Photoresponsive Hydrogel System for Ultraviolet (UV) Controlled Drug Delivery: A Mini Review

Fatin Ayu Kartika Mohd Suzaki[1], **Norazlianie Sazali**[2,3,4], **Afdhal Junaidi**[5], **Mimi Sakinah Abdul Munaim**[1], **Noor Azizah Sidek**[6], **Wan Norharyati Wan Salleh**[7], **Norsuhailizah Sazali**[8]

[1] Faculty of Chemical and Process Engineering Technology, University Malaysia Pahang Al-Sultan Abdullah, 26300 Gambang, Malaysia

[2] Faculty of Manufacturing and Mechatronic Engineering Technology, University Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

[3] Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

[4] Mechanical Engineering Department, Sepuluh Nopember Institute of Technology Kampus Keputih Sukolilo, Surabaya 60111, Indonesia

[5] Department of Chemistry, Faculty of Science and Data Analytics, Institut Teknologi Sepuluh Nopember, Sukolilo, Surabaya 60111, Indonesia

[6] Department of Mechanical Engineering, Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia

[7] Advanced Membrane Technology Research Centre (AMTEC), Universiti Teknologi Malaysia, Skudai, Johor Darul Takzim, Malaysia

[8] Universiti Malaysia Perlis (UniMAP), Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis, Kampus Tetap Pauh Putra, 026000 Arau, Perlis, Malaysia

ABSTRACT - This review offers a depth examination of the latest developments in UV light-responsive hydrogels, emphasizing their role as advanced platforms for drug delivery, especially considering wound care and topical treatments. The discussion shows how photochromic compounds such as azobenzene, spiropyran, and spirooxazine are incorporated into hydrogel structures. These integrations assist precise and controllable drug release when exposed to UV light. The mechanisms involved in this process are analyzed through the behaviour like photoisomerization-induced swelling, alterations in porosity, and reversible molecular conformations. The comparison between UV-responsive hydrogels and traditional counterparts emphasizes their superior ability to offer spatial and temporal control, targeted therapy, and minimized side effects. The review critically evaluates various characterization techniques—including swelling tests, FTIR, UV-Vis spectroscopy, SEM, mechanical evaluations, and rheological assessments—to understand how these materials behave before and after UV exposure. Besides, the discussion addresses environmental sustainability, economic viability, and manufacturing scalability, acknowledging current challenges and proposing potential solutions for future innovation. Concluding with prospective research directions, the paper emphasizes advancements in dual-stimulus responsive hydrogels, alternative responsive to visible or near-infrared light, and the development of intelligent wearable patches. Overall, UV-responsive hydrogels demonstrate major promise as the next generation of drug delivery systems, particularly in wound management, though concerns regarding safety, biodegradability, and commercial translation still need to be addressed.

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1.0 INTRODUCTION

Biomedical research is one of the fields that is most favoured and has a wide range of biomedical materials. One of the most beneficial developments of stimuli-responsive hydrogels—smart materials that can change their structure and behavior when triggered by factors such as temperature, light, pH, or enzymes. Among these, UV light- and pH-sensitive hydrogels have attracted particular attention due to the great activation and precise control, delivering treatments to the target areas [1, 2]. Their reversible and flexible nature makes them ideal for applications in wound healing, targeted cancer therapy, soft robotics, and implantable devices [3, 4, 5].

One of the features of UV-responsive hydrogels is using the light-sensitive molecules like azobenzene, spiropyran, and spirooxazine as the activation properties for drug release. When exposed to UV light, these compounds can change shape then alter the hydrogel itself, showing the same concept as using light as a remote control to guide the material's behavior [1, 6]. In contrast, pH-responsive hydrogels will use the body's natural pH variations, such as the acidic environment of tumors or infected tissues, to trigger drug release to the target site [7, 8]. When both light and pH responsiveness are combined, a layered and more precise treatment strategy that helps reduce unwanted side effects can be obtained.

By using dual responsiveness, the pH and UV light radiation as main elements in producing smart hydrogels for wound healing, both characterizations fit perfectly with the personalized and flexible therapies, especially in the drug delivery system. For example, Li et al. [9] showed that spiropyran-based hydrogels can adjust their water absorption and optical properties in response to both light and pH, giving a better control over drug release. This system is similar to the hydrogels used in soft robotic systems [5] that demonstrate how these materials can mimic lifelike movement and reshaping—without relying on wires, batteries, or complex electronics.

