Hydrogels are networks of water-soluble polymers containing unique properties which make them ideal for use in biomedical applications. Hydrogels can be made of synthetic or natural polymers and they are capable of imbibing large quantities of water or fluids. Due to their considerable water content, hydrogels are flexible and similar to natural tissues which make them ideal for tissue engineering applications. Their ability for absorbing water results from the hydrophilic functional groups attached to the hydrogel backbone. Also, hydrogels exhibit high permeability for oxygen and nutrients which make them attractive for contact lens manufacturing. Hydrogels are valuable due to their easy fabrication process, small size, mouldability, immunity to electromagnetic radiation, and biocompatibility. More importantly, the physical characteristics of hydrogels can be tuned to provide specifications to match various applications. Hence, their applications cover a broad range, from drug delivery to the treatment of skin lesions (Figure 1). Hydrogel sensors for environmental applications such as temperature, humidity, pH, metal ions, and gases were reported. Furthermore, their applications extend to biomarker detection such as lactate, glucose, and proteins. More recently, synthetic hydrogels have been gradually replacing natural hydrogels due to their high potential for retaining water, high mechanical strength, and long functioning life; in addition, their degradability can be tailored. pH-sensitive hydrogels are able to alter their volume in response to a change in the pH of the environment they are placed in. They are able to swell significantly with high sensitivity – detection of minute pH changes of as small as $10^{-5}$ pH units. Hydrogels are promising for pH sensing due to their wide measuring range. Hydrogel-based sensors may be miniaturized and hence are of great importance
when combined into microsystems. Microcantilevers fabricated using silicon wafers have shown significant sensitivity with the detection of microscale changes in pH. This review aims to provide a brief introduction to the behavior of pH-sensitive hydrogels as well as the materials of various hydrogel compositions with their various applications.

**Working Principle of pH-Sensitive Hydrogels**

Stimuli-responsive hydrogels alter their volume in response to the variation in the environment they are exposed to. These volumetric changes have been reported to be more than a hundredfold. The amount of water in the polymer matrix varies from at least 20% to 99% by weight. The biocompatibility of hydrogels is directly linked to the degree of water retention within their volume – more than 95% of water retention is considered to have high biocompatibility. pH-sensitive hydrogels consist of a backbone polymer either containing weak acidic groups or basic groups which become more ionized in higher or lower pH environments, respectively. Mechanical stability is attributed to the backbone polymer while the ionizable component provides the pH sensitivity.

Figure 2 illustrates the swelling behavior of the hydrogel in basic pH obtained from the work of Tomar et al. Figure 2A shows the swelling observed at pH 7.4 while Figure 2B shows the shrunken state of the particles at pH 1.5. The particles were kept in the acidic (pH 1.2) and basic (pH 7.4) pH mediums for 6 hours. Tomar et al attributed the swelling of the particles to the carboxylic group ionization at pH 7.4 which leads to water...
uptake with the particles coalescing with each other. It was observed that the storage modulus was higher than the loss modulus at pH 1.2 indicating the elastic behavior at acidic pH, in comparison to the viscous property seen at basic pH.

### Hydrogel Compositions and Synthesis

Hydrogel preparation processes are generally simple and cost-effective. Cross-linking reactions between polymer molecules can be used to synthesize these stimuli-responsive hydrogels. Cross-linked polymers are insoluble but swell via solvent absorption because of the interconnections amongst the polymer chains. Various crosslinking methods are summarized in Table 1 and some references are cited for deep further details. The ionizable component within the polymer determines the working range of the hydrogel. Many different compositions of hydrogels exist, each with a varying sensitivity range (Table 2). Chitosan which is a natural polymer has been presented in many papers due to the useful properties it posses such as biodegradability and biocompatibility.

Recently, developments have seen in the usage of graphene oxide (GO) as a key ingredient in the fabrication of a pH-sensitive hydrogel for drug delivery. More et al developed a hydrogel using GO and para-aminosalicylic acid (PAS) which was lyophilized to give air-dried hydrogel (ADH). The hydrogel was optimized using varying concentrations of GO and PAS as well as drug content and it was found that equal concentrations of GO and PAS along with a drug (ratio of 1:1) led to optimal results. The supramolecular hydrogel was explored for the management of Mycobacterium tuberculosis. The fabricated hydrogel was found to have both pH-sensitive properties and different drug release profiles in neutral and acidic conditions, representing physiological pH of the blood and internal pH of the infected macrophages.

