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Review

Advances in Hydrogel Film Fabrication and Functional Applications Across Biomedical and Environmental Fields

Alberto Ubaldini [1,*] and Sara Calistri [1,2]

[1] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, C.R. Bologna, Via dei Mille 21, 40121 Bologna, BO, Italy; sara.calistri2@unibo.it
[2] Department of Pharmacy and Biotechnology, University of Bologna, 40126 Bologna, BO, Italy
* Correspondence: alberto.ubaldini@enea.it

Abstract

Hydrogel films are a promising class of materials due to their peculiar property of retaining water as well as responding to external stimuli. In contrast with conventional hydrogels, films provide enhanced responsiveness along with greater compliance to be integrated into devices as well as on surfaces. This review is designed to comprehensively explore the many aspects of hydrogel films. It covers the principles of gelation; preparation methods, such as solvent casting, spin coating, and photolithography; and characterization. This review also presents the most common polymers (both natural and synthetic) utilized for the preparation of the hydrogel, the systems, such as nanoparticles, liposomes and hybrid metal–organic structure, that can be used as additives and the aspects related to the biocompatibility of hydrogels. In the second part, this review discusses the potential applications of hydrogel films and the challenges that still need to be overcome. Particular attention is given to biomedical applications, such as drug delivery, wound healing, and tissue engineering, but environmental and agricultural uses are also explored. Finally, this review presents recent examples of real-world applications of hydrogel films and explores the possibility they have for a wide variety of needs.

Keywords: hydrogels; films; preparation methods; applications

Academic Editor: Richard Yongqing Fu

Received: 23 July 2025
Revised: 27 August 2025
Accepted: 28 August 2025
Published: 30 August 2025

Citation: Ubaldini, A.; Calistri, S. Advances in Hydrogel Film Fabrication and Functional Applications Across Biomedical and Environmental Fields. *Appl. Sci.* **2025**, *15*, 9579. https://doi.org/10.3390/app15179579

1. Introduction

Gels consist of a three-dimensional, physically or chemically, crosslinked polymeric network and a liquid phase, dispersed among the meshes and pores of this network [1]. The liquid content can even exceed 95% by weight ratio [2]. They are, therefore, a composite colloidal semisolid system, and they are normally very homogeneous. Many gels have the capacity to absorb large amounts of liquid and swell [3]. In general, the liquid phase can be of different natures and chemical compositions: when it is an organic liquid, these systems are called organogels, but the systems of greatest interest are those in which the liquid is water, and they are called hydrogels.

The interplay between the chemical–physical characteristics of the liquid phase and of the polymeric component determines the properties of the gels, and the possibility of their fine control, by controlling the chemistry of the chains, their average molecular weight, the degree of crosslinking and by the presence of possible additives, such as nanoparticles [4,5], liposomes [6,7], drugs [8] or others, makes gels very attractive and interesting [1,9–11]. There are various types of gels, including systems where the polymer

component is inorganic. However, the most significant are those in which the polymer is organic, often of biological origin.

Over the years, these materials have been the focus of intensive research, leading to the development of numerous practical applications, particularly in the biomedical field but also in other areas.

Hydrogels are highly attractive materials for medical applications due to their excellent biocompatibility and remarkable responsiveness to various stimuli [12,13]. They offer significant potential for controlled drug delivery [14], serve as effective media for cell growth [15], and are valuable in biological tissue engineering [1] as temporary scaffolds for cells [16].

In addition to biomedical uses, hydrogels have a wide range of other applications. They can function as optical biosensors [17], pressure sensors [18], functional coatings [19], food packaging materials [20], soft actuators [21], flexible electronic components [22], lubricants [23], and more. This stems from the fact that by changing the composition of the starting materials and processing conditions, the characteristics of the resulting materials based on polymers can be tailored. For example, it is easily possible to control the properties of alginate-based hydrogels [24,25], such as swelling capacity or mechanical properties, by controlling the concentration of the crosslinking agent (which can be calcium chloride, $CaCl_2$, or another salt of this element [26]) because higher concentrations lead to stiffer and less swellable structures due to the higher crosslink density.

Figure 1 shows a schematic representation of the possible uses of hydrogel and of their common sources.

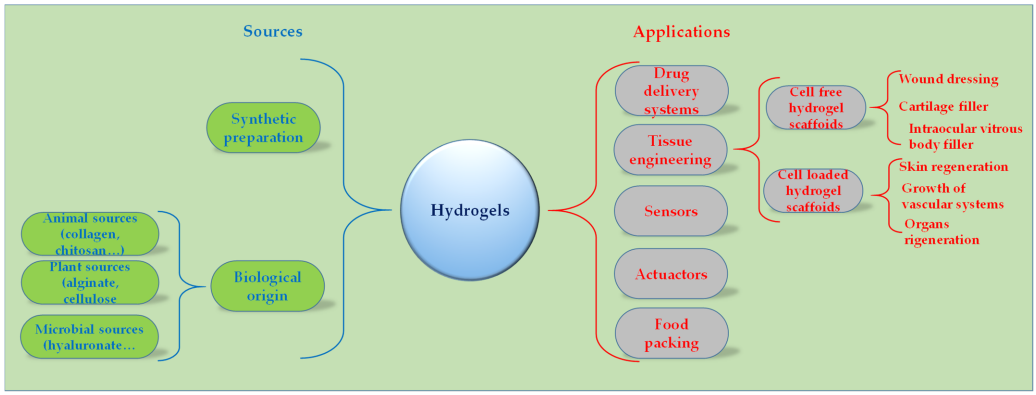

Figure 1. Classifications of hydrogels on the basis of their sources and applications.

Hydrogels have been extensively studied and investigated over the years, and many excellent articles and reviews exist on this topic. Numerous excellent reviews can be found on these topics, considering their importance. However, most of the studies have been based on bulk materials. Therefore, this review deals with hydrogels in the form of thin films. Hydrogels in film form can exhibit the same properties as in bulk form but also exhibit faster response speed and excellent ability to adapt appropriately to external environments and situations, great ability to integrate with other components and materials, and tuneable properties, particularly mechanical, making them ideal materials in many fields [9,27]. The properties of hydrogels can also be improved by adding functional components such as nanoparticles, liposomes and other systems, and this is also true in the case of films [28,29].

Actually, these investigations and papers focus primarily on a specific topic. Reviews may concern the chemical and physical aspects of hydrogel synthesis, gelation, or film preparation methods. There are many studies on their applications. Many of them concern biomedical applications, but there are also numerous studies concerning environmental, agricultural and other applications.

The purpose of this review is to provide an overview of everything related to these systems, from the general aspects of gelation to those concerning film formation. A discussion on the materials used to synthesize them, which can be both natural and synthetic, to present the main preparation methods and their applications in the biomedical, environmental, food preservation, and other fields is presented.

2. Hydrogel Synthesis and Film Preparation

The initial step in producing a hydrogel film involves the formulation of the gel. This typically requires blending polymeric materials with a solvent, most commonly water, to achieve a gel-like consistency. The specific formulation will depend on the desired properties of the hydrogel film. By definition, gelation is the process of formation of a gel from a system with polymers [30]. One of the requirements is that the chains have or can support branches. They can form links between the chains, leading to progressively larger polymers. As the linking continues, larger branched polymers are obtained, and at a certain extent of the reaction, links between the polymer result formally in the formation of a single giant molecule. The viscosity of the system becomes very large, at a specific point in the reaction, which is defined as the gel point. The onset of gelation is accompanied, therefore, by a sudden increase in viscosity. The so-formed giant polymeric unit coincides with the gel network and does not dissolve in the solvent but can swell in it.

From a chemical point of view, gelation is the result of a complex series of processes that can be both chemical and physical, and many techniques are explored for the fabrication of hydrogel films. The fabrication of a film starts, in most cases, with a precursor solution that can be either a monomer or un-crosslinked polymer [28]; it undergoes a sol–gel transition of the solution to form the network structure [31]. The synthesis methods can be basically grouped into two main categories, namely the monomer polymerization route, in which polymerization, branching and gelation proceed simultaneously, and the polymer crosslinking route, in which polymerization occurs first and then crosslinking occurs subsequently [32]. Gelation itself can be of a chemical type when the crosslinking points are actual chemical bonds [33] that form between distinct chains or of a physical type, if other mechanisms intervene, for example, the formation of rigid crystalline zones or ionic bonds [34]. The two cases are not necessarily mutually exclusive.

Figure 2 shows a representation of the steps in hydrogel synthesis and the differences between chemical and physical crosslinking.

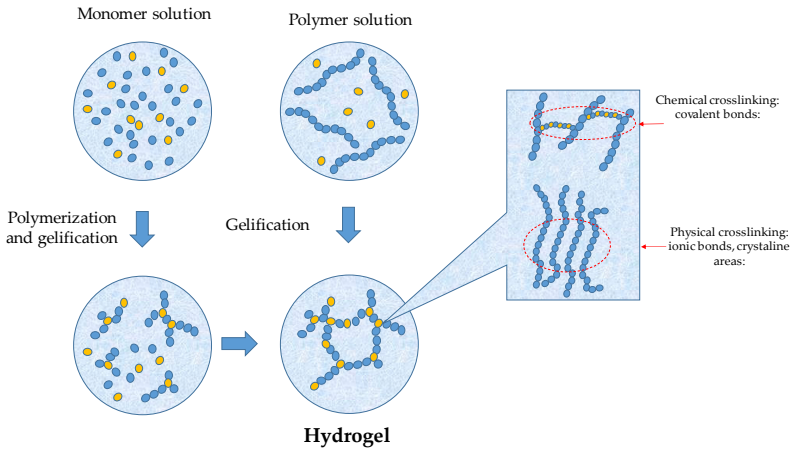

Figure 2. Steps for hydrogel synthesis and differences between chemical and physical crosslinking.

In general, hydrogels can be prepared through physical or chemical crosslinking of polymers. In the case of chemical crosslinking, new strong covalent bonds form among the polymer chains, while physical crosslinking involves non-covalent interactions like

hydrogen bonding or electrostatic interactions. In former case, the preparation involves using free radicals to initiate polymerization, followed by crosslinking between polymer chains with a crosslinking agent, like citric acid, glutaraldehyde, or epichlorohydrin, that can be used to create a crosslinked network [35]. The second situation is commonly used for systems like alginates, where calcium ions, Ca^{2+}, and other bivalent or trivalent ions are used to crosslink the chains [36]. Also, exposure to ionizing radiation can induce crosslinking in certain polymers, creating a hydrogel network [37].

There are many molecules that can act as crosslinking agents [38], and Figure 3 shows some of the more common ones.

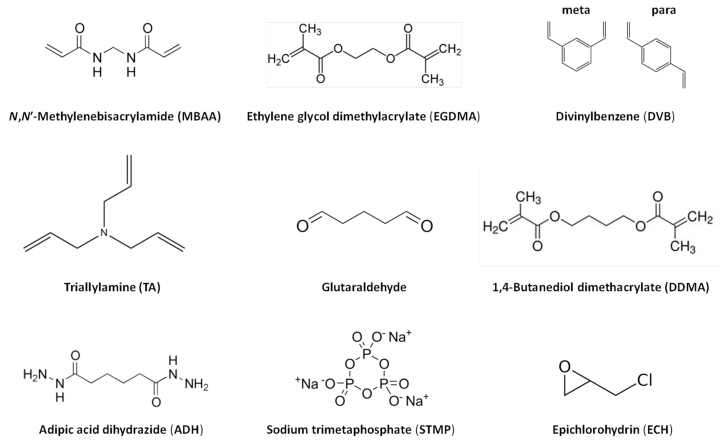

Figure 3. Common crosslinker agents for hydrogel synthesis.

Hydrogels show complex responses to various external stimuli, which can be chemical, physical or even biological [39]. Possible stimuli include changes in pH, ionic strength, the nature of the solvent, changes in temperature or pressure or even responses to electric or magnetic fields and enzymatic stimuli, and the changes can concern the water content, swelling or deflation, the release of drugs and molecules, changes in shape and volume, changes in catalytic or bioactive capacity. This makes these materials very attractive, because these responses can be regulated very precisely, allowing for a variety of possible useful applications. Figure 4 shows a schematic representation of the possible external stimuli, which can be chemical, physical or biological, to which hydrogels can be subjected and the possible responses to such stimuli, highlighting their adaptability and functionality.

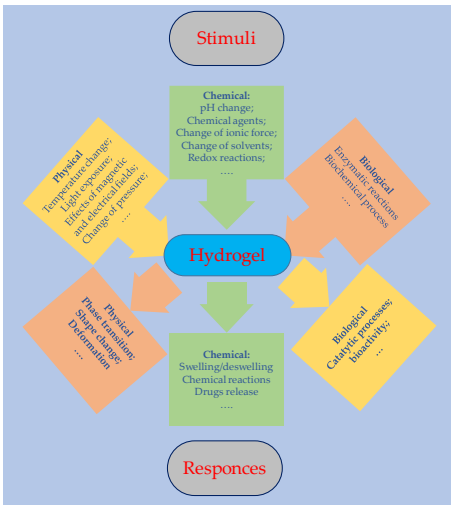

Figure 4. Possible stimuli to which a hydrogel can be subjected and possible responses that it can provide.

The potential of hydrogels depends on their chemical structure, type and degree of crosslinking. These factors influence key properties, such as thermal and chemical stability, photostability, structural and glass transitions and, consequently, affect the hydrogel's mechanical strength, swelling behavior, release profile, biodegradability, and biocompatibility.

2.1. Film Formation

There are several techniques for preparing hydrogel films. Some of these methods are broadly applicable to various materials, while others are more specific. These techniques can be classified in different ways, but a primary distinction is based on the gelation process, whether it occurs concurrently with polymerization and film formation or subsequently. The former case is the "in situ crosslinking" method [40]; the other is instead defined as "post-synthetic crosslinking" [41]. The in situ crosslinking method relies on the formation of the polymer chain from a solution of precursors, which can be monomers or oligomers, in the presence of a crosslinking agent, which induces the formation of the network structure. It is worth noting that the crosslinking agent can be a chemical substance that leads to specific chemical reactions, but it can also be a physical promoter, such as radiation, electronic plasma, UV rays and others, capable of breaking some chemical bonds and promoting the appearance of new ones [42].

In the post-synthetic crosslinking method, on the contrary, initially, a polymer film is prepared on a substrate from a soluble precursor polymer, and then, in a second step, it is crosslinked. This process can be due to the action of chemical molecules but also to physical mechanisms such as exposure to elevated temperatures or to various types of radiation. Figure 5 shows a schematic representation of the two possible film preparation paths.

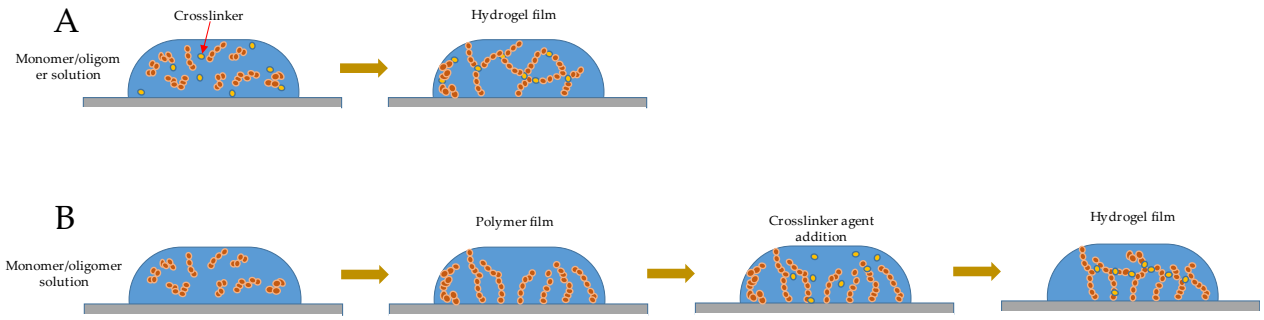

Figure 5. Schematic representation of (**A**) in situ crosslinking polymerization and gelification (1) and (**B**) post-synthetic crosslinking process, which consists of the deposition of a precursor solution on a substrate, followed by the formation of a polymeric film, the addition of the crosslinking agent and finally gelation.

