor,Sunil Kumar,Ravi Joshi ,2011)

3.2 Properties

Viscoelasticity

Materials having both viscous and elastic characteristics are described by viscoelasticity, and organogels exhibit this behavior in accordance with the Maxwell model. Organogels have elastic properties and behave like solids at low shear rates. The interactions inside the fiber structure, however, deteriorate with increasing shear stress until shear stress reaches a critical threshold, at which point flow occurs. It is possible to characterize this process as plastic flow behaviour. (Esposito, C.L.; Kirilov,2021)

Hydrophilic-lipophilic balance

Organogels exhibit a good balance of hydrophilicity and hydrophobicity since they are made up of both oil and water. They have the capacity to dissolve a wide range of guest molecules. Polar drugs can dissolve in the polar phase, while lipophilic drugs can dissolve in the non-polar phase. Lecithin molecules are inherently amphiphilic, featuring polar headgroups that attract polar drugs and non-polar tails that solubilize nonpolar drugs.

Non-birefringence and optical transparency

The organogel is isotropic and exhibits non-birefringence, appearing as a single-phase system. From an optical perspective, it is transparent, which allows for visual inspection and enables easy detection of any particulate matter.

Thermostability

As the temperature of the organogel system rises, lecithin molecules take in kinetic energy, reducing the degradation of the organogel structure. At cooler temperatures, lecithin molecules come together again, which is why organogels possess inherent thermostability, making them beneficial for the delivery of bioactive agents and for use in cosmetic applications.Micro-organisms thrive in environments that contain water, but their growth is restricted in environments without water. In the case of organogels, the outer phase lacks water while the internal phase is aqueous, allowing lecithin molecules to be effectively shielded from microbial contamination. (Tarun Garg,Ajay Bilandi,Bhawana Kapoor,Sunil Kumar,Ravi Joshi ,2011)

3.3.Examples of Organogel

- **Lecithin organogels**
  The properties of lecithin-based organogels have been demonstrated to be thermodynamically stable, thermoreversible (with a sol-to-gel transition temperature at 40°C), viscoelasticity, non-irritant and biocompatibility. These organogels can either solubilize or trap multiple guest molecules within their structure. The lecithin organogel is utilized as the controlled delivery mechanism due to its specific characteristics.
- **Poly [ethylene] organogels**
  The use of organogels as bases for ointments is widespread. It is likely that the formation of a gelled structure is due to the physical interactions between the solid fibers, which are generated by the precipitation of polyethylene molecules.
- **Pluronic lecithin organogel [PLO]**

PLO possesses thermostable, viscoelastic, and biocompatible properties. PLO has also been shown to cause minimal skin irritation. It has been employed as a delivery vehicle for both lipophilic and hydrophilic substances for topical and transdermal applications.(M, Nagpal & I, Khan & Aggarwal, Geeta & Kaur, Raman & Singh, & Behl, Tapan & Jain, Upendra & V, Gupta.,2014)

- **Gelatin stabilized micro emulsion based organogel [MBG]**

Gelatin organogels exhibit thermostability and ease of preparation. The MBGs have been utilized to develop topical and/or transdermal controlled delivery vehicles for hydrophobic bioactive agents. A protein called gelatin is used as a structuring agent in many food preparations that have an excess of liquid phase.(Garg T, Bilandi A, Kapoor B, Kumar S, Joshi R, 2011)

4.XEROGEL:

Xerogels, a type of dried gel derived from hydrogels, are gaining significant attention due to their unique properties and versatile applications, particularly in the food processing industry. They are formed by evaporating the liquid within hydrogel pores, resulting in a dense, porous, and stable structure. This review delves into the fabrication processes, properties, and diverse applications of xerogels, with a particular emphasis on food science.(Almeida A, Ferreira C, Costa J, Correia I, Coimbra P, Gil M, 2024)

The food industry faces challenges in meeting consumer demands for safe, high-quality, and functional food products with extended shelf lives. Gels, particularly biopolymer-based hydrogels, are crucial in this context due to their compatibility with food applications, environmental friendliness, and adaptability. Xerogels, a variant of these gels, stand out for their mechanical stability, higher density, and efficient fabrication methods.(Shrestha S, Khan GM, Chawla A, 2023). Their large surface area and porous structure make them suitable for innovative applications such as 4D printing, biosensors, encapsulation, and controlled delivery systems.(Almeida A, Ferreira C, Costa J, Correia I, Coimbra P, Gil M, 2024)