This review highlights the design, development, and medical applications of these hydrogels by focusing on dual-stimuli systems that are currently being developed by using smart material design. To enhance these hydrogels in clinical potential, these hydrogels are being paired with nanocarriers, injectable platforms, and photothermal agents [2, 10] to obtain better drug release into the body.

1.1 IMPORTANCE OF ULTRAVIOLET LIGHT RESPONSIVE HYDROGEL IN DRUG RELEASE

Using light only to control time and area of the drugs to be released will give difficulty, but UV light-responsive hydrogels can help improve the process of wound healing by using hydrogels that are design with the properties to absorb UV radiation as an activator for drug release to the wound area. These smart materials give the ability to deliver the drugs precisely at the right place and time, simply by applying UV light. This makes treatments more targeted, reduces side effects, and creates a more personalized and effective approach to care [1,11].

What makes these hydrogels a great wound dressing is the reaction of the hydrogels to light through molecules such as azobenzene and spiropyran. The properties of the molecules that can change shape—like flipping a molecular switch—when exposed to UV light can cause the hydrogel to swell, shrink, or open up (expand). This controlled response allows the drug inside to be released in a very precise way [1,12]. This behavior is useful for localized treatments, for example, applying a UV-sensitive gel directly to a wound or skin condition and use a UV light to activate it.

Since the drug is only released at the targeted site, less risk of harming healthy tissues can be obtained, and only take shorter period of time to heal [3,7,8]. Wang et al. [7] introduced a clever “time bomb” hydrogel that releases medicine after a specific pH change followed by UV radiation, creating a two-step release process. Rwei et al. [11] demonstrated another example where UV-triggered hydrogels provided pain relief exactly when needed, making treatment more responsive. These systems are also less invasive, patients can receive the hydrogel through a simple injection and then activate it with UV light, without needles or complicated equipment. This helps the process of wound dressing can be possibly use for more comfortable outpatient or even at-home care [5,12].

Unlike heat or dangerous chemicals, UV light can trigger drug release without damaging other ingredients such as proteins or enzymes [1,2]. But, there are a few case or situation where the UV light does not penetrate farther into tissue, making the hydrogels hard to use to avoid harm. New abilities of the hydrogels are now being studied by designing new materials that are safer, longer-wavelength light, and by developing layered hydrogels that extend the possibilities of the drug release consume lesser time to reach the target site [6,13].

In clinical phase, UV light-responsive hydrogels could help reduce healthcare costs. These hydrogels can minimize the waste and reduce the needs for repeated hospital visits due to the properties that made the hydrogels’ release time of the drugs is more accurate site reached. This leads to faster recovery times and makes it easier for patients to follow treatment plans, and lowers overall costs [2,4]. These hydrogels also can work together with inexpensive UV devices, making them suitable for outpatient care or even home use. This reduces the need for costly infusion machines or constant clinical monitoring [11,14].

Due to the high demand of wound healing by using great drug delivery systems that widely growth, smart hydrogels are the new solutions that are very useful to help increasing the benefit of healing in the medical field. The hydrogels can be scaled up for broader use while remaining sustainable, offering practical benefits for both the healthcare company and patients.

1.2 COMPARISON OF ULTRAVIOLET LIGHT RESPONSIVE HYDROGEL WITH BASIC HYDROGEL IN DRUG RELEASE

Hydrogels have been known in medical applications due to their ability to hold onto drugs and release them gradually over time. Their soft, water-rich structure and tiny pores make them gentle on the body, which is why these hydrogels are so effective for drug delivery. Most hydrogels can be made from materials like PVA, PEG, or PAM, and usually rely on basic mechanisms such as diffusion or slow breakdown to release the drugs into the target area. These methods are affordable and easy to use, but also need to be improved in terms of precision delivery of the drugs, which can be limiting for more advanced treatments [8, 15].

Instead of using hydrogels with no precision of drug release, the UV-responsive hydrogels are created. By using light-sensitive molecules such as azobenzene and spiropyran with the ability that can change shape when exposed to specific wavelengths of light. Once the hydrogels are exposed to the right wavelengths, the hydrogels can swell, shrink, or open its pores, to adjust the release time of the drugs to the targeted site of area [1, 4]. This ability to control the time of drug release is the main issue in clinical practices, where both timing and location are important. Unlike traditional hydrogels that release drugs continuously, UV-responsive hydrogels remain inactive until these hydrogels are exposed to light and activates them, helping in reducing the side effects and makes treatment more precise [7, 11].