Even if strong covalent bonds can form, the interactions between hydrogel films and substrates are often mainly due to van der Waals forces [43], like forces between the chains and the substrate itself, and, for this, there is no need for specific functional groups on the substrate surfaces or specific preparation or treatments of the surfaces. This allows the hydrogel coating to be applied to various materials.

Crosslinking and gelation can also be achieved through alternative approaches. Among these, microwave synthesis is certainly worth mentioning.

In this case, hydrogel films are created by using microwave irradiation to crosslink polymers in an aqueous solution [44,45]. This method offers several advantages over traditional methods, including faster synthesis times and the possibility of reducing waste.

Recently, this technique has been used, for instance, by Sun et al. [46], for preparing carbon dot-crosslinked sodium alginate hydrogel films and by Thongsuksaengcharoen et al. [47] for polyvinyl alcohol/polyvinylpyrrolidone/citric acid (PVA/PVP/CA) hydrogel preparation.

Microwave irradiation can induce crosslinking in polymer solutions and can minimize the need for chemical crosslinkers, leading to a potentially safer and cleaner product, often resulting in higher yields of hydrogel.

2.2. Preparation Methods

The choice of one route or another described in the previous subsection depends on numerous factors, including the chemical nature of the polymers that make up the gel, the adhesion capacity to the substrate, the kinetics and also the cost-effectiveness of the process.

Regardless, there are numerous techniques that have been explored for the preparation of hydrogel films. They can be formed by coating a substrate with a precursor solution. The drying process contributes to the removal of a solvent and favors the crosslinking of the polymer molecules, creating a solid and compact film. Although this list is not exhaustive, among the possible routes, these methods should be mentioned:

- Solvent casting [48]: In this case, the film is obtained by dissolving the polymer in a suitable solvent, subsequently casting the solution onto a substrate and then evaporating the solvent, which leaves a thin film.
- Dip coating [49], which consists of the application of a polymer solution to a substrate using a dipping technique.
- Spin coating [50], which consists of the application of a polymer solution to a substrate using a spinning technique.
- Spray coating [51], which consists of the application of a polymer solution to a substrate using a spraying technique.
- Blade coating [52]: a method where the film is obtained by spreading the starting solution on the substrate using a blade.
- Bar coating [53]: It is very similar to blade coating; solution is spread across a substrate via a cylindrical bar with wire spiraling around it.
- Slot die coating [54], in which the solution is coated directly onto the substrate. The solution flows through a 'head' at a determined rate as the substrate moves relative to the head.
- Photolithography [55], which is a technique used to create films on a substrate by exposing a photosensitive material to light radiation, usually ultraviolet. Often, a mask can be used to create complex structures.
- 3D printing [56], which is a manufacturing technique to create structures, building them up layer by layer, often by extruding a viscous hydrogel ink through a nozzle, although there are other modalities, such as, for instance, stereolithography (SLA), in which a photosensitive resin is polymerized layer by layer by a laser beam or light source, creating objects with high precision and detail.

These methods can be used in most cases for either in situ crosslinking or post-synthetic crosslinking. Each of them has advantages and strengths, but, at the same time, it is not a priori said that it can be used for any material. In this subsection, the principles of these processes and methods will be described.

Solvent casting is probably the easiest way to create polymeric films, including hydrogel films. It involves preparing a solution by dissolving a polymer and any required additives in a solvent, spreading the solution on a substrate, and then evaporating the solvent to form a solid film [57]. This process allows for control over the film thickness, uniformity, and properties of the resulting material. The solution is then poured or spread onto a substrate. Then, the substrate together with the solution is allowed to dry, leading to solvent evaporation. This forces the chains to align and form a solid film. In the case of hydrogel, the last stage is gelation.

This method is straightforward and cost-effective, as it does not require specialized equipment, thereby reducing production expenses. It is also highly versatile, allowing the fabrication of films from a wide range of polymers and additives. Additionally, the film thickness can be precisely controlled by adjusting the solution concentration and the volume of solution used. Its main limitations concern the need for toxic solvents and, in general, the fact that the solvents themselves can remain in non-negligible quantities in the film matrix, reducing their quality, limiting their applications when high biocompatibility and purity are required. Furthermore, the mechanical properties of the films, in particular the resistance, are often inferior to those obtained with other methods. A schematic of this method is shown in Figure 6.

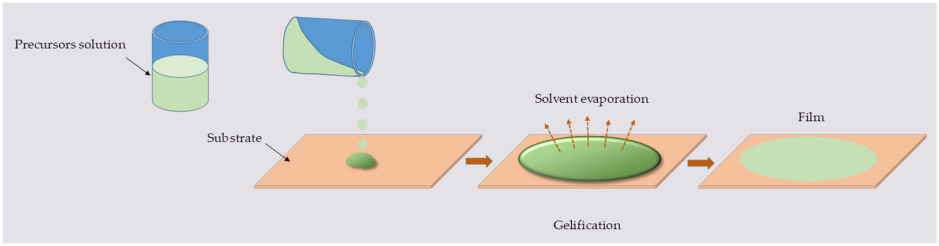

Figure 6. The solvent casting method.

The dip coating process consists of immersing a substrate into a tank containing a precursor solution, removing the piece from the tank, and allowing it to drain [40,51]. The coated piece can then be dried by force-drying or baking. It is a very popular way of creating thin film-coated materials because of its simplicity and possibility of being automated.

Film thickness can vary from top to bottom and is controlled by coating viscosity and the rate of withdrawal from the tank. The faster the substrate is withdrawn from the tank, the thicker the coating material. Since the solvent is evaporating and draining, the fluid film acquires an approximate wedge-like shape that terminates in a well-defined drying line, and when the receding drying line velocity equals the withdrawal speed, the process is steady state. Gelation usually occurs in this upper part of the layer adhering to the moving substrate, because, in this area, the concentrations, both of polymers and of the eventually present crosslinking agent(s), increase.

Figure 7 shows a schematic representation of this process.

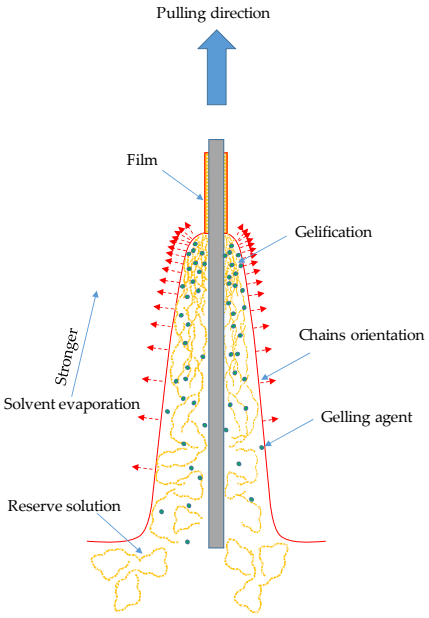

Figure 7. Schematic representation of dip coating process.

The spin coating process is a simple and very effective method for depositing films on substrates. The principle on which it is based is to produce films, normally very uniform and thin, by rapidly rotating the substrate [58]. The liquid solution of precursors is dispensed onto the center of the substrate, and centrifugal force helps to spread it out.

The solution can be placed, dropping a puddle, when the substrate is stopped, or, dynamically, it can be dispensed while the substrate is slowly rotating. In any case, the substrate is then accelerated to high rotation rates, typically between 500 and 4000 rpm (rotation for minutes). The resulting force generated by the rotation causes the solution to spread out, making it thin. The thickness of the resulting film is controlled by factors like spinning speed, solution viscosity, and solvent evaporation. In fact, among the key process parameters to be taken into consideration are the centrifugation speed, as higher speeds generally produce thinner films; the viscosity of the initial solution, because higher viscosities tend to produce thicker films; the evaporation rate of the solvent; and the total volume of the parent solution.

Figure 8 shows a schematic representation of the spin coating method.

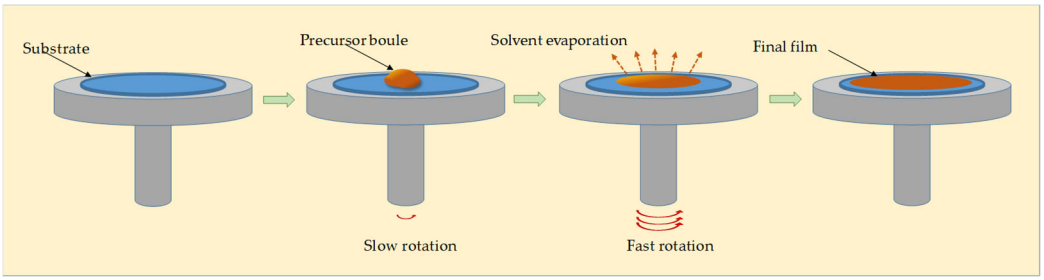

Figure 8. Schematic representation of spin coating process.

In the case of the spray coating method, hydrogel films are prepared by spraying a liquid hydrogel precursor solution onto the substrate [59]. This technique allows for the creation of thin, uniform, and often porous hydrogel coatings. Since the films prepared in this way can be adapted to different substrates and even complex geometries, this route is very versatile and attractive.

This method requires that a solution of precursors is broken up by a stream of pressurized gas and dispensed in a continuous flow of fine droplets onto the substrate using a spray gun or nozzle. After spraying, the solvent in the solution evaporates, leaving a thin, dry layer of the hydrogel precursor. This layer can then be crosslinked to form a stable hydrogel network. Crosslinking can be achieved via physical or chemical methods. Spraying parameters, such as pressure, nozzle type, and spray time, can be adjusted to control the thickness, roughness, and porosity of the resulting hydrogel film. The resulting hydrogel film can be porous or non-porous, depending on the specific materials and parameters used in the spray coating process.

Spray coating has the advantages of being scalable, even for large-scale production; flexible, because the substrates can also have complex geometries; and quite economical. In addition, the coating parameters can be adjusted to control the thickness and roughness of the hydrogel film, and this method can also be used to create porous hydrogel films.

Blade coating, also called doctor blade coating, involves running a blade over the substrate to spread a solution evenly across its surface [60]. There is a small gap between the blade and substrate, which, along with the viscoelastic properties of the solution and the speed of coating, determines the thickness of the wet film. Blade coating is a simple technique, inexpensive to set up, and with high productivity. By depositing the solution in a semi-controlled manner, solution waste is reduced. A small gap between the blade and the substrate defines the thickness of the wet film, which is then dried to form the final

hydrogel film. Different factors (e.g., substrate velocity or gap size) can be optimized to produce films of different thicknesses. Also, the shape and angle of the blade affect the uniformity and thickness of the film. A perpendicular blade is ideal for very thin, uniform coatings because it provides the greatest shearing. The blade is positioned to create a shear force on the coating material, effectively limiting its movement and controlling the thickness of the residual layer. At 45°, the blade creates a shear force against the liquid. This angle creates a balance between removing excess material and keeping some material on the substrate, which contributes to a medium layer thickness. When a blade angle is between 15° and 30°, thicker coatings are created by reducing the pressure on the material. These angles can be useful for applications where greater material deposition is required if working with highly viscous materials.

Figure 9 shows a schematic representation of the spin coating method.

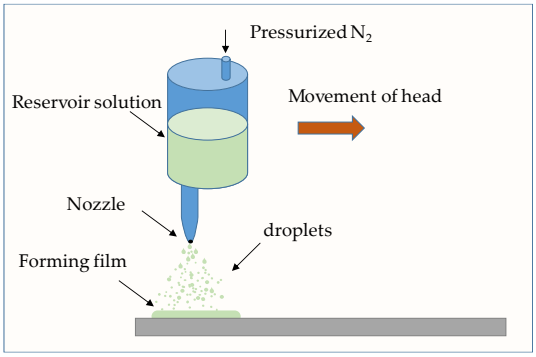

Figure 9. Schematic representation of spray coating process.

Blade coating is also suitable for solutions with a wide range of viscosities and both rigid and flexible substrates. Blade coating is scalable and ideal for producing thin films on an industrial scale. However, it is generally not possible to create films with thicknesses less than tens of microns. The film thickness of the wet layer has poor reproducibility. Films produced by blade coating may not be as uniform as those produced by other methods.

The principle of this method and the effect of inclination of the blade are shown in Figure 10, A and B, respectively.

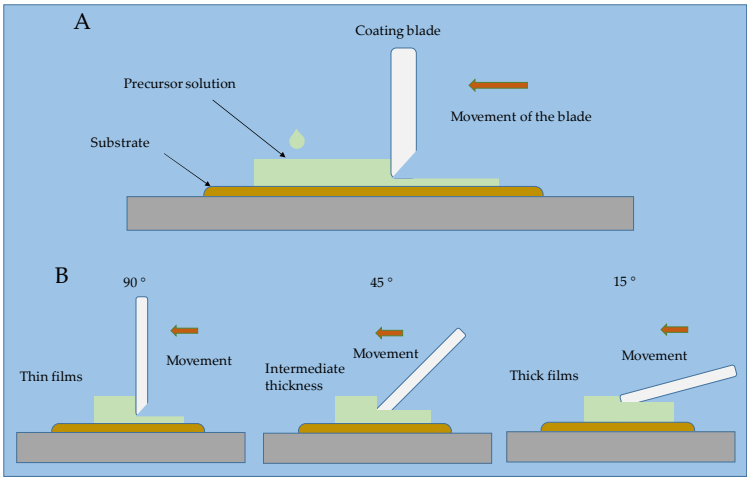

Figure 10. Principle of blade coating (**A**) and effect of the angle of blade on film thickness (**B**).

Bar coating is very similar to blade coating; the solution is distributed onto a substrate via a cylindrical rod with a wire spiraling around it [52,60]. A bar is placed above the substrate and then dragged across it.

The amount of solution that can pass is determined by the space available between the wire and the substrate. This, in turn, determines the film thickness; i.e., the bar is adjusted to a specific height above the substrate to control the thickness of the resulting film. The process can be optimized by adjusting the height and pressure of the rod, the deposition rate, the concentration and the viscosity of the solution.

Bar coating is cheap and easy to use. It allows for the use of very large surfaces and allows good scalability. As in the previous case, the film thickness is rarely less than about 10 microns. It is a slow process. The maximum speed is determined by the speed with which the gaps can be filled by capillary force. Patterns or gradients are not possible.

The scheme of this method is shown in Figure 11, in perspective view (A) and lateral view (B).

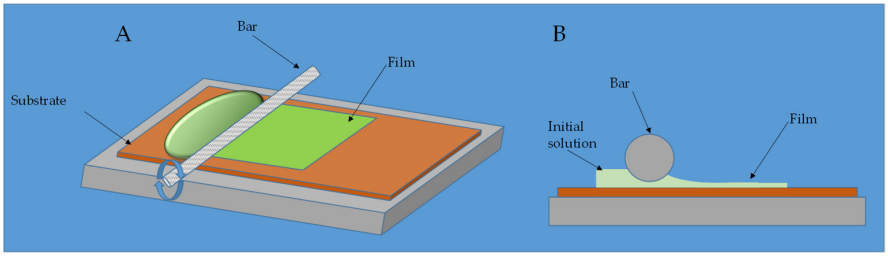

Figure 11. Principle of bar coating method: perspective view (**A**) and lateral view (**B**).

Slot die coating is a method for applying thin films, by metering liquid material through a narrow slot and onto a moving substrate [54,61]. Slot die coating technology is used to deposit a variety of liquid solutions, including polymer solutions, onto substrates of various materials such as glass, metal, and ceramic. This process creates a controlled meniscus or liquid curtain, ensuring uniform film deposition. The solution flows through a "head" at a set velocity. The wet film thickness is determined by the amount of solution applied to the substrate. All other parameters, such as solution flow rate, coating width, velocity, and viscosity, can be optimized to improve the uniformity and stability of the thin film deposition. Uniform films can be produced with both high- and low-viscosity solutions, achieving a wide range of thicknesses. By controlling the amount of solution deposited, solution waste during slot die coating is minimized. Slot die coating is easily scalable and allows for high coating speeds. It is a complex process with multiple parameters that need to be optimized. Most slot die coating machines are often designed for production. In general, slot die coating can be slower, more expensive, and more difficult to optimize. Figure 12 shows a schematic of this method.