4.1. Preparation of Xerogels

The fabrication of xerogels involves converting hydrogels into solid, porous materials through various drying methods. Key steps include:

- Hydrogel Formation: Polymers like gelatin, pectin, cellulose, and alginate are used to form hydrogels, often incorporating crosslinking agents to improve stability and functionality.(Shrestha S, Khan GM, Chawla A, 2023).
- Drying: Techniques such as freeze-drying, vacuum drying, or ambient drying are employed to remove the liquid while retaining the porous structure. Slow and controlled drying prevents shrinkage and cracking
- Tailoring Properties: The precursor materials, solvent types, drying conditions, and crosslinking agents significantly influence the xerogel's physical and chemical properties.

For example, soybean protein isolate (SPI) combined with soybean soluble polysaccharide (SSPS) produces xerogels with tailored texture and bending properties, making them suitable for 3D structural applications. Similarly, pectin xerogels demonstrate high density and prolonged drug release capabilities, indicating potential for pharmaceutical and food applications. (Almeida A, Ferreira C, Costa J, Correia I, Coimbra P, Gil M, 2024)

4.2. Properties of Xerogels

Xerogels are characterized by their high density, low porosity, and tailored mechanical properties. Factors influencing these properties include the precursor material, drying method, and solvents used. Key attributes are:

- Porosity and Surface Area: Xerogels typically have a porous structure with a large surface area, making them effective for encapsulation and adsorption applications.(Wang Z, Zhang H, He H,2023)
- Mechanical Stability: The dense structure enhances mechanical strength, making xerogels ideal for structural applications in food and pharmaceuticals.
- Thermal and Chemical Stability: Crosslinking agents improve thermal resistance and reduce swelling, enhancing the xerogels' functional range.

Examples include starch-based xerogels, which exhibit high solubility and swelling power, making them suitable for pharmaceutical uses. Acetylation of starch xerogels further enhances their properties for applications like film formation and packaging.(Xu Z, Zhang H, Tan X,2020)

4.3. Applications of Xerogels

4D Food Printing

Xerogels are pivotal in the emerging field of 4D food printing, which involves shape-shifting materials responding to external stimuli such as heat, moisture, or pH changes.

- Shape Transformation: Tapioca and corn xerogels, treated with constraints like cellulose acetate, transform from flat 2D structures to intricate 3D shapes when exposed to specific conditions (e.g., frying or hydration).
- Cold Plasma Treatment: Enhances the surface properties of xerogels, enabling more pronounced and controlled transformations.

The use of 4D printing reduces material costs, optimizes packaging, and allows customization of food shapes and textures.

Biosensors

The porous structure and large surface area of xerogels make them ideal for biosensor applications in food safety and environmental monitoring.

- Mechanisms: Active agents such as enzymes, antibodies, or receptors are immobilized within xerogels for detecting target molecules.
- Examples: Vanadium pentoxide xerogel sensors detect ammonia and amines in spoiled fish.

- Silica xerogels doped with fluorophores identify pollutants like pentachlorophenol.
- Bismuth-doped carbon xerogels detect heavy metals such as lead and cadmium.
- Xerogel-based biosensors are rapid, sensitive, and customizable, but their specificity can limit scalability. (Almeida A, Ferreira C, Costa J, Correia I, Coimbra P, Gil M, 2024) (Wang Z, Zhang H, He H,2023)

Encapsulation and Delivery Systems

Xerogels are effective carriers for bioactive compounds, nutrients, and drugs due to their high encapsulation efficiency and controlled release properties.

- Drug Delivery: Pectin and starch xerogels demonstrate prolonged drug release, maintaining integrity under various conditions.
- Functional Foods: Cereal-based xerogels impregnated with bioactive compounds show potential in developing nutraceuticals and targeted nutrient delivery systems.

Adsorption and Contaminant Removal

Xerogels are effective in removing contaminants such as dyes, heavy metals, and organic pollutants.