Polyethylene glycol dimethacrylate (PEGDMA) and methacrylic acid (MAA) in molar feed ratio of 1:2 with ammonium sulfate (1% of monomer concentration) as a free radical initiator were used to develop pH-sensitive hydrogel particles by Tomar et al (Figure 3A). To synthesize the particles, a polymerization reaction was performed for 4h at 60°C with the use of water as the continuous medium. The particles obtained were washed with deionized water and were then placed separately in the acidic and basic buffer for 6h to analyze their response to pH. Dai et al fabricated a hydrogel from dibenzaldehyde-functionalized polymer (DF-PEG) and polyaspartylhydrazide (PAHy) polymer with the incorporation of black phosphorus nanosheets (BPNSs) – Figure 3B illustrates the composition of the injectable DF-PEG-PAHy/BPNSs hydrogel. The fabricated hydrogel is capable of responding to both pH and near-infrared (NIR) light and showed ideal mechanical and

### Table 1 Various Crosslinking Methods for Synthesizing pH-Responsive Hydrogels

| Synthesis Methods                  | Advantages                                                                 | Disadvantages                                                                 | Ref.  |
|------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------|-------|
| Free radical polymerization        | The most economic and simple method                                         | Not suitable for synthesis controlled molecular weight polymers, nor well-defined architectures | [33]  |
| Anionic polymerization             | Provides control over the molecular weight of the synthesized polymer       | Very sensitive for the used solvent                                           | [34]  |
| Cationic polymerization            | Provides control over the molecular weight of the synthesized polymer       | Requires high temperatures and cooling during polymerization                  | [35]  |
| Nitroxide-medical radical polymerization | Simple and produces high purity polymer                                      | Requires long time for polymerization                                          | [36]  |
| Atom transfer radical polymerization | Appropriate for polymerizing a wide range of polymers including (meth)acrylates, styrenics, and some (meth) acrylamides | Requires high temperature                                                     | [37]  |
| Reversible addition-fragmentation chain transfer | Suitable for synthesis variety of architectures such as block, star, and branched | Has limitation in polymerizing (meth)acrylates, and (meth)acrylamides          | [38]  |
swelling properties. The chemotherapy drug (doxorubicin (DOX)) was efficiently contained in the hydrogel structure for cancer therapy. The fabricated DF-PEG-PAHy/BPNSs composite hydrogel was tested in vivo by conducting experiments in tumor-bearing nude mice.

**Fabrication Processes**

Long-period fiber grating (LPFG) coated with a pH-sensitive hydrogel has been presented by Mishra et al.\(^3\) The LPFG used was written in a germanium-boron co-doped fiber using a CO\(_2\) laser. The fiber was then coated with the hydrogel by dipping it into the solution for 5 minutes and leaving it overnight to dry. The hydrogel was made of acrylamide and ammonium, persulphate was used as an initiator, and N-tetramethylethylenediamine (TEMED) was used as a catalyst. The pH sensing capability of the fabricated hydrogel-coated LPFG was investigated through the comparison of the transmission spectra obtained for the varying pH values, using the setup in Figure 4. Upon introducing pH solutions into the fiber’s attached hydrogel, the hydrogel swelled/deswelled resulting in a change in its refractive index, consequently the effective refractive index of the fiber cladding.

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**Table 2 Overview of Compositions and Applications Presented in a Few Published Papers**