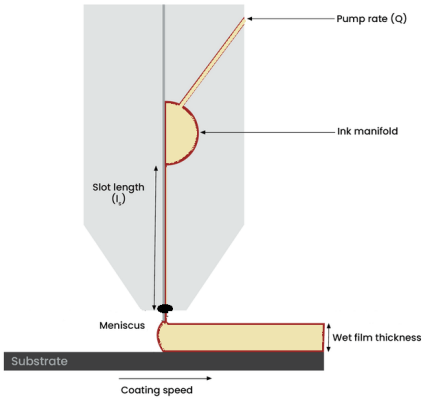

Figure 12. Principle of slot die coating method.

Photolithography is a modern technique for the preparation of a film based on polymer materials, including hydrogels [62].

It involves using light to selectively modify a photosensitive polymer film usually few micrometers thick, creating a pattern. This film can be prepared using one of the techniques described previously, most commonly spin coating. This process is fundamental in microfabrication and nanotechnology, allowing for precise patterning of materials at the nanoscale. A thin film of photosensitive polymer (called photoresist) is applied to a substrate. Its properties change when exposed to electromagnetic radiation (ranging from visible light to X-rays), either through some lens or by illuminating the whole sample, and, in particular, crosslinking can occur. Complex patterns can be obtained by using masks that selectively prevent some parts of the film from being illuminated and, therefore, from being modified. If different polymers, having different optical properties and different responses to light, are successively deposited on each other, it is possible to obtain selective crosslinking even along the vertical axis. Figure 13 shows a schematic representation of the photolithography method in the case of hydrogel films.

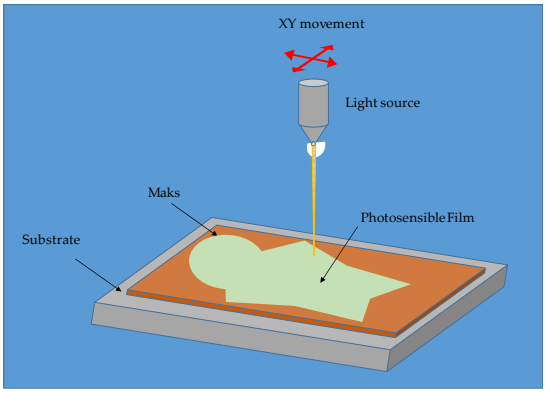

Figure 13. Principle of photolithography method.

Three-dimensional (3D) printing is a versatile strategy to construct gel films with sophisticated structures. It permits a wide-spectrum design of materials with the programmed geometry of a construct. The principle involves melting or curing the polymer material and precisely depositing it according to a digital model, building the object layer by layer until the desired shape is achieved [63].

Three-dimensional (3D) printing allows for the creation of objects and films in short timeframes, enabling rapid design iteration. It has the advantage of enabling the production of custom-made pieces for specific needs, without the need for expensive molds, enabling the creation of complex shapes and intricate geometries that would be difficult or impossible to achieve with other methods. Three-dimensional printing also offers the advantage of using only the material needed to create the object, reducing waste compared to traditional manufacturing methods. Its main limitations, however, are that it is suitable for the production of small batches of parts. Figure 14 shows a schematic representation of the principles of 3D printing for hydrogel films.

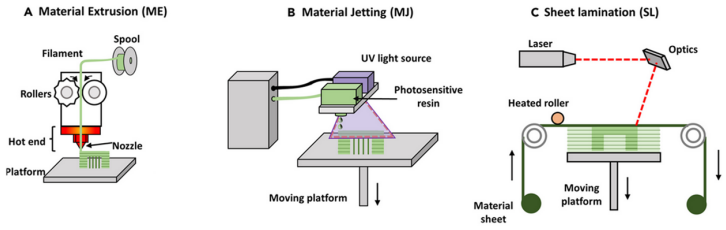

Figure 14. Schematic of the main 3D-printing techniques: (**A**) material in which the solid filament is melted, extruded through the nozzle, and deposited layer by layer; (**B**) material jetting in which products are made by selectively depositing the droplets of build materials; (**C**) sheet lamination in which thin sheets of material are bonded together layer by layer to fabricate an object.

Table 1 shows a comparison of the main characteristics of these methods [9,27,64].

Table 1. Comparison among film preparation methods.

Characteristics	Solvent Casting	Dip Coating	Spin Coating	Spray Coating	Blade Coating	Bar Coating	Slot Die Coating	Photolithography	3D Printing
Relative Cost	Low	Low	Medium	High	Medium	Medium	High	High/very high	High
Scalability		Limited	No	Possible	Possible	Limited	Possible	Possible	No
Complexity	Low	Low	Low	Medium	Medium	Low	Medium	medium	High
Uniformity of Films	Good	High	High	Low	Medium	Medium	High	High	Medium/high
Minimum thickness possible	Ten of micrometer	Nanometers	Nanometers	From tens to hundreds of nanometers	Ten of micrometer	Ten of micrometer	Nanometers	From tens to hundreds of nanometers	Micrometers
Patterning In Situ	Possible	Possible	No	No	Possible	No	Limited	Possible	Possible
Coatable Surfaces	Many types of surfaces they must be smooth and flat	Complex, rigid shapes	Small, flat substrates only	Flexible or rigid substrates, curved or flat surfaces	Flexible or rigid substrates	Flexible or rigid substrates	Flexible or rigid substrates	glass, polymeric, inorganic; pretreatment is often necessary	glass, polymeric, inorganic; pretreatment is often necessary
Solution wastage	High	High	High	Moderate	Moderate	Moderate	Low	high	Low
Drying Times	High	Slow	Fast	Fast	Slow	Slow	Slow	Slow	medium
Coating Speeds	Slow	Slow	Very slow	Fast	Fast	Slow	Fast	Low/medium	Fast

It is not easy to compare these methods and determine which one performs best. The choice is certainly influenced or even determined by intrinsic factors, such as the specific application the film is intended for, the nature and properties of the material, and even economic considerations. Furthermore, it should be kept in mind that often, and quite simply, the choice is based on the equipment available to a team, researchers, or companies.

Nevertheless, in some cases, important differences have been reported in films of the same type prepared via different methods. For example, Koto et al. [65] reported different viscosities in calcium alginate films prepared by spin coating or dip coating, which leads to different properties, including particle and drug release.

Thus, it can be said that for biomedical applications, techniques that allow the fabrication of hydrogel films with precise control over shape and structure and allow the creation of complex systems are preferable [27,66]. Very often for these applications, the creation of complex and customized hydrogel structures with precise control over their shape, size, and mechanical properties is required [67]. In this sense, the primary and most preferable preparation techniques are photolithography [68,69] and 3D printing [56,70], but slot die coating and dip coating are also useful.

On the contrary, these aspects, such as for agricultural applications, are not so decisive, and the preparation method is chosen based on other considerations [71]. Among these, scalability, repeatability, ease of production (possibly also for large products), the possibility of industrialization, as well as economic and cost aspects are very important. In these cases, techniques such as dip coating or spray coating are more useful [72].

Finally, in some sectors, such as sensors or electronic systems, where interaction with other materials and devices is important, factors such as the uniformity and thickness of the hydrogel film determine the preference for one method over another. Spin coating is often used for this purpose [73,74].

These aspects will be described in more detail in the following sections.

3. Characterization Techniques

The chemical–physical characterization of samples is an essential aspect in the field of hydrogels, both for the study and the assessment of their physical, mechanical, and biological properties and for the evaluation of their quality and the success of the preparation. Alongside general characterization techniques for these systems, there are many that more specifically concern hydrogels in film form. Among the former, spectroscopic investigations, XRD characterization, swelling tests, thermal and mechanical properties' analysis should be mentioned, while, among the latter, microscopic analyses are certainly relevant.

Spectroscopic characterization of hydrogels allows for the study of their chemical nature and composition and helps us to understand their functional groups, molecular interactions, and their structure. Among the main methods, it is worth mentioning the following:

- Fourier-transform infrared spectroscopy (FTIR);
- Raman spectroscopy;
- UV-Vis spectroscopy;
- Nuclear Magnetic Resonance (NMR) spectroscopy;
- Fluorescence spectroscopy.

Fourier-transform infrared spectroscopy, which is widely used to identify the functional groups present in hydrogels, helps us understand the chemical composition and interactions between the different components of a hydrogel. It allows for the analysis of various functional groups that can be present in the gel. Changes in peak intensity indicate the formation of new chemical bonds or modifications during hydrogel synthesis or they can be the result of different environmental conditions. Indeed, FTIR can help determine the degree and type of crosslinking in the hydrogel, by analyzing the spectral changes associated with crosslinking agents.

Raman spectroscopy is another vibrational spectroscopic technique and provides information on the vibrational modes of molecules within the hydrogel. It can be used to study the molecular structure, crystallinity, and interactions between the different components of the hydrogel. Similar to FTIR, Raman spectroscopy can also be used to monitor the gelation process and trace changes in molecular structure. This technique is also particularly useful for investigating network formation and interactions within hydrogels, including those containing nanoparticles or other materials

UV-Vis spectroscopy can be used to study the electronic transitions in hydrogel components. It can be used to monitor the kinetics of self-healing reactions in supramolecular hydrogels and to study changes in hydrophobicity. By analyzing how light is absorbed and transmitted by the hydrogel, information about its composition, structure, and properties can be obtained. UV-Vis spectroscopy can help identify the different components within a hydrogel, such as polymers, crosslinkers, and additives, and it can be used to follow the progress of hydrogel formation by observing changes in the absorption spectra as the polymer network develops.

In addition to this, this technique can be used, and is particularly important, to study the optical properties of hydrogels, such as their transparency and light scattering behavior, which is important for applications like tissue engineering and photonics.

NMR spectroscopy provides insights into their structure, dynamics, and interactions. By analyzing how atomic nuclei in the hydrogel respond to magnetic fields, NMR can reveal information about the polymer network, the water content, and the behavior of molecules within the gel. NMR can identify the specific monomers, and other molecular systems eventually present in the hydrogel matrix and their arrangement within the polymer chains that form the hydrogel network. NMR can differentiate between different water

populations within the hydrogel, such as bound water (associated with the polymer) and free water, thanks to changes and modifications in the chemical shifts.

It can also be used to study the mobility of molecules within the gel and the interaction of water with the polymer network. Finally, it can be used to estimate the mesh size of the hydrogel network. Actually, it can furthermore measure how freely the molecules in the gel can move. This can be affected by factors like crosslinking, swelling, and temperature. As hydrogels are semisolid in nature, solid-state NMR (ssNMR) is often used. Techniques like magic angle spinning (MAS) are often employed to reduce line broadening and improve resolution. Proton NMR relaxometry is a specific NMR technique that can provide detailed information about the water distribution and mobility within the hydrogel.

Fluorescence spectroscopy can be used to study the local environment around fluorescent probes within the hydrogel. It can be used to investigate the heterogeneity of the hydrogel system and the dynamics of encapsulated species or the gel network.

Various fluorescence techniques, such as fluorescence quenching, fluorescence polarization, and excimer fluorescence, can be employed to gather different types of information. These techniques provide a powerful toolkit for unraveling the complexities of hydrogels, enabling the development of advanced materials for various applications.

X-ray diffraction is a valuable technique for characterizing hydrogels, providing insights into their crystallinity, phase identification, and structural order. By analyzing the diffraction patterns, it is possible to determine the presence of crystalline phases, identify the specific crystal structures, and assess the degree of crystallinity within the hydrogel. This information is crucial for understanding the physical and mechanical properties of the hydrogel and its potential applications. This is particularly useful and important in the case of hybrid systems where crystalline components, often inorganic, are added to the hydrogel.

A swelling test measures how much a gel expands when exposed to a liquid, water in the case of hydrogel. This test is very important for understanding the properties of these materials and their potential applications. The swelling behavior is influenced by factors like the hydrogel's composition, crosslinking density, and the surrounding environment (e.g., pH, temperature, ionic force. . .).

In general, hydrogels with a high reticulation degree swell less because there is less space for water to enter and because of the more rigid network matrix. However, this behavior depends on many factors, such as the nature of gel, and on the external parameters. Hydrogels with more hydrophilic groups will generally swell more.

Actually, changes in pH can affect the charge of the hydrogel network, influencing its interaction with water; temperature can affect the solubility of the polymer chains and the interactions between the polymer and water. The presence of ions in the solution can also affect the swelling behavior.

The swelling test provides insights into their water absorption capacity and how they respond to different environments. This information is crucial for tailoring hydrogels for specific applications, such as drug delivery, tissue engineering, and other biomedical uses.

Thermal analysis of hydrogels allows one to study the variation in their property changes with temperature. This analysis helps explain the hydrogel's structural behavior, phase transitions, and thermal stability. Thermal analysis can indicate temperatures at which hydrogels undergo phase transitions and the decomposition temperature. In particular, they are useful for determining the temperature range where hydrogels remain stable and identify the onset of degradation or decomposition, which is crucial for their long-term use.

Indeed, thermal analysis can reveal how water interacts with the polymer network and how its behavior changes with temperature and offer information about the water that can be absorbed and released, both from a thermodynamic and kinetic point of view.

Among the most common thermal analysis techniques (worth noting that, often, many of these techniques can be used together in the same moment with the advantage of reducing the total analysis time, requiring a mass of the sample and allowing the identification of transformations and transitions with higher precision and greater ease), the following are presented:

- Differential Scanning Calorimetry (DSC), which measures heat flow into or out of a sample as temperature changes, allowing for the detection of phase transitions like melting and crystallization.
- Thermogravimetric Analysis (TGA), which measures the weight loss of a sample as it is heated, providing information about thermal stability and decomposition.
- Differential Thermal Analysis (DTA), which is a technique used to study the thermal behavior of materials, including hydrogels, by measuring the temperature difference between a sample and a reference material as they are heated or cooled.

Hydrogel mechanical characterization involves assessing their ability to withstand deformation and force. Knowledge of the response to these stimuli and of the hydrogels' behavior has great importance for applications like tissue engineering and drug delivery. This includes determining properties, like Young's modulus, tensile strength, fracture toughness, and viscoelasticity, which are affected by factors like polymer composition, crosslinking, and water content. Common techniques include tensile testing, compression testing, and indentation, with careful consideration needed due to the gels' hydrated nature and potential for time- and strain-rate dependence. In particular, it is important to measure the following:

- Elastic modulus, also known as Young's modulus, which indicates stiffness, often measured using tensile or compression tests. It reflects the hydrogel's resistance to deformation under stress.
- Tensile strength, which is the maximum stress a hydrogel can withstand before fracturing under tension.
- Fracture toughness: a property related to a hydrogel's resistance to crack propagation, and that is important for understanding its ability to withstand damage.
- Viscoelasticity, i.e., the time-dependent behavior of hydrogels, including stress relaxation and creep.

Different techniques and instruments are used for acquiring information about the mechanical properties.

Extensiometry involves stretching a hydrogel strip or ring and measuring the force and elongation to determine stress–strain curves. A tensile force is applied to a sample of a specific shape for tensile testing, and a device that measures deformation is used to track the elongation of the hydrogel as the force is applied.

The force and elongation data are plotted to generate a stress–strain curve, providing information about Young's modulus, yield strength (the stress level at which the hydrogel begins to deform permanently), and tensile strength, i.e., the maximum stress the hydrogel can withstand before breaking.

Compression testing is used for measuring the mechanical response to compressive forces. This test helps determine a hydrogel's ability to withstand deformation under pressure.

The process typically involves applying a compressive load to a hydrogel sample and measuring the resulting deformation. A hydrogel sample is placed between two parallel

plates of a testing machine. A compressive force is applied to the sample, and the resulting deformation (change in height or thickness) is measured. The force and displacement data are recorded to generate a stress–strain curve. This type of test allows you to acquire information about Young's modulus, compressive strength (the maximum stress a material can withstand before failure), compressive strain (the amount of deformation a material experiences under compression) and, in general, for the viscoelastic properties.

Hydrogels in fact exhibit viscoelastic behavior, meaning their mechanical response depends on both time and the rate of loading.

Indentation testing and micro/nanoindentation are techniques allowing for the assessment of local mechanical properties and time-dependent behavior.

This type of analysis consists of pressing a (micro/nano) indenter into the hydrogel and measuring the resulting force and displacement as a function of time. By analyzing these data, properties like shear modulus, water diffusion coefficient, and pore size can be determined. The indenter, with suitable shape and size, is pressed into the hydrogel samples, often prepared as thin layers or discs, at a controlled rate. The applied load and the resulting displacement of the indenter are continuously recorded during the indentation process, allowing us, using an appropriate model, to determine some key parameters such as shear modulus (a measure of the material's resistance to shear deformation), water diffusion coefficient (that indicates how quickly water can move through the polymer network), and relaxation time (i.e., the time required by a hydrogel to recover from deformation).