- Applications: Chitosan-based xerogels remove food dyes, while carbon xerogels with copper remove caffeine from water.
- Mechanisms: Adsorption occurs through porous entrapment, hydrogen bonding, or ionic interactions.

4.4.Challenges and Future Prospects

While xerogels offer immense potential, challenges remain:

- Scalability: Adapting fabrication processes for industrial-scale production.
- Stimuli Responsiveness: Exploring responses to multiple stimuli for 4D applications.
- Biosensor Versatility: Enhancing specificity without compromising scalability.
- Cost Efficiency: Reducing production costs to broaden accessibility. (Almeida A, Ferreira C, Costa J, Correia I, Coimbra P, Gil M, 2024) (Shrestha S, Khan GM, Chawla A.,2023)

5.Evaluation of gels:

5.1. Measurement of pH: The pH of various gel compositions is measured with a digital pH meter. One gram of gel is mixed with 100 milliliters of freshly prepared distilled water, and the mixture is left to dissolve for two hours. The pH of each formulation is measured three times, using the average values are being calculated.(Kamal Saroha, Singh S, Aggarwal A, Nanda S.,2013)(Patil PB, Datir SK, Saudagar RB, Jun 15,2019)

5.2. Viscosity measurement: A Brookfield digital viscometer may be used to assess the viscosity of generated gel compositions. The gels rotate at 0.3, 0.6, and 1.5 revolutions per minute. For every speed, the corresponding dial reading is recorded. The viscosity of gel may be calculated by multiplying the dial value by a factor found in the Brookfield viscometer catalogs.(Goyal S.,Jan1, 2011)

5.3. Spreadiability: It shows the size of the region that gel spreads easily when applied to the skin or other afflicted area. The spreading value of a formulation also affects its therapeutic efficacy. The time, expressed in seconds, it takes for two slides to separate from the gel placed between them under a particular load is known as spreadability. When two slides are separated in shorter time, the spreadability improves.

S = M is the formula. It is calculated as L / T.
where, M is the weight attached to the top slide.
L is the glass slide length.
T is the amount of time needed to split the slides.

5.4. Diffusion studies: Diffusion experiments of the pre-arranged gels can be conducted in a Keshary-Chien dispersion cell in order to concentrate on the disintegrating arrival of gels via a cellophane layer. The gel test (0.5g) is taken in cellophane film, and the dispersion review is conducted at 37° using 25 ml of phosphate cradle (pH 7.4) as the disintegration medium. Five milliliters of each sample should be removed and replaced with an equivalent volume of brand-new disintegration medium at regular intervals of one, two, three, four, five, six, seven, and eight hours. After that, the example is examined for total fulfillment at 362 nm employing a phosphate support as a clear.(Verma, A. & Singh, & Kaur, Raman & Jain, Upendra. ,2013)

5.5. Study for extrudability: The formulations were put into the collapsible tubes once the gels had solidified in the container. The formulation's extrudability was determined by calculating the weight in grams required to extrude a 0.5 cm gel ribbon in 10 seconds.(Chhatrani B, Dhiren P, Shah, Lalbhai N,2017)

5.6. Homogeneity: The produced gels are all visually examined for homogeneity after being put in the container. They are searched for aggregates an their appearance is assessed.

5.7. Content of drugs: 100 ml of an appropriate solvent was combined with 1 g of the produced gel. After filtering the stock solution and measuring absorbance, aliquots of varying concentrations were made using appropriate dilutions. The formula, which was derived from a linear regression study of the calibration curve, was used to determine the drug content.

5.8. Gritty nature: Each formulation is examined under a light microscope to see whether any significant particle matter is present. Therefore, it

is clear that the gel preparation satisfies the necessary separateness from specific matter and grittiness for any topical application. (Loveleen P, Kaur, Garg R, Gupta G, 2024)

5.9. Stability: The process used was freeze-thaw cycling. Syneresis was seen when the product was exposed to 4°C for a month, 25°C for a month, and 40°C for a month. The gel is then allowed to come into contact with room temperature. Take note of the separated liquid exudate.