UV-responsive hydrogels have the characteristic of their spatial and temporal accuracy. With focused light sources, the drugs or medicine planted in the hydrogels can target drug release to very specific areas—even down to millimeter precision. This makes them very useful for localized applications such as topical treatments, eye therapies, or pain management after surgery [3, 5]. In contrast, conventional hydrogels tend to release drugs more evenly and less selectively that require higher doses to cover up for their lack of targeting. But UV-responsive systems can be programmed and are reversible where the light can be controlled either to turn on or off the light that will regulate the drug release into the body. In some development, exposing the hydrogels to the light source allows the delivery system to pause or resume drug release, offering a release rate of the drugs can be controlled according to the level of wavelengths needed compared to traditional traditional hydrogels [1, 13].

The dual-responsive hydrogels that combine UV and pH triggers also being developed farther since this hydrogel contains smarter systems that respond to both environmental conditions and external light stimuli [2, 7]. Some UV light has limited penetration in tissues according to the different wavelengths use, the deeper the area, the drugs release will need more time to reach the area and prolonged exposure can raise safety concerns. But, comparing to the traditional hydrogels—though less advanced—are generally safer and more durable, making them better suited for widespread or bulk drug delivery applications [10, 16].

Table 1: Summary of Comparison between UV Light-Responsive Hydrogels and Basic Hydrogels in Drug Release

Feature	Basic Hydrogel	UV Light-Responsive Hydrogel
Stimulus for Drug Release	Passive (e.g. diffusion, degradation)	External UV light triggers release [1,4,7]
Control Over Timing	Limited or none (constant or sustained release)	On-demand, real-time activation via light exposure [3,11]
Spatial Precision	Uniform release throughout the matrix	Highly localized release using targeted UV light [5,7]
Reversibility	Irreversible once drug release starts	Often reversible (release can be paused/resumed with light) [1,13]
Drug Retention Before Activation	The drug may leak or diffuse before intended release	High retention until exposed to light stimulus [2, 7]
Customization Potential	Limited to polymer type and crosslinking density	Highly customizable with different chromophores (e.g. azobenzene, spiropyran) [1,4, 6]
Application Suitability	Suitable for simple, sustained release systems	Ideal for localized therapy, pain management, wound healing, ocular systems [3, 7,11]
Responsiveness to Environment	Not responsive to external triggers	Can be engineered to be dual-responsive (e.g., UV + pH) [2,13]
Limitations	Lacks temporal/spatial control; may require higher drug loading	Limited tissue penetration of UV; potential cytotoxicity with prolonged use [1, 10, 16]

2.0 OVERVIEW OF MECHANISMS AND APPLICATIONS OF ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS IN DRUG DELIVERY

UV light-responsive hydrogels have been developed to enhance controlled drug delivery. What makes these hydrogels special is the ability to release drugs from a distance and in a reversible way. These systems typically contain photochromic molecules, such as azobenzene, spiropyran, or spirooxazine, embedded within the hydrogel. When exposed to ultraviolet (UV) light, these molecules undergo photoisomerization—a change in their shape—that alters the hydrogel's physical properties. As a result, the material can swell, soften, or open its pores, allowing the drug inside to be released [1, 4].

One of the advantages of this UV-responsive light hydrogel is how the control rate of UV light for drug release itself. Unlike traditional methods that rely on slow diffusion, UV-responsive hydrogels can be activated on when and where needed, reducing side effects and improving the result of the treatments [5, 11]. This precision helps for localized therapies, such as wound care or eye treatments, where light can be directed to a specific spot without affecting the rest of the body [3, 7]. Different mechanisms also help the drugs to be released precisely to the target site. For example, azobenzene-based hydrogels shift from a trans to a cis form when exposed to UV light. This structural change disrupts the arrangement of molecules, causing the hydrogel to swell or become more porous and enabling controlled drug release [1].

These mechanisms have already been applied to deliver drugs such as lidocaine, anti-cancer agents, and antibiotics, depending on the medical need [4, 7, 11]. Depending on the function of the hydrogels which is for wound healing, the combination of UV sensitivity with pH responsiveness is one of the reliable solutions. These dual-stimuli hydrogels are designed to release drugs only under specific conditions, such as the acidic environment found in inflamed or cancerous tissues, when triggered by both pH changes and UV light [2, 7, 13]. Another application is in injectable therapies. A drug in liquid form can be injected and then solidified in place using UV radiation, ensuring that the hydrogel conforms the different routes and spaces while delivering drugs in a minimal pass through the body [4, 17].