In the case of film-form gels, in addition to these techniques, other mechanical characterizations may be useful and sometimes necessary, for instance, the scratch and adhesion tests, and, in a broader sense, the contact angle measurement.

A hydrogel film scratch test involves assessing the film's ability to resist scratches and, in some cases, its ability to self-repair minor scratches. A hydrogel adhesion test evaluates how well a hydrogel adheres to different surfaces, such as biological tissues or synthetic materials. This is important for applications such as advanced wound dressings, prosthetics, or biocompatible implants, where good adhesion is crucial to the success of the therapy. The contact angle measurements determine the surface wettability and hydrophilicity of the hydrogel film.

Finally, microstructural analyses are extremely important for films. They can be optical observations or they can require electronic microscopies, such as scanning electron microscopy (SEM) or transmission electron microscopy (TEM).

Optical microscopy is the first step in observing the structure of a hydrogel film. Alongside traditional microscopy, there are newer and more effective techniques. The most important of these are fluorescence microscopy, which, especially when combined with confocal systems, allows for the visualization of specific components or features within the hydrogel network. Furthermore, confocal microscopy allows for sectioning and 3D reconstruction of hydrogel networks, providing a comprehensive view of their structure.

Hydrogel film characterization using electron microscopy typically involves techniques like scanning electron microscopy and transmission electron microscopy to visualize the material's structure at the nanoscale. Specialized techniques such as cryo-SEM and environmental SEM (ESEM) are also employed to examine the hydrogel in its hydrated state. These methods help in explaining the hydrogel's morphology, pore structure, and how it interacts with water.

Atomic Force Microscopy (AFM) is a technique of the probe microscopy group that allows one to analyze surface morphology. It is a powerful technique for characterizing hydrogel films, providing information about their surface topography, mechanical properties, and other nanoscale characteristics. AFM can be used to visualize the surface structure of hydrogels, measure their elastic modulus, and assess their adhesion and friction properties.

4. Materials for Hydrogel Films

Hydrogel films are made from both natural and synthetic polymers [27,75]. The number of polymers suitable for hydrogel formation is potentially vast; in fact, the only essential requirement is the presence of functional groups or unsaturated bonds (such as double or triple bonds) that enable crosslinking. Figure 15 shows some of the monomers that can be used for the synthesis of polymers, which, in turn, can be used to prepare gels [76,77].

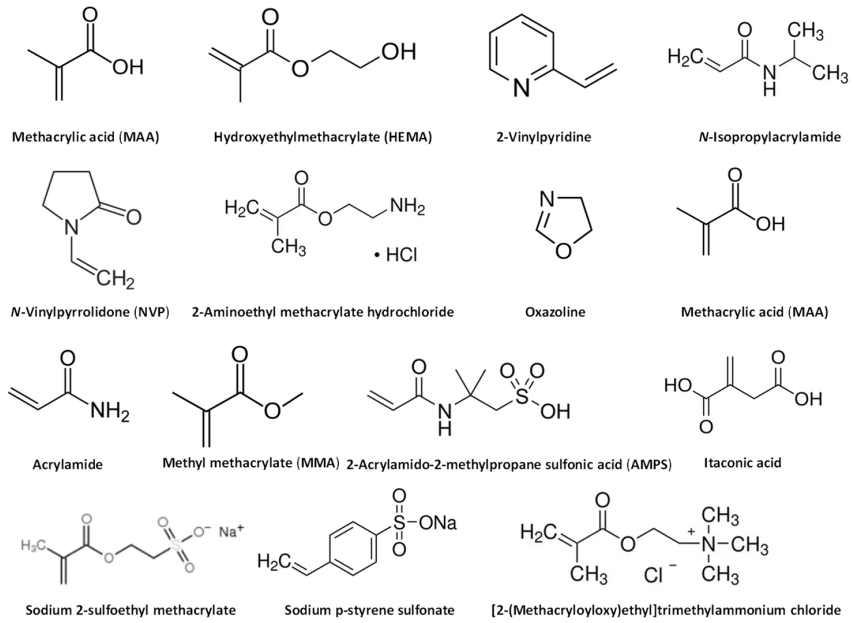

Figure 15. Common monomers used for hydrogel synthesis.

Naturally, not all of these systems are extensively studied or applied in real-world scenarios. For certain applications—particularly in the biomedical field—materials of natural origin are often preferred due to their superior biocompatibility. In most cases, the matrix of these hydrogels is composed of biopolymers, predominantly from the polysaccharide family. However, other materials, such as protein-based polymers like collagen and aromatic biopolymers like lignin, are also commonly employed. However, alongside common systems materials of natural origin, including alginate, chitosan, gelatin, carrageenan, hyaluronic acid, collagen, silk fibroin and others, other synthetic polymers such as PVA, polyacrylic acid (PAAc), and polyacrylamide should be cited.

In general, both types of gels possess distinct advantages and limitations, making it impossible to declare one category as universally superior. The choice between them ultimately depends on the specific functional requirements and intended applications, which must be evaluated on a case-by-case basis.

Table 2 summarizes the main characteristics of natural and synthetic hydrogels [78].

Table 2. Advantages and disadvantages of natural and synthetic hydrogels.

	Natural Hydrogels	Synthetic Hydrogel
Advantages	High biodegradability; High biocompatibility; Low cost	Easily controllable composition; High reproducibility Excellent mechanical properties
Disadvantages	Worst mechanical properties; Batch-related variability; Low long-term stability; Possible low reproducibility	Possible cytotoxicity; Possible low biocompatibility

It would be impossible to exhaustively describe all the possible materials used to produce hydrogel films; therefore, the main ones will be mentioned in the following sections. It is worth noting that, in any case, several different materials can be used for the preparation of hydrogels, and hybrid systems formed by natural and synthetic polymers are also very common.

4.1. Materials from Natural Sources

The polymers used for the matrix of these types of gels come from sources such as plants, microorganisms (bacteria and other unicellular living beings) and even animals and they are prepared through numerous biotechnological processes [79,80].

Alginate is a natural, hydrophilic, biodegradable and non-toxic polysaccharide derived from brown algae and some bacteria [81]. It is a linear polymer composed of residues of α-L-guluronic acid (G) and β-D-mannuronic acid (M) linked by 1,4-glycosidic bonds [82]. While sodium alginate, a salt of alginic acid, is soluble in water, it forms gels when crosslinked by cations with higher valence like calcium, magnesium, or iron [83]. When sodium is substituted by these cations, gelation occurs. The type and concentration of crosslinking agents determine the film's strength and water resistance.

Alginate films are flexible and transparent. They are often used in food packaging to reduce dehydration and control respiration and biomedical applications [84]. In addition, alginate films are used in cosmetics for their thickening properties and to improve the properties, such as consistency and viscosity, to prevent phase separation in emulsions of other products as well [85].

Films based on this material can be modified to enhance their properties, such as by incorporating essential oils for antimicrobial and antioxidant activity or by using plasticizers to improve flexibility.

Chitosan films are made from chitosan, another biodegradable polysaccharide derived from deacetylation of chitin, found in the exoskeletons of crustaceans, insects and also in some fungi [86]. It is a linear copolymer of (1-4)-2-amino-2-deoxy-b-d-glucan (GlcN) and (1-4)-2-acetamido-2-deoxy-b-d-glucan (GlcNAc) [87]. The hydrogel can be prepared through different methods, including the combination with other polymers, the use of crosslinking agents and the chemical modification of chitosan. The hydrogel films based on chitosan are flexible and transparent or at least translucent.

These films are used in food packaging and preservation due to their antimicrobial and antioxidant properties, as well as their ability to act as a barrier against oxygen and moisture. There are also many medical applications based on chitosan hydrogels, ranging from wound treatment to controlled drug release [88].

Chitosan can be grafted using chemical processes, attaching polymer side chains to the chitosan backbone and creating graft copolymers with modified properties like enhanced solubility, biocompatibility, and mechanical strength. This technique uses chitosan's reactive amine and hydroxyl groups to initiate the growth of new polymer chains, thereby tailoring chitosan's properties. It can be chemically modified by reacting its reactive amino and hydroxyl groups with agents like alkyl halides, carboxylic acids, and aldehydes to form derivatives, such as quaternary ammonium salts, esters, ethers, and Schiff bases. These modifications enhance chitosan's solubility, biocompatibility, mechanical strength and other physicochemical properties. For example, it is possible to introduce alkyl by reacting the amino group or by reacting its hydroxyl groups with carboxylic acids or their derivatives, and it is possible to esterify the chains of chitosan with alogenated hydrocarbons or sulfates. This can also be used for creating a copolymer, where the main chitosan structure is branched with other polymer chains (the so-called grafts). Often, these copolymers have superior performance.

Carrageenan is another polysaccharide derived mainly from algae. However, it is characterized by the presence of sulphate groups, along the chains. Its chemical structure consists of repeating units of galactose and 3,6-anhydrogalactose (3,6-AG), linked by alternating α-(1,3) and β-(1,4) glycosidic bonds [89]. These structures also contain varying amounts of ester sulfates. Carrageenan can exist in several different types, among which three main ones are kappa (κ), iota (ι), and lambda (λ), depending on the number and position of sulfate groups and the amount of 3,6-anhydrogalactose present [90].

Similar to chitosan, carrageenan can be gelled either physically or chemically. In particular, the different types of carrageenan can be combined with other polymers such as agarose or even with chitosan to create hybrid films and tailor their properties for specific applications [91].

Hyaluronic acid is one of the fundamental components of mammalian connective tissues [92]. It is also found in the extracellular matrix. It is an unbranched, non-sulfurized polyglycosaminoglycan, resulting from the condensation of thousands of disaccharide units formed in turn by glucuronic acid and N-acetylglucosamine residues, linked together alternatively by β1→4 and β1→3 glycosidic bonds, as well as by intramolecular hydrogen bonds, which stabilize their conformations [93]. Hydrogels are normally formed by inducing chemical bonds between hyaluronic acid chains. This is achieved by reaction with (relatively) low-molecular-weight copolymers of vinyl ether and maleic anhydride [94].

The films are flexible and resistant, and they often have a very high capability for adsorbing water, meaning that they can have a considerable degree of swelling.

Collagen hydrogel films are derived from a protein that occurs naturally in the body of animals. It is a fibrous protein that forms the primary structural component of connective tissues like skin, bone, and cartilage [95]. It is characterized by its unique triple-helix structure. In particular, this structure is formed by three polypeptide chains, each twisted into a left-handed helix, which then further intertwine to form a right-handed superhelix [96]. This triple-helix structure is also stabilized by the presence of several hydrogen bonds between the polypeptide chains. Collagen is formed by glycine, proline and hydroxyproline, arranged in such a way that after a glycine residue, there is normally a proline in a position called X and subsequently by hydroxyproline in a position called Y, so that the chains are formed by repeating units made up of $(Gly\text{-}X\text{-}Y)_n$ [97].

Hydrogels are formed by crosslinking collagen chains, often using methods such as heat, UV light, or chemical crosslinking agents using molecules such as glutaraldehyde and carbodiimides [98]. This kind of hydrogel is often used in the biomedical field [99], for instance, as scaffolds for tissue, wound healing and for mimicking the extracellular matrix [100].

Silk fibroin is a natural fibrous protein produced by spiders, Bombyx mori larvae, and other insects. It is the major protein component of silk fiber, along with sericin, and is arranged in separate filaments surrounded by a layer of cementing sericin [101]. It is composed mainly of amino acids such as glycine, alanine and serine, with a prevalence of glycine and alanine [102]. These amino acids are arranged in sequences of Gly-X-Gly-X-Gly-X, where X is often alanine or serine, forming crystalline and amorphous regions within the protein structure. In particular, it folds in beta-folded sheets (lamellar), also stabilized by the presence of hydrogen bonds and ionic bonds [103].

Although silk fibroin can gel spontaneously, following changes in pH or temperature or even by other physical methods, such as by the action of ultrasound, crosslinking is usually achieved chemically [104]. Crosslinking can be achieved enzymatically, using enzymes such as horseradish peroxidase (HRP), glutaminase, and tyrosinase, or chemically by reaction with crosslinking agents, such as genipin, glutaraldehyde, epoxide, and carbodiimide,

which can be covalently combined with the hydroxyl, amino, carboxyl, and other active groups in the silk fibroin molecule chains [105].

Another protein material from which hydrogels can be obtained is casein [106]. It is the most abundant protein, about 80% of the total, in cow, goat, sheep and buffalo milk [107]. It is a phospho-protein and is found in the form of micelles, soluble aggregates that form the basis of the coagulation process.

The crosslinking process starts from the denaturation of the micelles, which can be obtained physically, through temperature variations, enzymatically, for example, thanks to transglutaminase, or chemically, by controlling the pH or the ionic strength of the solution [108].

Subsequently, the polymer chains thus obtained can form the three-dimensional network in various ways, which include the formation of disulfide bridges, the reaction with oligomers, but also the crystallization of some traits (physical crosslinking) [93].

Cellulose [109] and lignin [110] can also be used to obtain hydrogels, even in the form of films. They are both important components of biomass, especially wood. Cellulose is a polysaccharide, formed by chains of glucose molecules, which provides the structure, while lignin is a complex polymer that provides strength and rigidity [111].

In particular, cellulose consists of glucose monomers linked by (β-1,4)-glycosidic bonds, forming long, unbranched chains. These chains are held together by hydrogen bonds, creating a strong, fibrous structure, held together by bonds strong enough to make the fibers insoluble in water [112]. Reticulation of the cellulose is mainly of chemical type, because the physical crosslinking in this case leads to pseudo hydrogels, also called thermally reversible hydrogels [112]. A network can be formed thanks to van der Waals forces, hydrogen bonds, ionic bonds, and hydrophobic interactions. However, the physical crosslinking is reversible, and the structure of the gel can be destroyed with the change in physical conditions such as a variation in temperature.

On the contrary, hydrogels formed through chemical crosslinking are stable, because of the presence of strong covalent bonds. Several crosslinking agents can be used for this purpose. Among them, there are dialdehydes, acetals, polycarboxylic acids, epichlorohydrin and polyepichlorohydrin [112,113].

Lignin is a highly branched, amorphous biomacromolecule that normally presents molecular masses between 1000 and 20000 g/mol, consisting mostly of phenolic compounds [114]. More precisely, lignin derives from the combination of phenylpropyl acids and alcohols, including p-coumaryl alcohol, coniferyl alcohol (4-hydroxy-3-methoxycinnamyl alcohol) and sinapyl alcohol (4-hydroxy-3,5-dimethoxycinnamyl alcohol). Their random coupling gives rise to a three-dimensional and amorphous structure [111,115,116]. Lignin has numerous phenol hydroxyl groups. These hydroxyl groups allow the chemical reaction traditionally via hydroxymethylation and epoxidation, by reacting with formaldehyde and epichlorohydrin, leading to reticulation [117].

Even complex patterns can be obtained if a photomask is used, to selectively prevent some areas of the film from being illuminated.

The main limitations in the use of lignin-based hydrogels are related to manufacturing costs. Actually, lignin-based hydrogels are not widely used commercially due to high manufacturing costs and complex production processes. Indeed, mechanical properties are sometimes not particularly useful, stemming from their complex and variable structure.

Figure 16 shows the chemical structures of the most commonly used biopolymers to prepare hydrogel films.