| Hydrogel Composition | pH Range | Ref. |
|----------------------|----------|------|
| Hydroxyethylcellulose (HEC)/hyaluronic acid (HA) | Release of the drug: 55.37% at pH 3 and 71.53% at pH 7 (application: treatment of skin lesions) | [25] |
| Carboxymethyl chitosan (CMC) | At pH 7.4 hydrogel swells, swelling in basic pH (application: theophylline release in intestine) | [23] |
| Polyethylene glycol dimethacrylate (PEGDMA) and methacrylic acid (MMA) | Swelling at pH 7.4, shrinking at pH 1.2 (application: the release of peptide drugs in the intestinal region) | [20] |
| Cationic hydrogels like chitosan and poly(ethylene imine) | Swell at low pH (application: delivery to stomach) | [24] |
| Anionic hydrogels like carboxymethyl chitosan | Swell at higher pH (application: drug delivery at pH 7.4 in the intestine) | |
| Cationic hydrogels like chitosan and poly(ethylene imine) | Swell at low pH (application: drug delivery to the stomach during ulcers) | |
| N-(Hydroxypropyl)methacrylamide (HPMA) | Stable at physiological pH. At pH 5.0, nearly 50% was released (application: release of doxorubicin (Dox) for targeted cancer treatment) | [26] |
| Copolymers of poly(ethylene oxide) and poly(propylene oxide) blended with poly(β-aminooxyester) | Stable, insoluble form at physiological pH but undergo a rapid dissolution at pH values below 6.5 (application: cancer therapy) | [27] |
| Poly(dimethyaminooxetathyl methacrylate) (PDMAEMA) | Exist in an ionic state at physiological pH. Increasing the pH above pKa will collapse the gel (application: cancer therapy) | |
| 4-Amino-N-[4,6-dimethyl-2-pyrimidinyl]benzenesulfonamide (sulfamethazine) | No transmittance detected at pH below 6.7 (application: the pulsatile release of drugs around physiological range) | [28] |
| PEG-PAMA-P(C6A\(_x\)-C7A\(_y\)-DPA\(_z\)-DBA\(_m\)) (EAASh) | pKa value of 7.0, hence swell in this range (application: small interfering RNA (siRNA) delivery) | [29] |
| Hydroxypropyl methacrylate (HPMA)/N,N-dimethylaminoethyl methacrylate (DMA)/tetra-ethyleneglycol dimethacrylate (TEGDMA) | Sharp transition region between pH 7.8 and pH 6.8 (application: includes treatment of diabetes and diabetes-related disease) | [30] |
| Dibenzaldehyde-functionalized polymer (DF-PEG) and polyaspartylhydrazide (PAHy) (F-PEG-PAHy/BPNSs) | At pH 5.5, greater drug release is seen compared to pH 6.5 and pH 7.4, with sufficient release at pH 6.5 (application: targeted Dox delivery to tumor sites) | [31] |
| Graphene oxide (GO) and Para-aminosalicylic acid (PAS) in solution phase lyophilized to obtain air-dried hydrogel (ADH) | Higher drug release rate at pH 4.2 compared to pH 7.2 (application: the release of para-aminosalicylic acid (PAS) to treat tuberculosis) | [32] |
altered. Thus, the resonance wavelength of the fiber shifted. Swelling of the hydrogel is resulting from dissociation of the carboxylic ions immobilized in the hydrogel that in turn increases the electrostatic repulsion due to generating more ionized carboxylic groups. A wide operating range from pH 2 to 12 was reported.

Hydrogel contact lenses sensitive to pH have been looked at for drug delivery utilizing the pH changes in tears. Noh et al (2017) prepared the hydrogel solution by adding a cross-linking agent (EGDMA) and initiator (AIBN) to HEMA. Two different ionic polymer groups (poly(vinylpyrrolidone) PVP, poly(N-isopropyl acrylamide NIPAAm) were used in this study (Figure 5). This solution was then filled onto plastic molds and the polymerization took place using an oven at 100 °C. The tested drug was hydroxypropyl methylcellulose (HPMC) which is commonly used to treat dry eye disease. The drug was stored onto the contact lenses by immersing the dried contact lenses into 1% HPMC for 3 h. The expansion of the lens structure regulates the drug diffusion with drug release, activated in basic conditions for the p-HEMA-VP (20 wt%) lens. The p-HEMA-NIPAAm (20 wt%) lens was found to de-swell in basic solution, decreasing drug release. The prepared artificial tears had a pH value of between 5.8 and 8.35.

Microcantilevers coated with a pH-sensitive hydrogel solution have ultrahigh sensitivity enabling microscale detection of changes in pH (Figure 6). Bashir et al (2002) fabricated cantilevers using silicon wafers on which the prepared hydrogel solution was patterned. SOI wafers, with a 1 μm silicon layer and 1 μm oxide layer, were used to fabricate cantilevers on which the prepared polymer was patterned. An oxide layer was grown and the photoresist mask was used to anisotropically etch the wafer. A further oxide layer was grown on the sidewall and the oxide from the substrate-exposed silicon surface was etched using a dry anisotropic etch. Finally, a release etch was performed to free the cantilever and the wafers by immersion in a 10 wt% acetone solution. A mole ratio of 80:20 methacrylic acid:poly(ethylene glycol) 200 dimethacrylate was prepared with DMPA as the initiator. The prepared mixture of poly(methacrylic acid) (PMAA) and poly(ethylene glycol) dimethacrylate was spin-coated onto the cantilever samples and patterned using UV polymerization. As the pH around the structure increased, the polymer expanded resulting in a change in surface stress and hence causing the microcantilever to bend. A maximum deflection sensitivity of 1 nm/5 × 10⁻⁵ ΔpH was reported.