These developments expand the possibilities for targeted treatments in clinical practice, offering more precise, adaptable, and patient-friendly drug delivery systems.

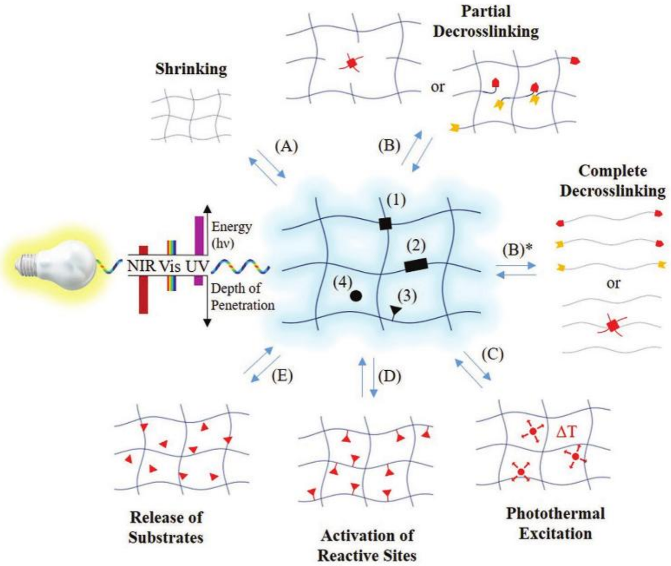

Figure 1. Schematic representation of photochemical and photothermal mechanisms in UV, visible, and NIR light-responsive hydrogels. These transformations, such as decrosslinking and photothermal activation, enable precise drug release from the hydrogel matrix [18].

2.1 MATERIALS AND MECHANISMS IN ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS FOR CONTROLLED DRUG RELEASE

To obtain UV-responsive hydrogel abilities from light-sensitive molecules and flexible polymers that react when exposed to UV light, the reactions can alter the hydrogel's structure, making it possible to control the release rate of the drugs, and allowing treatments to be designed for medical needs. Some of the main components that make this possible include:

1. Azobenzene

   This molecule can change the structure between two shapes—trans and cis—when exposed to UV light. That change in polarity and structure loosens molecular bonds or expands the hydrogel's pores, making it easier for drugs to pass through [1, 18].

2. Spiropyran and spirooxazine

   These molecules are in water-repelling form at the start. Under UV light, they shift into a water-loving state, causing the hydrogel to swell. This swelling helps drugs to be released making the material more effectively reach to the target area [2, 7, 13].

3. o-Nitrobenzyl and coumarin derivatives

   These are built into the hydrogel's bond and break apart when exposed to UV light. The breakdown opens the structure and releases the drug. Coumarin is commonly use due to its gentle on the body and can be activated with low-energy light [1, 5].

4. PEG-based monomers

   Materials such as PEGMEMA, PEGDA, and azoPEGMA are commonly used to form the hydrogel itself. They are safe, flexible, and easy to shape or print into different forms, making them well-suited for medical applications [4, 10].

To ensure these hydrogels form properly, photo-initiators like PEG-BAPO are used. When exposed to UV light, they trigger the gelation process, allowing the hydrogel to mold itself to complex body shapes or surfaces [10].

The way these hydrogels function depends on several mechanisms:

1. Photoisomerization, where molecules such as azobenzene switch from trans to cis, disrupting interactions within the matrix or with host molecules like cyclodextrin. This breakdown of drug-carrier bonds enables controlled release [18].
2. Photocleavage, where UV light breaks specific chemical bonds (such as o-nitrobenzyl ester), leading to gel–sol transitions or increased porosity that allows drugs to diffuse outward [5].
3. Photothermal conversion, where agents like gold nanorods or graphene absorb light and convert it into heat. This localized heating triggers thermosensitive phase changes that regulate drug release [5].
4. Dual responsiveness, where some hydrogels react not only to UV light but also to other triggers such as pH or redox conditions. For example, spirooxazine-based hydrogels can respond to both UV light and acidic environments, making them useful for targeting tumors or inflamed tissues [2, 13].

By combining light-reactive molecules with biocompatible materials, UV-sensitive hydrogels help enhance the drug delivery systems. They can be fine-tuned to match different medical needs, whether timing, location, or both are critical. This ability to use light to precisely modify the hydrogel's structure opens up ways for more treatment solutions develop to help more patients.