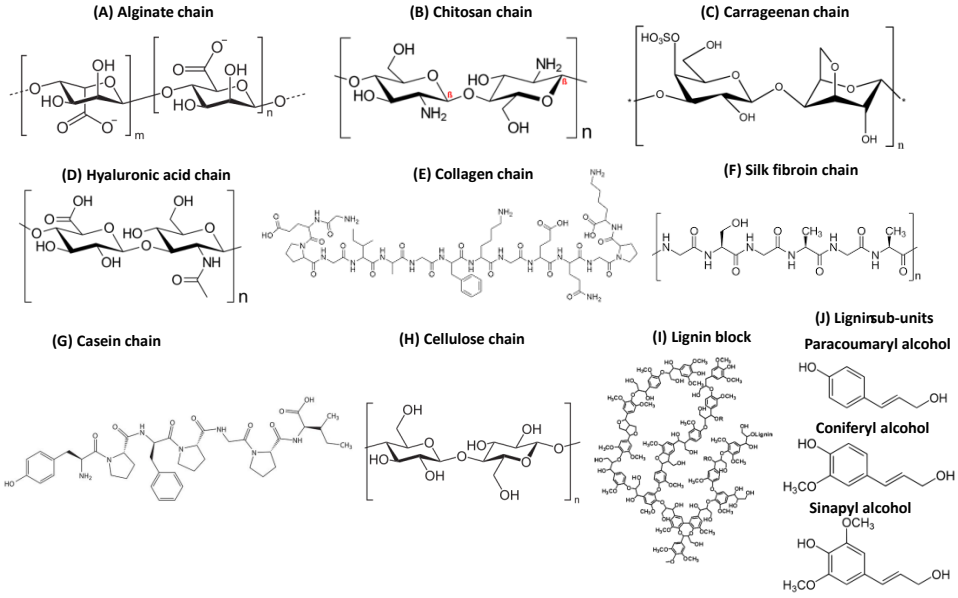

Figure 16. Chemical structures of the most commonly used biopolymers for the preparation of hydrogel films: alginate chains (**A**), chitosan (**B**), carrageenan (**C**), hyaluronic acid (**D**), collagen (**E**), silk fibroin (**F**), casein (**G**), cellulose (**H**), lignin (**I**) and its sub-units (**J**).

Natural hydrogel films are promising materials due to their unique combination of properties and because they come from natural sources, offering a sustainable and biocompatible solution for a wide range of applications. They exhibit biocompatibility, biodegradability, and the ability to mimic biological environments. Even if there are some limitations, ongoing research is focused on improving their mechanical properties.

They have the advantage of having a very high water absorption capability, able to release drugs and nutrients in a very controlled way and to have a low cost. On the other hand, they have non-excellent mechanical properties and have a limited industrialization capacity due to repeatability problems between one batch and another.

The actual applications of these materials depend on numerous factors, including, obviously, their chemical properties. For example, in the case of chitosan-based hydrogels [118], the molecular weight together with the origin of the raw material is determined. Chitosan with high viscosity and high molecular weight, derived from sea urchin spiny powder, is used to produce hydrophobic and highly stable films [119]; chitosan with medium molecular weight is used as a potential material for nutraceuticals and cosmetics [120].

4.2. Synthetic Materials

Synthetic polymer hydrogels are a type of hydrogel derived from synthetic polymers, offering controllable properties and diverse applications. Among the most common synthetic polymers used in hydrogel synthesis, polyvinyl alcohol (PVA), polyethylene glycol (PEG), poly(2-hydroxyethyl methacrylate) (pHEMA), poly(acrylic acid) (PAA), polyacrylamide (PAM), and poly(lactic-co-glycolic) acid (PLGA) should be cited.

The range of synthetic polymers that can be used to prepare hydrogels is potentially very broad; however, current trends increasingly favor those with higher biocompatibility, particularly for biomedical and environmentally sensitive applications. It should be considered that, sometimes, this property can be reduced by the presence of monomers, reagents, catalysts or other molecular systems, residues of the synthesis processes of the polymers and gels themselves. These molecular systems are often toxic or harmful and should be removed, mediated by appropriate extraction methodologies.

Polyvinyl alcohol (PVA) is a polymer with the idealized formula $[CH_2CH(OH)]_n$, very soluble in water. PVA-based hydrogels can be prepared by both physical and chemical

crosslinking [121]. In the first case, it is common to use the hot-pressing technique, in which PVA solutions are heated under pressure. This method avoids the use of organic solvents and allows for obtaining very transparent hydrogels. Alternatively, some crosslinking agents can achieve chemical gelation. Among them, one of the most important is glutaraldehyde, which forms strong covalent bonds between PVA chains. Polyethylene glycol (PEG) acts similarly, leading to hybrid hydrogels [122].

Polyethylene glycol (PEG), also called polyethylene oxide (PEO) or polyoxyethylene (POE), is a polymer prepared by the polymerization of ethylene oxide [123]. PEG is a linear polymer composed of repeating units of ethylene glycol, water-soluble and non-toxic.

PEG hydrogels are usually chemically acylated to yield more reactive derivatives. PEG is reacted with acryloyl chloride to form PEG diacrylate (PEG-DA). Other substances such as methacrylate, allyl ether, maleimide lead to the formation of similar PEG derivatives [124]. They are then exposed to UV light to form a crosslinked network. Alternatively, these PEG derivatives can be crosslinked enzymatically or classically chemically by reacting with diisocyanates and triols.

Poly(hydroxyethyl methacrylate) (pHEMA) is a polymer whose monomer is hydroxyethyl methacrylate (HEMA), whose chemical formula is $H_2C=C(CH_3)CO_2CH_2CH_2OH$ [125].

This polymer contains a main chain of repeating units with a hydrophilic hydroxyethyl side group ($-CH_2CH(OH)CH_3$). The crosslinking is obtained for the action of crosslinking agents, such as ethylene dimethacrylate (EDMA) [126].

Polyacrylic acid (PAA) is a polymer made via the polymerization of acrylic acid, which has a carboxylic acid group (-COOH) on each monomer unit [127]. Because of the presence of these functional groups, the hydrogels formed from this polymer are anionic in nature, and this makes them highly hydrophilic; they have great capability for absorbing water. At present, the most common method to achieve crosslinking in this case is exposure to ionizing radiation, like electron beams or gamma rays [128].

Polyacrylamide (PAM, sometimes called pAAM) has the formula ($-CH_2CHCONH_2-$). It has a linear-chain structure [129]. PAM is highly water-absorbent, forming a soft gel when hydrated. Polyacrylamide hydrogels are characterized by their chain length and ability to retain water and ionic strength while using water molecules to embed water and ions. Polyacrylamide hydrogels synthesize acrylic amide monomers by redox polymerization and crosslinking with *N*,*N*′-methylene *bis*-acrylamide. The polyacrylamide structure has an amide functional group that enables water absorption and facilitates physical interaction with the hydrogel network structure. Polyacrylamide hydrogels are widely used in food packaging products, ophthalmic surgery, medication, and water purification.

Poly(lactic-co-glycolic) acid (PLGA or PLG) is a copolymer widely used for therapeutic devices, owing to its biodegradability and biocompatibility [130]. It is synthesized by means of ring-opening copolymerization of two different monomers, glycolide and lactide, the cyclic dimers (1,4-dioxane-2,5-diones) of glycolic acid and lactic acid, respectively. Polymers can be synthesized as either random or block copolymers. Depending on the ratio of lactide to glycolide used for the polymerization, different forms of PLGA can be obtained; these are usually identified in regard to the molar ratio of the monomers used (e.g., PLGA 75:25 identifies a copolymer whose composition is 75% lactic acid and 25% glycolic acid). The crystallinity of PLGAs will vary from fully amorphous to fully crystalline depending on block structure and molar ratio.

Figure 17 shows the chemical structures of the most commonly used synthetic polymers to prepare hydrogel films.

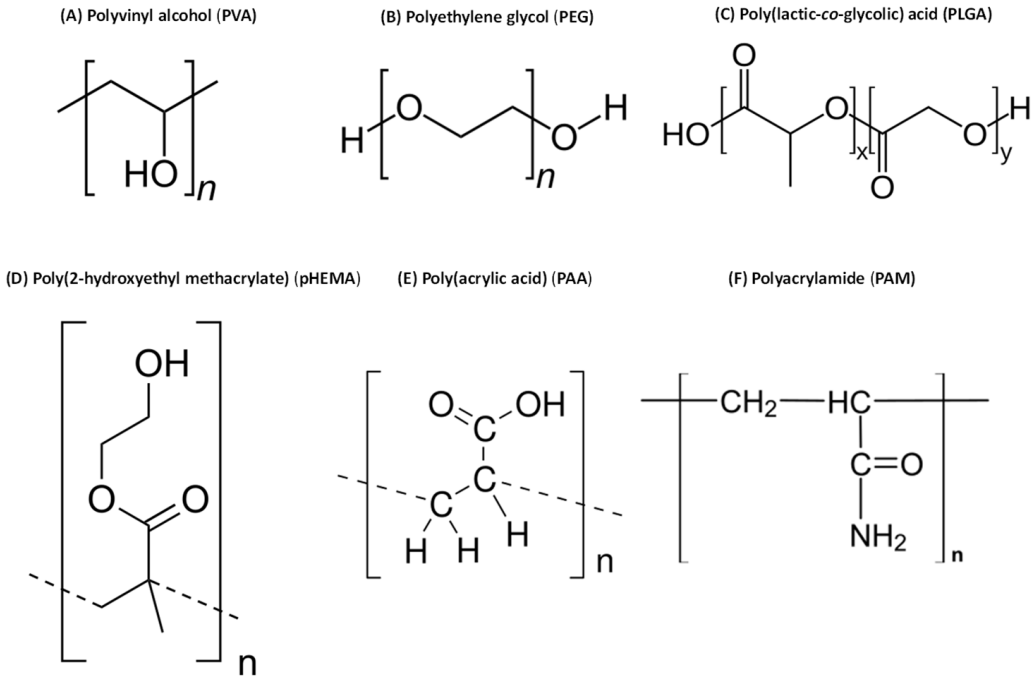

Figure 17. Chemical structures of the most commonly used synthetic polymers for the preparation of hydrogel films: polyvinyl alcohol (PVA) (**A**), polyethylene glycol (PEG) (**B**), poly(lactic-co-glycolic) acid (PLGA) (**C**), poly(hydroxyethyl methacrylate) (pHEMA) (**D**), polyacrylic acid (PAA) (**E**), polyacrylamide (PAM) (**F**).

Hydrogels derived from synthetic polymers have the great advantage that they can be tailored to have specific properties, such as mechanical strength, biodegradability, and responsiveness to different stimuli. Because these polymers are derived from well-known and controllable processes, they can be easily industrialized. This type of hydrogel is scalable and can be easily prepared even on large scales in a repeatable manner.

As an example of the possible applications of these materials, PAA-based hydrogels can be mentioned. Their excellent adhesion properties make them suitable for use in wound healing dressings [131]. In a very different field, PAA films can be used as sensors for the detection of polluting heavy metal ions in aqueous solutions [132].

4.3. Additives for Hydrogels

The properties of gels, whether in bulk or film form, depend not only on their chemical nature, their (micro) structure, parameters such as the degree of crosslinking or water content, but also on the presence of additives, which can often regulate and tailor them sensitively and precisely. They can improve gels' mechanical strength, thermal stability, can act as barrier properties, and can induce other functionalities such as the capability of a magnetic response, increase the electrical conductibility and others [133,134].

These additives can be of different nature and morphology, depending on the intended purpose. They can be inorganic particles, including noble metals [135–137], compounds such as oxides [138,139], nanoclays [140], nanostructures derived from graphene [141] or graphene oxide [142], liposomes [6,7] and other organic nanostructures and even metal–organic hybrid systems (MOFs) [143].

The additives can be incorporated into hydrogels through various methods [133], including in situ synthesis (where nanoparticles are formed within the hydrogel matrix) and ex situ methods (where pre-formed nanoparticles are added to the hydrogel), but in the case of hydrogel films, it may often be necessary to develop innovative or alternative strategies for incorporating these additives into the hydrogel matrix. For example, a new

method for creating silver nanoparticles in situ within calcium alginate films prepared by spin coating has recently been reported [26].

Noble metal, such as Ag or Au, nanoparticles are among the most common additives with which hydrogels can be loaded [144,145]. This also stems from the fact that it is quite easy to prepare these hybrid systems, for example, by in situ controlled chemical reduction. They can provide some useful properties like high antibacterial capability.

Many oxide nanoparticles, like ZnO, CuO, and TiO_2, exhibit antibacterial properties [146]. Furthermore, they can be designed to selectively adsorb specific molecules, making them useful for environmental remediation and drug delivery [29]. Some of them, like iron oxide nanoparticles, are magnetic, allowing for remote control of the hydrogel's properties (swelling, shape, drug release) using an external magnetic field [147].

It is also worth keeping in mind that both metallic nanoparticles (e.g., gold) and those of many oxides can effectively contribute to the crosslinking process, both physically and chemically, by promoting the formation of ionic and even covalent bonds.

Hybrid nanoclays are interesting and promising hydrogel film systems [148], despite many investigations being required. Various clay minerals like montmorillonite, kaolinite, and halloysite are used for specific and targeted drug delivery.

Hybrid graphene hydrogel films are typically prepared through controlled self-assembly methods, which exploit supramolecular interactions between the graphene sheets and the hydrogel matrix. Graphene is a two-dimensional material with unique features and extraordinary properties. The combination with it enhances the characteristics of the traditional hydrogels. The specific features of graphene, such as good mechanical properties, optical properties, high thermal conductivity, and high electrical conductivity, cause the graphene to form unique hydrogel [149]. The structure and properties of the films can be customized by adjusting the synthesis parameters, such as graphene concentration, hydrogel composition, and processing conditions. This makes them suitable for a wide range of applications, particularly in biomedicine, energy storage, and environmental remediation [150].

Similar considerations can be conducted for graphene oxide-loaded hydrogels [142]. Graphene oxide (GO) is a two-dimensional, single-layer sheet of carbon atoms with oxygen-containing functional groups attached to its surface. These groups make GO hydrophilic, which is crucial for forming bonds with the hydrogels. The addition of GO can significantly improve the mechanical strength of hydrogels, making them more robust and durable [151].

Systems formed by the combination of liposomes and hydrogel film are also very interesting [152]. This kind of hybrid material can be seen as a drug delivery system that combines the benefits of both liposomes and hydrogels. Liposomes, which are microscopic vesicles made of lipid bilayers, encapsulate and protect drugs, enhancing their delivery to target tissues. The combination of these two systems creates a platform that can offer sustained, controlled, and targeted drug delivery.

This integration can also enhance the stability of liposomes by preventing aggregation and fusion. Liposome-in-hydrogel systems are being explored for various applications, including topical drug delivery, wound healing, and controlled release of therapeutic molecules [153].

MOF (metal–organic framework) hydrogel films are composite materials that combine the unique properties of MOFs with the flexibility and biocompatibility of hydrogels [154]. They are formed by incorporating MOF particles into a hydrogel matrix, resulting in a material with enhanced functionalities and potential applications in diverse fields like gas storage, catalysis and others [155]. MOFs are crystalline materials composed of metal ions or clusters connected by organic linkers. This unique structure gives them a high surface area, porosity, and tunable properties [156].

MOF hydrogel films offer a combination of flexibility, biocompatibility, and tunable functionalities [157]. For instance, they can be used to encapsulate and deliver drugs, with the hydrogel matrix controlling the release rate and the MOF enhancing drug loading and stability. Furthermore, MOF–hydrogel films can be used as array sensors for detecting various analytes, taking advantage of the MOF's selectivity and the hydrogel's biocompatibility.

It should be noted that the presence of multiple additives in the same hydrogel can have synergistic effects and result in a great improvement in the properties of these composite systems. For example, Panda et al. [158] studied chitosan films blended with cerium oxide and graphene oxide that have excellent potential for food packaging applications. In fact, they found that composite chitosan–graphene oxide–cerium oxide films showed high antioxidant activity for both dose- and time-dependent effects. Moreover, these chitosan/GO/CeO_2 samples exhibited rather low film water solubility, moisture absorption and water vapor transmission rate.

4.4. Biocompatibility and Cytotoxicity Issues

Hydrogels are often considered very biocompatible, precisely because of their intrinsic nature. However, this does not mean that cytotoxicity aspects can be overlooked or underestimated. Potential problems associated with these systems also arise from the fact that hydrogels may contain traces of unreacted monomers or low-molecular-weight oligomers, as well as solvents, catalysts, and other substances necessary for their synthesis. These are often much more toxic and dangerous than the final product. Another possible source of compatibility problems with living cells could be the release of secondary products due to the decomposition of the gel itself over time [159]. The stability of the hydrogel in a biological environment is important. If the hydrogel degrades rapidly, it may release harmful substances.

This aspect depends on the gel composition, on the concentration of secondary molecules, and the cell type being tested. Some hydrogel formulations may exhibit cytotoxicity at certain concentrations [160].

Another aspect to consider is the additives added to hydrogels for various functions, such as nanoparticles. These typically have positive effects, but nanocytotoxicity is an issue that should not be underestimated and requires in-depth study.