Figure 3 (A) Materials and preparation method presented by Tomar et al. Reprinted from Tomar LK, Tyagi C, Choonara YE, Kumar P, Pillay V. Rheological and swelling behavior of pH sensitive hydrogel particles. APCBEE Procedia 2014;9:192–196. Creative Commons Attribution-NonCommercial-NoDerivs 3.0 Unported (CC BY-NC-ND 3.0) (https://creativecommons.org/licenses/by-nc-nd/3.0/legalcodes). (B) Schematic diagram showing the composition of DF-PEG-PAHy/BPNSs hydrogel presented by Wu et al. Reprinted from Wu RS, Lin J, Xing YM, Dai ZL, Wang LW, Zhang XP. pH-sensitive black phosphorous-incorporated hydrogel as novel implant for cancer treatment. J Pharm Sci. 2019;108(8):2542–2551. Copyright 2019, with permission from Elsevier.
The usage of 3D printing has slowly evolved to generate structures and devices for a wide range of industrial applications. 3D printing enables the production of components with complex geometries at high precision and low cost.

Recent work has mainly focused on 3D printing of natural polymers in the field of tissue engineering, such as gelatin/chitosan and alginate. Yan et al developed a cell assembling machine that enabled the formation of 3D living tissue/organ analogies. Gelatin/chitosan at a ratio of 10:1 was used to form the 3D structure. Biodegradable oxidized alginate was used as a bioink for bioprinting by Jia et al. RGD-modified oxidized alginate hADSCs bioink was printed to form a lattice structure on a substrate made of gelatin. The printing of synthetic hydrogels has been limited due to the lack of suitable bioinks available. Panhuis et al reported the fabrication of degradable hydrogels using 3D printing. Bioinks based on hyaluronic acid (HA) have been investigated by Burdick et al for the use in cartilage or cardiac tissue engineering.

Figure 4 (A) Experimental setup used by Mishra et al showing the grating. (B) Graph showing the variation of resonance wavelength with pH for the hydrogel-coated LPFG. © 2016 IEEE. Reprinted, with permission, from Mishra SK, Zou B, Chiang KS. Wide-range pH sensor based on a smart-hydrogel-coated long-period fiber grating. IEEE J Sel Top Quantum Electron. 2016;23(2):284–288.

Figure 5 Schematic showing the swelling of the lens in solutions with different pH. Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature; Kim G, Kim HJ, Noh H. pH sensitive soft contact lens for selective drug-delivery. Macromol Res. 2018;26(3):278–283. Copyright 2018. https://www.springer.com/journal/13233.

Figure 6 (A) Schematic of the cantilever/polymer structure. (B) Equilibrium cantilever deflection as a function of pH around the polymer. Reprinted from Bashir R, Hilt JZ, Elibol O, et al. Micromechanical cantilever as an ultrasensitive pH microsensor. Appl Phys Lett. 2002;81(16):3091–3093. With the permission of AIP Publishing. © 2002 American Institute of Physics.
Healthy skin is slightly acidic while during healing the pH of the wound (7.15–8.93) shifts from an alkaline to the neutral state. Tamayol et al developed hydrogel microfibers incorporated with a pH-responsive dye which changes color based on the pH of the wound indicating the condition and healing of the wound. Alginate-based microfibers were loaded with pH-responsive mesoporous silica beads. Sodium-alginate (2% w/v) mixed with glycerol (0–60% w/v), and bead density (0–0.5 million/mL) was injected through the core channel with a flow of CaCl₂ (2% w/v) around the core. The use of hydrogels for epidermal applications is beneficial as they enable the wound to be maintained in a moist environment. The pH range studied was from 6.5 to 9 to assess the response of the fiber to the pH variation of the environment. Figure 9 shows the fabrication of the microfibers presented by Tamayol et al.