5.10. Skin irritation study: For the purpose of testing for skin irritation, ten healthy male and female volunteers were chosen. For six hours, a 2 cm patch of 100 mg gel was put to the inside of the upper arm, and it was wrapped with a cotton bandage. The sites were cleansed with acetone after six hours, and measurements were taken using the Draize scale. No irritation: 0 Mild irritation: 1 High irritation: 2 (Ravali, P., Swetha, M., & Battu, S, 2024)

6. Applications of gels:

6.1. Hydrogels:

- Hydrogels as Transdermal Delivery Systems: Hydrogels have been extensively investigated as transdermal delivery systems for pharmaceutical and cosmetic applications to promote the percutaneous penetration of active ingredients, thereby improving the therapeutic effectiveness of topically applied medicaments as well as cosmetic products.
- Hyaluronan-Based Nanohydrogels for Injectable Formulations: Recent developments in hyaluronan-based nanohydrogels that show an improved stability against hyaluronidase have made it possible to develop injectable cosmetic formulations with extended long-term efficacy. Hyaluronan-based nanohydrogels provide a biocompatible and safe option for achieving long-lasting effects of aesthetic procedures.(Montanari E, Zoratto N, Mosca L, Cervoni L, Lallana E, Angelini R ,2022)
- Hydrogels in Dermatology and Cosmetology: Hydrogels are known to play a vital role in the field of dermatology and cosmetology as well. They act as a vehicle for the controlled release of active substance benefitted by their biocompatibility and their ability to interact with living tissues employed in various cosmetic purposes. (Zagórska-Dziok M, Sobczak M, 2020)

6.2. Organogels:

- Lipstick Formulations with Enhanced Photoprotection: Incorporation of low-molecular-weight organogelators (LMOGs) such as 12-hydroxystearic acid (12-HSA) into lipstick formulation has been shown to increase the sun protection factor (SPF). The presence of these organogels enhances the thermal and mechanical properties, improve resistance to heat and UV radiation.(Esposito, C.L.; Kirilov,2021)
- Acai Oil-Based Organogels for Anti-Aging Applications: Application of organogels structured with 12-HSA for encapsulation of acai oil and hyaluronic acid have been explored for possible anti-aging application. Acai oil shows antioxidant potential while hyaluronic acid provides moisturizing effect. The presence of the organogel matrix helps to stabilize and facilitate controlled released behaviour.(Sanches SC da C, Ré MI,2023)
- Organogels as Emollient Vehicles in Topical Treatments: Use of organogels as emollient vehicles in topical drug delivery system has been reported. Organogel forms a protective layer on the skin, leading to better permeation and more improved effect of drugs, which makes it potent candidate for the development of several cosmetic and pharmaceutical products.(Chauhan I, Chopra H, Arora P, Sharma V,2018)

6.3. Xerogels:

- Xerogel Films for Active Ingredient Loading: It has been reported that xerogel films can load active compounds such as salicylic acid in topical applications. The releases of these actives from the film provide controlled release, like a reservoir system, and other skin treatments appear to be more stable and effective with such actives.(Almeida A, Ferreira C, Costa J, Correia I, Coimbra P, Gil M,2024)
- Carbon xerogels in cosmetic applications: Carbon xerogels (CXs) have been created for a variety of uses, such as catalysis, insulation, separation, and adsorption. These special materials may be used as encapsulants or fillers29 in cosmetic formulations to enhance the stability and performance of the final product.(Xu Z, Zhang H, Tan X, et al,2020)
- Silicone-Based Organic–Inorganic Hybrid Xerogels:Silicone-based organic–inorganic hybrid xerogels have been developed, with the intent to improve the mechanical properties of aerogels, by designing different hybridization routes. These materials have boosted properties that could bring benefits in terms of performances and stability of final products.(Peppas, N. A., &Bures, P,2000).

7.CONCLUSION:

Topical gels are becoming effective and patient-compliant dosage forms because of their simple forms and stable formulation that allows for easy application and targeted delivery systems via topical drug delivery. Hydrogels, organogels, and xerogels present their own benefits for different dosage forms and are suitable for a multitude of cosmetic and pharmaceutical uses. The unique challenges may remain such as issues with stability and irritation from some gels but there are still endless avenues for advancement in formulation. Gels are expected to play an increasing role in both therapeutic and cosmetic innovations**.**

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