Recent studies have shown potential issues of cytotoxicity in some PLGA-PEG-PLGA hydrogels (Stewart et al. [161]) and in loaded alginate (Urzedo et al. [162]) or chitosan hydrogel (Tyliszczak et al. [163]) in vitro studies. For medical applications, it is, therefore, essential to carefully evaluate the cytotoxicity of hydrogels. The choice of polymer, additives, and preparation method must take into account biocompatibility and safety for human tissue.

There are many methods to evaluate the toxicity of these systems, and the evaluation of hydrogel cytotoxicity requires many tests. These include the MTT assay, a common method for assessing cell viability by measuring metabolic activity; cell morphology analysis, which involves examining the shape and appearance of cells to indicate stress or cellular damage; and live/dead cell staining, a technique that distinguishes between live and dead cells, providing a direct measure of cytotoxicity.

Additionally, release studies can be conducted, i.e., evaluating the release of potentially toxic substances from the hydrogel into a medium that can help determine the source of cytotoxicity.

5. Application of Hydrogel Films

The excellent properties of hydrogels, such as flexibility and biocompatibility, discussed in the previous sections justify their numerous technological applications, also in the biomedical field. In this case, they are used in wound care, drug delivery systems and tissue engineering. Furthermore, these properties can often be improved when the materials are in the form of thin films, because they allow better permeability and exchange with gases or with environmental humidity and allow faster and more effective interaction with added molecules and substances.

Hydrogels derived from natural sources are generally well tolerated by the body and do not cause adverse reactions, so they can be used as scaffolds for tissue regeneration, mimicking the natural tissue environment and facilitating cell growth, and they are used in contact lenses, lubricants, and other medical devices [164].

They can act as a supportive environment for cell growth, survival, and differentiation, mimicking the natural extracellular matrix, i.e., the framework of cells and tissues. Hydrogels play a crucial role in tissue organization, in cells survival and proliferation and eventually in their behavior and differentiation [165]. As an additional advantage, the properties of hydrogels, such as structure, porosity, and degradation rate, can be tailored to suit specific tissue regeneration needs [11]. The principle of tissue regeneration using hydrogels is to gel the materials in the presence of desired cells, prepared or recovered separately beforehand, and possibly molecules or other factors necessary for growth. Inside the gel, they can multiply and proliferate and induce the gradual degradation of the polymer matrix. Once the degradation is complete, the tissue is regenerated.

Hydrogel dressings are used for various types of wounds, including large and deep wounds, chronic wounds with necrotic tissue, burns, ulcers. In the form of films, hydrogels are extremely flexible and have great extensibility; they exhibit good adhesion properties so they adapt to the shape of the body and move with the skin [164,165]. Hydrogels can provide a moist environment, which makes them useful for wound healing and skin hydration, allowing, at the same time, the removal of exudates. They allow gas exchange as well. Furthermore, they can be customized with antimicrobial agents or other biomolecules to enhance the healing process or, for example, to alleviate the pain.

More generally, hydrogels can be used as carriers for therapeutic agents, delivering drugs directly to the target area with reduced side effects. Using hydrogels, drug release can occur in a controlled, gradual and prolonged manner over time [166]. They also offer advantages such as protecting drugs from degradation or exposure to air or the external environment. The release kinetics of drugs and molecules can be controlled and modulated very precisely. It can be due to chemical diffusion, to the specific response of the gel to specific stimuli, such as pH or temperature changes, or to the swelling behavior, linked to the variation in water.

Hydrogel films are also useful and widely used in agriculture, diagnostics and biosensing [9]. In fact, hydrogel films can be used as absorbent materials to improve soil moisture and reduce water consumption in agriculture. They can be used to neutralize and remove toxic chemicals from contaminated surfaces. Hydrogels can be used in biosensors to detect specific biomolecules or cells, and they are used in various microfluidic applications, including cell culture, biosensors and separation devices. Hydrogels can be used in food packaging and as additives to improve texture and moisture [167].

5.1. Biomedical Applications

Hydrogels, especially those of natural origin, have attracted great interest for biomedical applications due to their easily controllable chemical and physical properties and remarkable biocompatibility.

Hydrogels play a very important role in tissue regeneration due to their bioactivity and ability to mimic the natural extracellular matrix in three dimensions by acting as scaffolds that mimic the extracellular matrix, supporting cell growth and tissue development.

They can be used as tissue scaffolds by promoting the influx of cellular metabolites and the disposal of cellular waste through their pores [168]. Hydrogels provide a physical surface for the adsorption of biomolecules and the immobilization of proteins, growth factors and others. It should be noted that most human cell types require adequate anchorage to support tissue regeneration, and, therefore, their absence can cause cell necrosis and defective tissues. In this sense, hydrogels are becoming the reference material for tissue engineering applications [169]. In addition, specific hydrogel could be prepared to create networks that are specific to a particular tissue.

It has been demonstrated [170] that some chitosan-based hydrogels provide a favorable surface for cell adhesion and growth, making them suitable for tissue engineering applications. These materials have shown excellent mechanical properties, biocompatibility, and little or no cytotoxicity. In the proper conditions, the cells within the hydrogels maintained high viability and their ability to proliferate.

The ability to be an excellent culture medium allows hydrogels to be valuable medical devices also in other cases, including wound care. Suitable and appropriately designed materials to reduce the risk of scarring, facilitate wound closure and accelerate healing are needed. Hydrogel films can represent great progress in this sector, because, together with their excellent biocompatibility, a hydrogel-based patch can adhere tightly to the human skin [171].

They can create a moist and adaptable environment for cells, promote gas exchange and possibly allow the removal of waste substances produced on site [172]. One of their most important advantages is their ability to be loaded with additives and useful substances that can easily exchange with biological tissues. Among them, there are growth factors, antibiotics and painkillers.

Hydrogels and their hydrogel films are very useful for controlled drug release, due to their microstructure [173]. They can be loaded with many substances that can then be gradually released in a prolonged and potentially targeted manner [28]. The advantage provided by hydrogels is that they allow for control of the rate at which the useful molecules they contain are released into biological tissues, for numerous purposes.

These films can be designed to respond to stimuli, such as temperature or pH, triggering or modulating drug release at specific points, minimizing systemic side effects [174]. The hydrogels are initially able to retain the drug, but when they begin to swell due to a change in humidity (for example, due to the presence of body fluids), it allows the drug to diffuse at a controlled rate, ensuring prolonged release over time. Alternatively, hydrogels can be designed, changing their composition, degree of crosslinking, thickness, to respond to specific stimuli, such as changes in temperature, pH, or the presence of certain molecules. Drug release can then be triggered or modulated by these external stimuli. Finally, the release of active substances can be due to the degradation of the polymer matrix. Each of these possible mechanisms corresponds to different release kinetics [175].

The release rate is linear if the release is controlled mainly by chemical diffusion, mainly asymptotic (i.e., initially very rapid and then tending to constant, over a certain time) if controlled by swelling, and increasing in steps if controlled by degradation [176].

Figure 18 summarizes these major biomedical applications of hydrogels.

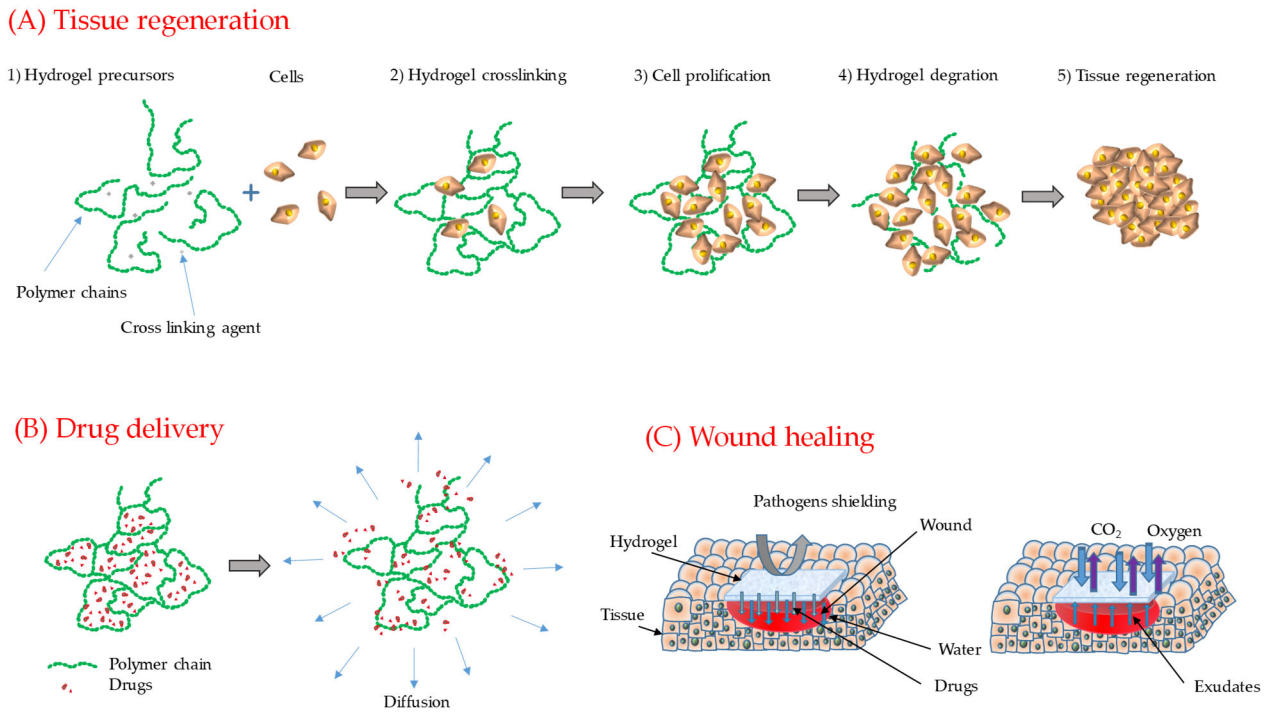

Figure 18. Schematic representation of the main biomedical applications of hydrogel films. (**A**): Regeneration of biological tissues (**A**). In this case, the process goes through some stages, which can be generalized in formation of the hydrogel matrix in the presence of living cells (1), crosslinking of the gel (2), cell proliferation (3), degradation of the polymeric matrix (4) and tissue reformation (5). (**B**): Drug and molecule release. The hydrogel can be loaded with numerous chemical substances and possibly also nanoparticles, which can be released gradually and modulated. The diffusion can be chemical or be due to the response of the material to external stimuli such as changes in pH, ionic strength or temperature. (**C**): Hydrogel films can be used for wound healing because they allow for the release of the required humidity, and possibly drugs and painkillers constitute an effective barrier for many pathogens and allow gas exchange and exudate removal. Different arrows indicate different flows of different gases.

It is important to note that hydrogels are not universally suitable for all applications. Rather, specific hydrogel formulations have been investigated and optimized to meet the requirements of particular uses, demonstrating efficacy only within defined functional contexts. Table 3 shows a summary of hydrogels used for biomedical applications. Some of them are still at the laboratory research level [177].

Table 3. Summary of the main characteristics of hydrogels used for biomedical applications.

Type of Gel	Biocompatibility	Cellular Activity/Proliferation	Wound Dressing	Exudates Absorption	Mechanical Properties	Reference
Alginate	Yes		Yes	Yes	Low	[178,179]
Cellulose	Yes		Yes	Yes	Low	[180]
Chitosan	Yes	Yes	Yes		Low	[177,181]
Collagen	Yes	Yes	Yes		Low	[182,183]
Hyaluronic acid	Yes	Yes	Yes		Low	[184,185]
Poly(ethylen oxide) (PEG)	Yes	Yes		Yes	Good	[186,187]
Poly(hydroxyethyl meta acrylate) (PHEMA)	Yes	Yes	Yes	Yes	Good	[188,189]
Poly(vinly alcool) (PVA)	Yes		Yes	Yes	Good	[190]
Polyacrylic acid (PAA)	Yes		Yes	Yes	Good	[191,192]

Hybrid systems, which combine different materials like natural and synthetic polymers or incorporate nanomaterials, can offer better performance due to their tunable properties and ability to incorporate various functionalities and offer the possibility of overcoming the difficulties and challenges that are inherent to pure materials [193]. The field of hybrid hydrogel films is rapidly evolving, with ongoing research exploring new materials, designs, and applications.

In particular, integrating nanoparticles into hydrogel matrices could be an extremely promising approach in the medical field. These nanoadditives can have completely different chemical natures; in fact, they can be inorganic materials, metallic, oxides or others, or organic, such as liposomes, peptides, particles containing genetic materials, antibodies and antigens and more. They can have different sizes, shapes, and surface chemistry and can enhance the biofunctionality of hydrogels and enhance their chemical and physical properties, including mechanical properties [194].

Figure 19 shows a schematic representation of a hybrid hydrogel, made of different polymers and loaded with different types of particles.

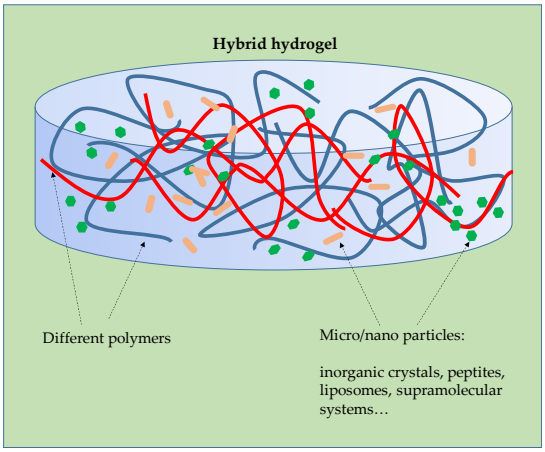

Figure 19. Schematic representation of a hybrid hydrogel, made up of different polymer matrices containing different types of nanoadditives.

The widespread use of hydrogels in the biomedical field, however, still faces significant challenges. These include sterilization, skin adhesion, and long-term stability.

Hydrogel film sterilization is highly challenging due to the high water content, which can be altered by sterilization methods. Ethanol is often the most effective chemical sterilization method for preserving mechanical properties and eliminating bacterial contamination. Irradiation by γ-rays o other energetic radiation can be effective but may cause polymer degradation, toxicity, or changes in pore size. Steam sterilization is a common method but can significantly reduce hydrogel stiffness and transparency. The optimal method depends on the specific hydrogel composition and intended application.

Adhesion of hydrogels to skin is critical for nearly all of their medical uses and is complicated by the inherent wrinkles, hair, and roughness of the skin that prevent complete and seamless contact between the hydrogel and the skin surface; the presence of sweat, which, containing ions and water, can alter the internal structure of the hydrogel and weaken the adhesive interface; and the fact that dynamic and natural movements, such as stretching and flexing the skin, can easily cause hydrogel adhesives to peel off. One possible solution is to integrate materials with strong intrinsic adhesion, such as biologically derived adhesive proteins, into hydrogels, as this can lead to stronger and more durable bonds with the skin. Furthermore, scientific research is focusing on creating hydrogels capable of improving their adhesion in response to sweating, for example, by increasing the number of available binding sites or triggering a pH-dependent change in adhesive properties.

5.2. Biosensing Applications

A biosensor is an analytical device, used for the detection of a chemical substance, that combines a biological component with a physicochemical detector [195,196]. The biological element sensitive to the analyte, e.g., tissue, microorganisms, organelles, cellular receptors, enzymes, antibodies, nucleic acids, etc., is a material of biological origin or a biomimetic component that interacts with, binds to, or recognizes the analyte under study. The detector element, often called a transducer, responds to the interaction between the analyte being studied and the biochemical detector, generating a physicochemical signal that can be electrical but also often optical, piezoelectric, or electrochemical. This signal can be easily measured and quantified. The biosensor's readout device connects to the associated electronics or signal processors that are responsible for displaying the results.

Figure 20 shows a schematic representation of a biosensor. It consists of an active layer deposited on a transducer; this layer hosts receptors that selectively detect only certain analytes and not others. The transducer generates a signal, proportional to their nature and concentration, which is amplified, processed, and analyzed.