Hydrogels based on pH-sensitive hydroxyethyl cellulose (HEC)/hyaluronic acid (HA) fabricated by Kwon et al are skin-compatible and may be used for the treatment of skin lesions. Maintaining the pH of the skin is important in order to provide an effective barrier. The hydrogels were tested in vitro for the release of isoliquiritigenin (ILTG) drugs. The swelling properties of the hydrogels were investigated at pH values in the range 1–13. The efficiency of drug release was found to be greater than 70% at pH 7 due to the larger pore size. As the pH increases, the hydrogel swelling ratio also increases which has been attributed to electronic repulsion and the nature of HA.

Additionally, Schulz et al investigated and tested a hydrogel-based sensor in vitro in the physiological pH range and found that a sharp transition period was seen between pH 7.8 and pH 6.8. The application presented combined the tested hydrogel with a micromachined piezoresistive pressure transducer for the application of online pH monitoring. This combination provides a cost-efficient design.

Applications

Many papers have previously looked at the properties of a variety of different pH-sensitive hydrogels with various sensitivity ranges suitable for a wide range of applications such as drug delivery in the stomach. The success of these numerous hydrogels has been investigated by evaluating the swelling capability as well as the drug release for hydrogels with drug delivery capability. Others have investigated sensitivity by monitoring changes in pH. Below are a few examples of some of the applications of pH-sensitive hydrogels.

Remote pH Monitoring

pH-sensitive hydrogels suitable for biological use have previously been investigated in the application of monitoring epidermal wounds as presented by Tamayol et al (2016). Healthy skin is slightly acidic while during healing the pH of the wound shifts from an alkaline to the neutral state. Tamayol et al developed hydrogel microfibers incorporated with a pH-responsive dye which changes color based on the pH of the wound indicating the condition and healing of the wound. Alginate-based microfibers were loaded with pH-responsive mesoporous silica beads. Sodium-alginate (2% w/v) mixed with glycerol (0–60% w/v), and bead density (0–0.5 million/mL) was injected through the core channel with a flow of CaCl₂ (2% w/v) around the core. The use of hydrogels for epidermal applications is beneficial as they enable the wound to be maintained in a moist environment. The pH range studied was from 6.5 to 9 to assess the response of the fiber to the pH variation of the environment. Figure 9 shows the fabrication of the microfibers presented by Tamayol et al.

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Applications

Many papers have previously looked at the properties of a variety of different pH-sensitive hydrogels with various
with the capability of miniaturization. The properties of the sensor depend heavily on the properties of the hydrogel layer. The hydrogel used was based on hydroxypropyl methacrylate (HPMA)/N,N-dimethylaminoethyl methacrylate (DMA)/tetra-ethyleneglycol dimethacrylate (TEGDMA) and shows high sensitivity in the physiological pH range.

A polyacrylamide coated no-core fiber (NCF) pH sensor was fabricated by Pathak et al (2017). The hydrogel
was made of the aqueous solution combining acrylamide and bisacrylamide (19:1) – forming a 3D structured mesh-gel network. This sensor was tested at increasing pH (3–10) and comparisons between the transmission spectra were conducted with the sensor showing a good linear response in acidic and basic ranges. With increasing pH, the hydrogel swells due to electrostatic repulsion which is produced from the ionization of the carboxylic group. Consequently, the refractive index (RI) of the hydrogel decreases. Increasing wavelength was observed over the range investigated by Pathak et al as seen in Figure 10. A sensitivity of 1.94 nm/pH was reported for the fabricated sensor as well as good stability and repeatability.

Many published papers have focused on the use of hydrogels in the human body for applications in drug delivery, particularly those hydrogels' response in the acidic region. A limited number of articles reported on the synthesis of hydrogels with sensitivity around the physiological range. The hydrogel compositions suitable for the possible application of monitoring changes in the pH of blood have been presented by Liechty and Peppas as well as Schulz et al. Schulz et al presented a sensor with an ideal pH range for the application, as they achieved sufficient sensitivity within the pH range of 7.4 to 7.0, while Liechty and Peppas investigated the release of chemotherapy drugs using different hydrogel compositions in conditions where pH was less than 6.5.