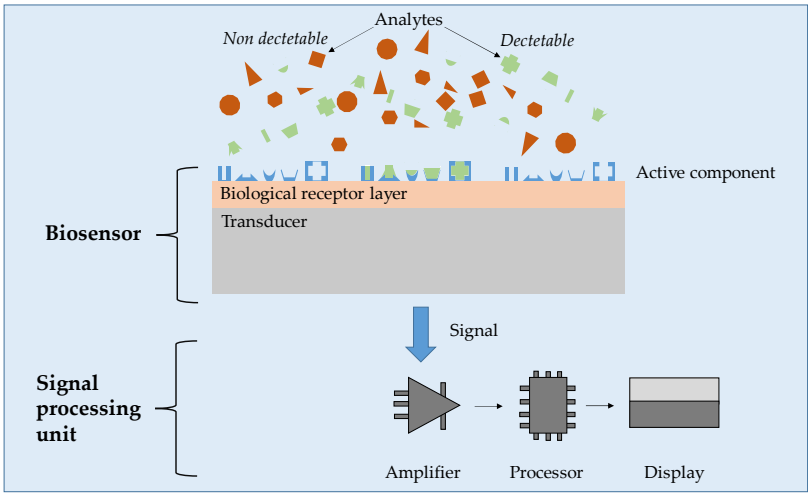

Figure 20. Schematic representation of a biosensor: it consists of an active layer deposited on a transducer; the active layer hosts receptors that selectively detect only certain potential analytes. The transducer generates a signal that is amplified, processed, and analyzed.

The hydrogels act as a platform for hosting and immobilizing bioreceptors (like enzymes, antibodies, or DNA) that specifically bind to target molecules. When the target molecule interacts with the bioreceptor, it triggers a detectable change, such as a change in electrical conductivity, or in optical transmittance, or a fluorescence effect, which can be measured to quantify the presence and concentration of the target [197].

It is possible to produce hydrogels, which, upon sensing a specific analyte, can adsorb it onto their 3D structure and can, therefore, be used to remove them from a given environment. High specificity can be obtained by using molecularly imprinted polymers. Typical detection principles involve optical methods including fluorescence and chemiluminescence, as well as electrochemical methods [198].

When the target analyte (e.g., glucose, DNA sequence, specific proteins) comes into contact with the hydrogel film, it specifically binds to the immobilized bioreceptor. This binding event triggers a change in the hydrogel itself or in a reporter molecule attached to the hydrogel. This change is then transduced into a measurable signal. For example, a hydrogel film biosensor can be used to detect the presence of a specific antigen in a biological sample, such as blood. The hydrogel film can be modified with antibodies specific to the target antigen, which will bind to the antigen present in the sample. The

binding of the antigen to the antibody can then be detected with appropriate methods, providing a signal indicating the presence of the antigen. Again, when in film form, they show superior performance compared to the same in bulk form. Indeed, one of the main problems is the diffusion kinetics of antigens and targets in hydrogels, which is slow and difficult to control, thus proving to be a major factor that negatively impacts sensing performance [199]. Because the volume of the active layer in films is small, the response is faster and superior.

5.3. Environmental and Agricultural Applications

Hydrogel films offer a versatile and sustainable approach to provide innovative solutions to various environmental challenges thanks to their properties of absorption and controlled release of water and other useful substances and the ability to bind to different types of pollutants, removing them.

Actually, hydrogels offer numerous environmental applications [200], including water conservation in agriculture, soil remediation, and pollution removal in wastewater treatment [201], especially in relation to their extraordinary capacity to absorb water and possibly release it in a controlled manner [202] and because of their capacity to selectively interact with pollutants [193,203]. Traditionally, some of these functions were performed by polymeric and plastic systems. They are efficient and cheap but not particularly environmentally friendly. From this point of view, hydrogels represent a very promising alternative. Figure 21 shows a scheme of the possible benefits of using hydrogels in agriculture.

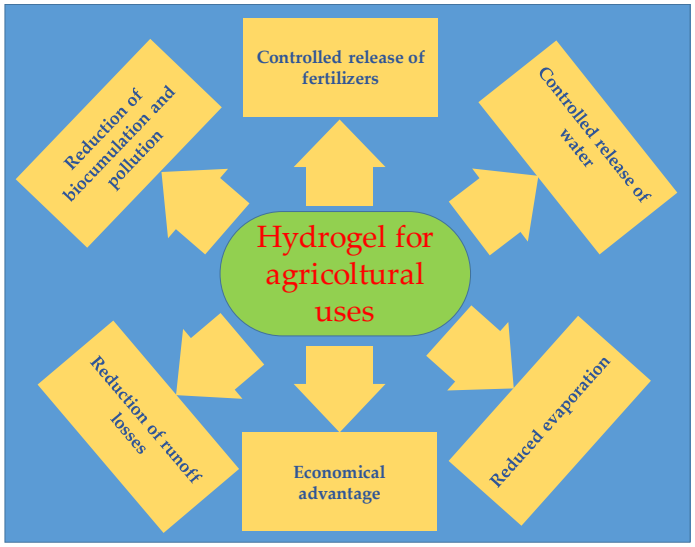

Figure 21. Schematic representation of the advantages of hydrogel in agriculture.

Hydrogels are particularly useful for removing pollutants like heavy metals and organic compounds from wastewater [203]. In addition, they can be used for water treatment, soil management, and agricultural applications. In film form, hydrogels may not be usable for very large-scale use, but there are still numerous specific possibilities where they can be very useful, especially for their rapid response to external stimuli.

In fact, hydrogels can act as water reservoirs and be added to the soil to increase its water retention capacity, which is very useful and allows for reducing the need for irrigation. They are very useful in agriculture, for making it more sustainable [204], as they allow and favor plants to grow in arid areas, facilitating seed germination [205], without the need for large quantities of chemicals.

For this type of application, it is not strictly necessary that the material is fast to adapt to environmental conditions but, instead, the extensive capacity of the material is

important, i.e., the total amount that can be released. However, in agriculture, hydrogel films can improve soil structure, aeration and drainage, which in turn increases productivity. Similarly, hydrogels can optimize the release of fertilizers and other products, minimizing the pollution associated with them.

Hydrogels, even in film form, represent a way to make resources, such as water and soil, more efficient and reduce waste. They can help fight pollution and consequently promote biodiversity. Therefore, they are also economically advantageous for farmers and entrepreneurs in the sector.

Above all, in the agricultural field, hydrogels are useful for their controlled release properties of water and fertilizers [206]. To fulfill these functions, hydrogels must exhibit certain general characteristics. Specifically, they should possess high water retention and slow-release capabilities, good permeability, and stability under environmental conditions, even over extended periods.

At the same time, they must be able to be biodegraded without compromising the quality of the soil [207]. The release speed depends on factors such as the degree of porosity of the gel and its three-dimensional structure, which in turn depend essentially on the degree of crosslinking and on the chemical nature of the material, i.e., the type of polymer, the functional groups present. Furthermore, other external factors, such as pH, temperature, ionic strength. . ., play a very important role. An ideal material should have good stability during swelling, exhibit good photostability, have desired porosity, have low residual monomer content, be non-toxic and low cost. Polymers of natural origin are usually preferable, even if they can be easily biodegradable. For this reason, hybrid materials are often used.

Table 4 presents a list, although not exhaustive, of gels that find applications in agriculture and their main functions.

Table 4. Use of natural and synthetic hydrogels in agriculture.

Type of Gel	Main Function	References
Acrylamide and acrylic acid-based hydrogels	Soil conditioner and water retention material	[208]
Acrylamide and N-hydroxymethyl acrylamide hydrogel	Soil conditioner and water retention material	[209]
Acrylic acid and acrylamide copolymers	Soil conditioner and water retention material	[210]
Acrylic acid-co-acrylic amide based hydrogel	Soil conditioner and water retention material	[211]
Alginate-cellulose nanofibers–poly(vinyl alcohol) hydrogel	Controlled release of phosphate fertilizer	[212]
Carboxymethyl starch-g-polyacrylamideCarboxymethyl starch-g-polyacrylamide	Controlled release of phosphate fertilizer	[213]
Glutaraldehyde crosslinked chitosan-poly(vinylalcohol) hydrogel	Controlled release of nitrogen fertilizer	[214]
Glycerol and poly(vinyl alcohol) hydrogel	Soil conditioner and water retention material	[215]
Hyaluronate-Hydroxyethyl acrylate blend	Soil conditioner and water retention material	[216]
Methylcellulose and hydroxypropyl methylcellulose-based hydrogel	Controlled release of potassium	[217]
N,N′-MBA crosslinked starch hydrogel	Controlled release of potassium	[218]
Poly(acrylamide) and methylcellulose-based hydrogels	Controlled release of nitrogen fertilizer	[219]
Poly(acrylonitril)-based poly acrylic acid hydrogels	Controlled release of nitrogen fertilizer	[220]
Poly(ethylene glycol) and Poly(acrylate) copolymer	Soil conditioner and water retention material	[221]
Poly(ethylene glycol) and poly(sodium acrylate)	Soil conditioner and water retention material	[222]
Poly(lactic acid)/cellulose-based hydrogel composite	Controlled release of potassium	[223]
Poly(maleic anhydride-co-acrylic acid) hydrogel	Controlled release of nitrogen fertilizer	[224]
Poly(vinyl alcohol)/chitosan crosslinked with glutaraldehyde	Controlled release of potassium	[225]
Poly(vinylalcohol)-phosphate gels	Controlled release of phosphate fertilizer	[226]
Polyacrylamide hydrogel	Controlled release of phosphate fertilizer	[227]

Table 4. *Cont.*

Type of Gel	Main Function	References
Polyvinylpyrrolidone (PVP)/carboxylmethyl cellulose	Controlled release of nitrogen fertilizer	[228]
Starch phosphate carbamate hydrogel	Controlled release of nitrogen fertilizer	[229]
Wheat straw cellulose hydrogel	Soil conditioner and water retention material	[230]
κ-carrageenan-based hydrogel	Controlled release of potassium	[231]

Hydrogels, even in film form, act as small water reservoirs and dissolve nutrients, which are released in a controlled manner, anchored to plant roots via capillarity. Hydrogels also maintain optimal water levels under water stress and reabsorb them under humid conditions, improving crop yield [232]. They prevent drainage or evaporation of rainfall or irrigation water due to interaction between the polymer and water molecules. When the soil around roots tends to dry up, the water from hydrogel is released for plant uptake. On the contrary, a local excess of water can be absorbed by the gel. This process helps in sustained use of available water resources [204].

In Figure 22, a schematic representation of this process is shown.

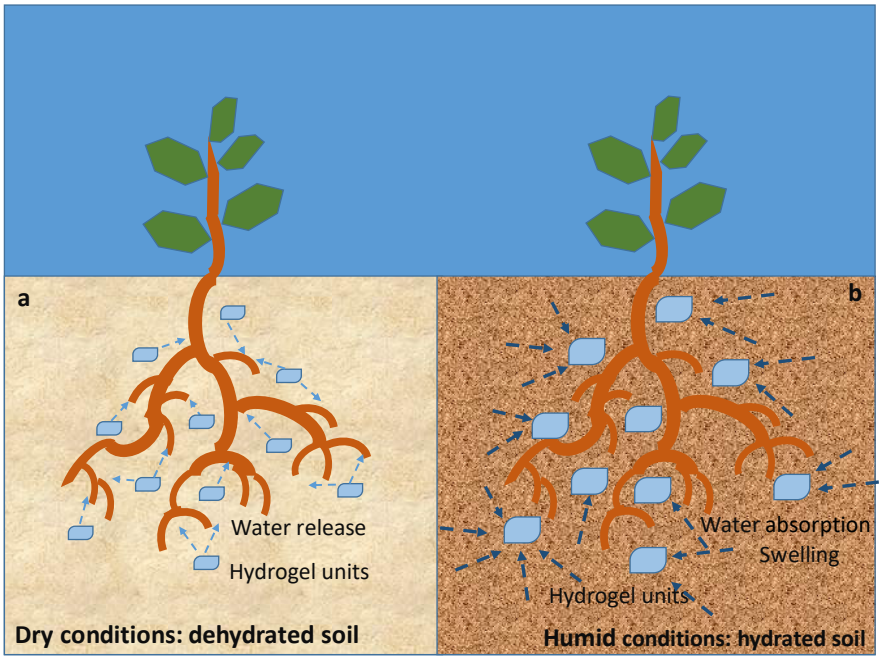

Figure 22. Schematic representation of the water release/absorption process by hydrogels used in agriculture: in case of dry conditions, the hydrogels release the water they contain towards the roots of the plants, which, thus, remain at the ideal humidity level (**a**); in case of humid conditions, the hydrogels absorb water from the soil, swelling (**b**).

By preventing water stress and providing consistent moisture supply, hydrogels can lead to increased crop yields and better-quality produce. They can help crops withstand drought conditions by providing a buffer of moisture during dry periods. Hydrogels used for agricultural applications can be synthetic, natural, or hybrid. Traditional synthetic hydrogels include polyacrylamide and polyacrylates. They have been successfully commercialized in recent decades due to their affordability. Synthetic polymer hydrogels exhibit specific mechanical and functional properties; however, they can have a negative impact on the environment and human health due to the accumulation of chemicals in the soil surface layer. Natural hydrogels are more biodegradable and environmentally friendly, thanks to biological degradation by soil microorganisms. These include alginate, agar-agar,

cellulose, chitosan, and starch. These hydrogels are highly sensitive to salinity, cation type, pH, and swelling time. They are valuable in agriculture due to their good water absorption and retention capacity.

Furthermore, hydrogels allow for the controlled release of fertilizers and other nutrients. This release follows a diffusion-driven mechanism that depends primarily on pH and temperature. The nature and microstructure of the gel, as well as the presence of specific additives, binders, and fillers, play a fundamental role. Hydrogels can then release the nutrients into the soil according to the plant's demand. This can increase nutrient use efficiency and reduce nutrient losses through leaching or volatilization.

Similarly, hydrogel films can also be engineered to improve the release of pesticides and other agrochemicals into the soil by acting as a slow-release carrier. They can be loaded with various pesticides, such as herbicides, insecticides, or fungicides. The hydrogel can then release the pesticides into the soil along with the water, depending on the pest's activity, optimizing their effectiveness and reducing overdoses [233].

Pesticides are hosted within the hydrogel matrix, either physically or chemically. The hydrogel swells in the presence of water, and the pesticide is released through diffusion of the polymer matrix [234]. Some hydrogels are designed to release pesticides in response to specific environmental stimuli like pH, temperature, or light or, in general, in trigged manner. Similarly, fertilizers can be released in place of pesticides. To some extent, the release of these substances resembles that of drugs in biomedical applications, and the kinetics are governed by similar rules.

PVA/PVP hydrogels loaded with both hydrophilic and hydrophobic environmentally friendly pesticides, namely hydrogen peroxide (HP), the essential oil thymol, and urea as a fertilizer, either separately or in combination, have proven very useful for this purpose [234]. These blends can store water and moisten soil to moisten plants while simultaneously trapping and releasing pesticides for their protection and fertilizers to provide them with nutrition in a controlled manner. Indeed, hydrogels films have a great advantage in conventional agricultural methods. They involve extensive utilization of water, fertilizers, and pesticides. However, a significant portion of these resources goes to waste due to processes such as seepage, evaporation, and rapid decomposition. This accumulation of residues over time has a notable adverse impact on the surrounding environment. Hydrogels, especially those composed of PVA and PVP, exhibit exceptional capacity in terms of stability, retention, and controlled release of water, fertilizers, and pesticides, something that is very useful in terms of sustainability.

5.4. Other Applications

The characteristics and properties of hydrogels make them interesting and suitable for other applications. Among them, the following functions are certainly worth mentioning:

- Food preservation: Hydrogel films for food prevent bacterial growth and the deterioration caused by them, extending the shelf life [90].
- Use in cosmetic industry: Hydrogels can be used in cosmetic products for skin hydration and care [235].
- Use for screen protectors: Hydrogel films are used for the screen of devices such as smartphones and tablets, due to their flexibility and self-healing properties. Additionally, hydrogels can be incorporated into electronic devices, allowing for lighter and more flexible devices [236].
- Applications as sensors: Hydrogels can be used to improve sample collection or act as filters in sensors [237].
- Contact lens preparation: Hydrogels are ideal materials for contact lenses due to their ability to absorb water and oxygenate the eye [238].