**Drug Delivery**

For the application of drug delivery, the drug is incorporated into the polymer backbone. pH-sensitive
Hydrogels have been investigated frequently for the use in drug delivery of peptide drugs. This is essentially due to the hydrogels protecting the peptide drugs in the acidic environment as suggested by Tomar et al. (2014). Yadav and Shivakumar (2012) used a derivative of chitosan that is soluble in water to enable drug delivery to the intestine as it offers sufficient sensitivity to pH. From their work, it was concluded that the hydrogel swelling is dependent on the concentration of the cross-linking agent. Carboxymethyl chitosan (CMC) and carbopol were used to formulate the pH-sensitive hydrogels containing theophylline. The study showed that the fabricated hydrogel could successfully be used to release theophylline in the intestine, making it useful for treating symptoms of nocturnal asthma. Prolonged drug release was shown in the in vitro and in vivo studies which is ideal.

Recently, the use of pH-sensitive hydrogels for cancer therapy has been investigated as a method of improving the efficiency of the released drugs. Dai et al. (2019) developed a hydrogel for delivering doxorubicin (Dox), an anti-cancer drug, to tumor sites where the pH has been shown to decrease below the physiological range. The composition of this hydrogel was mentioned in section 2. In vitro tests were used to identify the drug release profile of DOX from the DF-PEG-PAHy/BPNSS hydrogel (Figure 11). A slow and stable release of DOX was shown in this study and it was found that NIR irradiation accelerated the release of the drug. The release of Dox drug was also investigated in the work of Etrych et al. using water-soluble polymer N-(2-hydroxypropyl) methacrylamide (HPMA). Dox attached to an HPMA polymer backbone, through degradable hydrazone linkages combined with spacers stable in physiological conditions, was shown to release DOX sufficiently in the mild acidic environment. The effective release of DOX was found at pH 5.0 while a slight release was seen at the physiological pH, demonstrating that the hydrogel is more stable in physiological conditions.

Dong et al. (2017) fabricated a Salecan-based pH-sensitive hydrogel for controlled insulin delivery. The composition of this hydrogel was mentioned in section 2. In vitro tests were used to identify the drug release profile of DOX from the DF-PEG-PAHy/BPNSS hydrogel (Figure 11). A slow and stable release of DOX was shown in this study and it was found that NIR irradiation accelerated the release of the drug. The release of Dox drug was also investigated in the work of Etrych et al. using water-soluble polymer N-(2-hydroxypropyl) methacrylamide (HPMA). Dox attached to an HPMA polymer backbone, through degradable hydrazone linkages combined with spacers stable in physiological conditions, was shown to release DOX sufficiently in the mild acidic environment. The effective release of DOX was found at pH 5.0 while a slight release was seen at the physiological pH, demonstrating that the hydrogel is more stable in physiological conditions.
could be tailored according to the pH of the medium. Figure 12B and C illustrates the cumulative insulin release with time showing suppressed release at acidic pH and enhanced release at neutral pH. Buffer solution with a pH of 7.4 was used to model the pH of the colon and a pH of 1.2 to model the gastric environment at 37 °C. Applications of pH-responsive hydrogels extended to be utilized for measuring the response of cancer cells to anticancer drugs and to record the metabolism of cancer cells. Cancer cells consume glucose releasing lactate which leads to increase in the medium’s pH with a value 0.4 units while normal cells cause no pH change. In the presence of doxorubicin, multidrug-resistant cancer cells caused a drop in the pH of the medium.

**Food Industry**

Targeted delivery of bioactive food components considers encapsulation processes that are pH and time-dependent and hence pH-sensitive hydrogels are of interest in this field (Figure 13). Encapsulation of these components protects the functionality and may also allow the release to specific areas of the gut. P. de Vos et al briefly introduced the use of Chitosan for this application, which is highly compatible with living cells and dissolves at low pH. Chitosan is...
applied in combination with another polymer, such as alginate, that withstands the acidic environment in the stomach.