Food preservation materials must meet very specific requirements, and hydrogels can fulfil them very well [239]. Most of the traditional materials used for food packaging, although they are efficient in protecting food from biological and chemical effects, are not or at least poorly biodegradable and this represents a serious environmental pollution problem. On the contrary, hydrogel films can help reduce this impact [240]. In addition, they inhibit microbial growth and activity [241], because, as previously discussed, they can also contain antimicrobial agents [242] and promote gas and water vapor exchange with the external environment [243]. An important and highly desirable feature is the so-called active and intelligent packaging [244,245]. This refers to the material's ability to respond to changes in the food environment, ideally by preventing them, but at the very least by detecting and indicating them (e.g., through a color change), thereby enhancing safety [246]. This can be achieved by using specific additives, sensitive to variations in, for example, pH, particular gases, humidity or enzymes, which may indicate an alteration in the food [247].

More specifically, active packaging refers to packaging used to inhibit microbial growth and activity, as well as oxidation and food degradation. This functionality is achieved through materials containing antimicrobial/antioxidant agents that inhibit microbial growth and, thus, extend the shelf life of foods [243].

Intelligent packaging, on the other hand, is capable of providing direct monitoring of changes in the system's internal and external environmental conditions. Typically, these systems contain time–temperature indicators of food history or are sensitive to changes in gases, pH, humidity, or microbial activity. Intelligent packaging improves food safety and quality by sharing information on any issues [248]. The main goal is to avoid or at least minimize food losses by providing information on food safety and, at the same time, maintaining the high quality of food throughout the distribution chain up to the point of consumption.

Hydrogels, especially in film form, are potentially very useful for these purposes because they allow gas exchange in a controlled manner and because they can be loaded with nanoparticles and other useful systems that can work as antimicrobials and and/or as antioxidants.

They are also promising and attractive for smart packaging. Mainly, they can enable effective, practical, and very simple temperature monitoring throughout the food supply chain (the so-called time–temperature indicator, TTI) so that a product that has exceeded the expected limits can be immediately identified. In this case, the time–temperature indicator manifests itself in irreversible physical changes, mechanical deformations, or variations in biological composition, which translate into a color change or other noticeable modifications in the package.

What is particularly intriguing about the hydrogels used in this sector is the possibility of combining active and intelligent packaging in the same material, which in itself is not trivial [249].

Figure 23 highlights the characteristics required of a hydrogel film for food packaging. Hydrogels, with optimized formulations, can easily meet these requirements.

Another growing field of application for hydrogels—thanks to their flexibility and excellent mechanical properties—is the protection of smartphones and modern electronic devices, particularly display screens. Today, they represent a promising alternative to more traditional materials [250]. Interestingly, a hydrogel screen protector can have a longer lifespan than traditional glass options. Along with this, hydrogel films can be highly transparent, offering a better viewing experience from all angles [251].

Hydrogels themselves are electrical insulators, but conductive materials can be incorporated into them, making them at least partially conductive, allowing them to function as circuits or electrodes in flexible electronic devices.

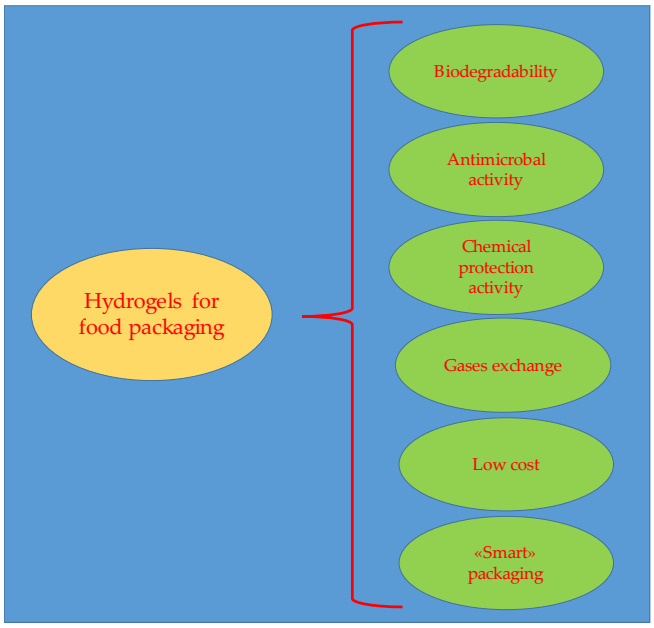

Figure 23. Main characteristics of hydrogel films for food packaging.

Hydrogel films, especially those with tunable properties, can be used as flexible, breathable, and comfortable interfaces for wearable sensors and monitors that track physiological signals like heart rate, body temperature, and even glucose levels [252]. Soft robotics, electronic skins, energy conversion, and health diagnosis are a few of the new fields that benefit from hydrogels' ability to combine conductivity and mechanical properties. Conductive hydrogels are, thus, designed by adding ions or electrons to the hydrogel matrix [253]. It is common for electron-conductive hydrogels to be used in bioengineering applications such as drug delivery systems, tissue engineering systems, and biosensors because they are compatible with biological tissues, as opposed to ion–ion-conductive hydrogels, which leak and diffuse ions into the surrounding environment in energy storage and conversion devices such as actuators and nanogenerators, as well as touch screens and displays.

Finally, one of the most important applications of hydrogels is contact lenses.

This is due to the fact that hydrogel lenses offer significant advantages. Among these are excellent comfort (due to the wettability, flexibility of the lens, and water content), long wear time (which, in the case of lenses made from traditional materials, is limited by their rigidity and modest oxygen permeability), excellent oxygen permeability (which indicates how much oxygen can pass through the contact lens and reach the surface of the eye), and ease of handling.

Hydrogels are extremely flexible, and this makes hydrogel contact lenses feel soft and comfortable on the wearer compared to rigid lenses. The main hydrogel material used for soft contacts is poly(2-hydroxyethyl methacrylate), usually called poly-HEMA. The oxygen permeability of hydrogel lenses depends on the water content. The higher the water content, the more oxygen that can pass through the lens.

5.5. Examples of Studies and Real Applications

The previous sections of this review were devoted to presenting the general aspects of hydrogel films, also for the benefit of an interdisciplinary reader. They covered their preparation, characterization, usable materials, and their potential applications.

This section presents application examples reported in the recent scientific literature. For clarity and ease of reading, these examples are organized by film material and, where possible, by preparation technique. Inevitably, this selection is limited and not exhaustive. However, it can offer a glimpse into the versatility of these systems.

5.5.1. Alginate-Based Films

Alhussaini et al. prepared a very interesting review on the major applications of alginate films in the period 2019–2025 [254], showing that they are very effective in combating bacterial and fungal infections. The incorporation of antimicrobial agents such as metal nanoparticles, essential oils, plant extracts, and antibiotics into alginate matrices has significantly enhanced their functionality, providing targeted and broad-spectrum antimicrobial activity. Ureña et al. studied [255] the properties of alginate for film or coating applications. The rheological and surface properties of the film-forming solutions were found to be strongly influenced by the molecular weight (MW). On the contrary, however, in the alginate films, any dependence from both molecular weight and monomeric composition was noticed when dealing with the tensile and oxygen and water vapor barrier performances as any significant differences were found when comparing the different alginates. Manna et al. [256] studied alginate-based target-specific bioadhesive drug delivery systems, providing insights about the potential and limitations of alginate as a bioadhesive excipient and will guide the future pharmaceutical applications in targeted drug delivery. Yang et al. [257] studied more specific applications such as the possibility of using degradable alginate hydrogel for catheters, highlighting a new approach in the preparation of biomedical devices that are more patient friendly and environmentally friendly. Dhalsamant et al. [258] studied biodegradable carbohydrate-based films for packaging agricultural products, addressing the research on composite and hybrid film development, incorporation of plasticizers and crosslinkers, and nanomaterial reinforcement to enhance flexibility, water resistance, and durability without compromising biodegradability. Equally important is the optimization of film fabrication techniques, which play a crucial role in determining the final performance and processability of biodegradable films. Techniques such as solution casting, extrusion, electrospinning, and layer-by-layer assembly offer distinct advantages depending on the application scale and film requirements.

5.5.2. Chitosan-Based Films

Radhakrishnan et al. [259] wrote an excellent review about chitosan-based biomaterials, highlighting the real-word applications. Wound care is considered one of the major clinical challenges, as it can lead to wound infections, and these materials can prove to be very efficient. Hashempur et al. [260] reported the antioxidant and antimicrobial properties of a chitosan film, prepared by different techniques, starting from solvent casting, and they found that chitosan-based xerogel film containing *Nigella sativa* extract was formulated, showcasing effective antimicrobial properties against different bacteria species and *Candida albicans*. The antioxidant activity of this formulation was another advantage of this novel product, suggesting its application as a reliable wound dressing. Similarly, Kaczmarek et al. [261] found that functionalized chitosan films represent a good solution for this goal. Nawaz et al. [262] studied chitosan samples for enhanced water retention in agriculture. Madihalli et al. [263] studied the performance of chitosan film as an innovative approach for sustainable cosmetic face mask applications.

5.5.3. Hyaluronic Acid-Based Films

Srinivasan et al. wrote [264] a compressive review about the diverse biomedical application of hyaluronic acid, with particular attention to its osteogenic potential. As a versatile biomaterial, it has the ability to influence cell morphology, promote biomineralization, and act as a chemically adaptable compound. Ahmadi et al. [265] studied hyaluronic acid-based composite films for wound dressing. Yu et al. [266] reported the fabrication of hyaluronic acid hydrogel films for persistent anti-fogging, with high transparency and durability via a facile ecofriendly method. Lee et al. [267] studied the synergistic moisturizing effect

of a cellulose nanofibril/hyaluronic acid/poly-γ-glutamic acid blend system. The water retention ability of these systems was assessed by measuring the evaporation rate under controlled temperature and humidity conditions. Some formulations demonstrated very high water retention capacity, which was evident based on its relatively slow drying rate.

5.5.4. Cellulose-Based Films

Lee et al. studied [268] the properties, preparation, and applications of cellulose-based hydrogels. They exhibit exceptional water retention capability, mechanical stability, and tunability, rendering them highly suitable for smart packaging, biomedicine, environmental remediation, sensing, and electronic applications. In particular, this kind of hydrogel plays a critical role in maintaining the freshness and quality of food and pharmaceutical products. In the field of biomedicine, they exhibit promising applications. Furthermore, cellulose hydrogels are applied in pollutant adsorption and water treatment technologies. Ungureanu et al. [269] studied the uses of cellulose gels in agriculture. Cellulose-based hydrogels have been shown to demonstrate significant enhancements (up to threefold) in soil water retention capacity. Additionally, their improved mechanical properties can play the role of a soilless potting medium. Both fertilizers and herbicides were proved to be successfully loaded into cellulose hydrogels. The release rate is lower in soil compared with water and decreases with higher gel content and crosslinking density in both media. In general, plants do not experience a phytotoxic effect. Furthermore, cellulose-based gels have been reported to improve the germination rate, root and shoot length, number of leaves, total biomass, crop yield, and some other parameters. Therefore, the application of these hydrogels as water reservoirs, soil amendments, and also as an independent soilless substrate is a highly effective method for enhancing plant growth and yield. This indicates that these materials are better suited for plants with relatively short life cycles, such as greens and vegetables.

5.5.5. Polyacrylic Acid-Based Films

Oouchi et al. [270] studied healing enhancement using polyacrylic acid hydrogel films. They demonstrated that a physically crosslinked PAA/PVP complex gel can adhere strongly to wet tissues and maintain a moist wound environment. This hydrogel significantly accelerated wound closure: wound size decreased to approximately 70–75% by day 4 and further reduced to 17–23% by day 11. Histological evaluation confirmed nearly complete re-epithelialization in the treated wounds, compared to poor regeneration in the controls. Shen et al. [271] studied this kind of material for application in sports medicine. They exhibit significant potential in sports medicine applications, including sports injury repair, sports health management, and sports injury protective equipment. This potential stems from their excellent biocompatibility, adhesion, tunable mechanical properties, and intelligent responsiveness. Mandal et al. [272] wrote a review on the use of these systems in smart agriculture. By offering slow and sustained nutrient release, these hydrogels ensure a more efficient nutrient supply that matches plant uptake rates, reducing environmental pollution. Hydrogels aim to minimize environmental impact. Assessing the degradation of products and their interactions with soil organisms is essential to avoid harming soil ecosystems.

5.5.6. Polyvinyl Alcohol-Based Films

Polyvinyl alcohol (PVA) and polyvinylpyrrolidone (PVP)-based hydrogels are the most popular water-soluble, biodegradable, biocompatible, non-carcinogenic, and extremely low-cytotoxicity synthetic polymers due to their good biocompatibility and have been used in numerous biomedical applications [273].

Skin wound healing using polyvinyl alcohol hydrogels was studied by Wong et al. [274]. In this case, as-prepared hydrogel films showed excellent mechanical properties,

which are favorable for application according to the shape of wounds. Additionally, these composite hydrogel films showed good swelling and hydrophilic performance, which facilitated cell adhesion and the absorption of wound exudate, with excellent cytocompatibility and capability of promoting cell proliferation, confirmed by MTT analysis. Composite polyvinyl alcohol (PVA)/chitosan/collagen film results were found by Kang et al. [275], who studied the efficiency of protecting wounds from infections. Specific chemical groups such as aldehyde groups can interact with hydroxyl or amine groups in chitosan, PVA or collagen to form a crosslinked network and increase the mechanical properties, cell viability and antibacterial activity of the films. Polyvinyl alcohol hydrogels have also shown very good antifungal properties [276]. These films have excellent antifungal activity against *A. fumigatus* hyphae growth. In agriculture, PVA/PVP hydrogels exhibit well-known characteristics such as extended release of essential substances and possible controlled irrigation of plants [233]. They have the ability to create various shapes using only physical crosslinking in many applications, which is more environmentally friendly compared to chemically crosslinked hydrogels, allowing for regulation of water absorption and transmissivity, enhancing compatibility with a wide range of entrapped chemical compounds. Various techniques are viable for generating a range of applications using hydrogels. One of the most widely used and scalable techniques for practical applications is solution casting. This process involves pouring the bulk solution into an inert mold of the desired shape or using a doctor blade to cast a thin film.

6. Conclusions

Hydrogel films are thin, flexible layers of a three-dimensional polymer network that can swell and retain water. They are composed of crosslinked natural or synthetic polymers. Crosslinking can be either chemical, with strong covalent bonds between the polymer chains, or physical, where the bonds and constraints can be of a different nature, for example, crystallized zones. These films have excellent properties, in particular mechanical, good biocompatibility, stimuli-responsiveness, and rapid response, making them suitable for a variety of applications.

There are several techniques for preparing hydrogel films, including solvent casting, dip coating, spin coating, slot die coating, photolithography, and 3D printing, among others. Each has its own strengths and disadvantages, and the choice of one depends primarily on the material and the intended use.

The polymers that can be used to create hydrogel films are numerous and can be of both natural and synthetic origin. Examples of natural polymers include chitosan, gelatin, and alginate, while synthetic options include polyvinyl alcohol (PVA), polyacrylic acid (PAAc), and polyacrylamide (PAAm).

The former is often preferable in terms of greater biocompatibility, while the latter has the advantage of being more controllable in production and having properties that can be easily adjusted.

Film hydrogels are, in both cases, versatile and have applications in a variety of fields, including the biomedical field. They can act as wound dressings due to their ability to absorb wound exudate and provide a moist environment for healing. They can be used to encapsulate and deliver drugs in a controlled manner, potentially reducing side effects and improving treatment efficacy.

Soft actuators and electronics: Their flexibility and responsiveness make them suitable for creating soft actuators and integrating into flexible electronic devices. Tissue engineering: They can be used as scaffolds for cell growth and regeneration in tissue engineering applications.

In addition, hydrogels are also used in non-biomedical areas like food packaging and agriculture, as actuators and sensors.

In agriculture, they have the great advantage over traditional materials of being much more biocompatible and biodegradable. They enable a type of "smart" agriculture, optimizing the use of resources, especially water, while also allowing for the controlled and sustained release of pesticides and fertilizers, making them highly sustainable.

Author Contributions: The authors A.U. and S.C. contributed equally to this study. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza—PNRR-I.3.3, DM 117-2023) ID: 8959, as a part of the European Union; by recovery programme NextGenerationEU (NGEU) and by regional project LINC-ER, funded by "Regione Emilia-Romagna", DGR N. 545/2019 Theranosti Centre srl.

Conflicts of Interest: The authors declare no conflicts of interest.

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