**Wound Dressing**

Wound medication represents a great challenge and poses a huge financial burden on the global healthcare system. Chronic diseases such as aging, diabetes, and obesity make handling wounds even harder. According to the World Health Organization (WHO) records, more than 30,000 deaths per year occur due to burns and scalds. The skin repairment for adults and overage individuals naturally occur; however, wound healing is accompanied by...
sca
cerring and the traditional approaches cannot achieve the
requirements. There was a speculate that the dry and un-
covered wounds recover faster. This speculation was dimin-
ished when Winter and his group introduced the first generation of
wound dressings. The dressings repaired wounded pig skin
twice faster as compared to air-exposed wounds.56 Since then,
dried wound dressings were developed such as woven cotton
gauze, and non-woven blends of rayon with other fibers. Dried
wound dressings were the most traded dressings till mid of
1970.57 Dried dressings maintain the wound area dry due to
absorbing the wound’s exudates and fluids. These fluids leak
out the dressings resulting in wound contamination. In ad-
nition, dried dressings cause strong pains during removing time
as they adhere to wound surface and suffer from low oxygen
permeability. Furthermore, they decrease the epithelialization
rate and cell proliferation due to maintaining the wound
in dry conditions.57 In 1970, moisten wound dressing were
introduced and showed faster healing rate than dried dres-
sings. Also, the wound healing was not accompanied with
inflammation and stigma.58 The high water content and oxy-
gen permeability of moisten dressing are considered the most
interesting characteristics. In addition, their wet nature allows
to maintain wound surface moist all the time, which enhance
the epithelialization rate and cell growth.

Hydrogels were found to be the best choice for wet
wound dressings application as they offer many advantages
such as keeping the wound moist, permeating oxygen,
removing wound’s exudates, protecting the wound from
infection and contamination, and easy and comfortable to
be removed.59 Among wet wound dressings, hydrogel
wound dressings are the market leader sharing with 43% of
the consumed wet dressings. Hydrogel dressings are sold
under various brand names, including GRX wound Gel,
Biolex, TegaGel, NuGel, Carrasyn, 2nd Skin Fexderm, Exu
Dry Dressing, and Cultinova Gel.59

Among the hydrogels used for wet dressings, Poly vinyl
alcohol (PVA) has been found to be the most frequently used
hydrogel because of the superior performance of the PVA-
based hydrogels as compared to their counterparts of other
hydrogels. To overcome the mechanical properties’ issue of
PVA, it is blended with some natural polysaccharides or
some synthetic ones.59

The pH of the skin is slightly acidic and varies in the
range of 4–6.60 However, skin injuries expose the skin to
the internal body fluids that have physiological pH (7.4)—result-
ing in an increase of the pH of the damaged skin. pH of
wounds was found to vary in the range of 6.5–8.5 depending
on the wound conditions.61 For wound healing, the wound
cells interact with a number of bioactive molecules: cyto-
kines, extracellular matrix proteins, and growth factors. The
interaction, is directly or indirectly influenced by the
wound’s pH.62 Hence, pH-responsive hydrogels can play
a significant role in cell growth reaction and monitoring the
wound status as well. Banerjee et al introduced a pH-
responsive hydrogel that sustained releasing growth factors
for accelerating the wound healing.61 The pH-responsive
hydrogel was made of poly(N-isopropylacrylamide-co-
acrylic acid) via radical copolymerization. The hydrogel
was loaded with bovine serum albumin (BSA), vascular
endothelial growth factor, and epithelial growth factor
which have been released at a different rate for 14 days
within the range of the wound’s pH (6.7–7.9). Releasing the
growth factors were progressive with an increase in wound
pH. The loaded hydrogel with growth factors was tested on
murine excisional wound model and showed an enhance-
ment of wound healing compared to conventional sustained
release growth factor therapy. The capability of pH-
responsive hydrogels to monitor the wound status and to
release drug simultaneously was recently reported.63 The
pH-hydrogel released antibiotic agents and monitored the
bacterial infections of wound sites using the pH detection as
an indicator (Figure 14). The hydrogel accuracy for detect-
ing bacterial infections was comparable with commercial
systems and the smartphone was used as a reader for the
wound conditions.

Conclusions

Hydrogels sensitive to pH have been investigated signifi-
cantly over the past years due to the properties they exhibit
which make them useful for a wide range of applications.
Hydrogel-based sensors are being developed for a wide range
of applications which include traditional fields of medicine.
Their biocompatibility and high sensitivity are some of the
properties which make them ideal candidates for such appli-
cations. Bashir et al reported a sensitivity of $5 \times 10^{-7}$ pH and
Zhao et al reported a sensitivity at 13 nm/pH at higher pH
region (8–10 pH).13,14 pH-sensitive hydrogels have been used
for a wide range of applications such as in contact lenses,
targeted drug delivery, and food protection/monitoring.
Many synthesis processes have been reported – from their
preparation using silicon wafers to 3D printing. The interest
in pH-sensitive hydrogels is still growing due to the range of
applications it can be used for and is seen to have great
utilization in our daily life in the near future.
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Disclosure
The authors report no conflicts of interest in this work.

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