2.2 COMPARATIVE EVALUATION OF MATERIAL USED IN ULTRAVIOLET LIGHT RESPONSIVE HYDROGEL FOR DRUG DELIVERY

Selecting the right materials is important when developing a UV-responsive hydrogel for drug delivery. The material or photochromic compounds and polymer used need to give impact on how the hydrogel responds to UV light but also can give influences in biocompatibility, drug retention, stability, and how it breaks down over time. From the various options studied, azobenzene, spiropyran, spirooxazine, and o-nitrobenzyl derivatives are the most commonly used as photo-responsive agents.

1. Azobenzene

   Azobenzene is a photochromic molecule used in light-sensitive systems. It can reversibly change its shape between trans and cis forms when exposed to UV light, which can disturb the interactions like cyclodextrins or cause physical changes in the hydrogel structure [1,18]. Due to its reversibility, this material shows its fast response, and its ability to be fine-tuned with different substitutions, making it easy to on-and-off the drug release, especially in topical or eye treatments [4].

2. Spiropyran and Spirooxazine

   These molecules can also change forms between states when exposed to UV light, changing from water-repelling (hydrophobic) to water-loving (hydrophilic). This shift makes the hydrogel swell as it absorbs more water, helping drugs diffuse out more easily [2,13]. These two materials work well in dual-responsive hydrogels where UV light and pH changes combine to trigger drug release [7].

3. o-Nitrobenzyl Derivatives

   Unlike azobenzene and spiropyran, o-nitrobenzyl groups use a photocleavage method, where UV light breaks chemical bonds in the hydrogel. This cause the gel to turn into a solution or lead to the broken matrix, resulting in a quick burst of drug release [1,5]. But since this process is reversible, it is less suited for situations to insert multiple doses over time.

4. PEG-Based Polymers

   For the hydrogel matrix itself, PEGDA, PEGMA, and azoPEGMA are the better choices because they offer excellent biocompatibility, very hydrophilic, and provide good mechanical stability and strength [4,10]. These PEG-based systems are good for injectables and 3D printing, giving plenty of options to customize how the drug is released. They can also bond covalently with photochromic agents or photo-initiators like PEG-BAPO and increase flexibility of the hydrogel.

Azobenzene and spiropyran are very useful in drug delivery systems because both materials can be controlled with light, making the release process of the drugs to pass through easily. Both materials are great for repeated doses, targeting specific tissues, and responding to different environments. Certain materials like o-nitrobenzyl derivatives are better suited for situations that require a quick response, one-time release of a drug. Plus, polymers made from polyethylene glycol (PEG) are also suitable to be used due to their compatibility with the body, safety in clinical settings, and have flexibility to be used in various formulations.

2.3 APPLICATIONS OF ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS IN DRUG RELEASE

UV-responsive hydrogels are increasingly used in drug delivery platforms, giving better medium for light-triggered activation and precise control over the time of drug released. Due to the new development of this UV light hydrogel, it helps to increase the rate of wound healing making it valuable in a range of biomedical applications, from localized cancer treatments and chronic wound care to ocular therapies and pain management. Increasing the rate of development of wound dressing to initiate drug release at specific sites and times, these systems enhance therapeutic as a result while minimizing side effects and reducing unnecessary dosing. As research continues to improve their tissue penetration and biocompatibility, UV-responsive hydrogels are steadily advancing toward becoming essential tools in personalized, stimuli-responsive medicine [1, 2, 7].

Table 2: Applications of Ultraviolet Light-Responsive Hydrogels in Drug Release

Application Area	Mechanism of Action	Advantages	References
Topical Wound Care	UV-triggered hydrogel swelling or degradation for antimicrobial release	Minimizes systemic exposure; reduces overmedication risk	[3, 7]
Cancer Therapy	Localized chemotherapeutic release triggered by UV and pH conditions	Targeted therapy with reduced systemic toxicity	[2, 6, 13]
Pain Management	On-demand release of lidocaine using pulsed UV light exposure	Repeatable dosing; avoids constant drug infusion	[11]
Ocular Drug Delivery	UV-sensitive gels enabling patient-controlled dosing and longer corneal retention	Improved drug retention; enhanced absorption	[1, 4]
Implantable Drug Reservoirs	In situ gelation with UV activation for minimally invasive therapeutic delivery	Non-invasive; conforms to complex tissue geometry	[4, 17]
Wearable Devices & Soft Robotics	Drug release coupled with movement or sensor response via UV activation	Combines therapy with actuation or feedback functions	[1, 5]

Current findings show that UV-responsive hydrogels can expand well in various therapeutic applications. The technical ability to provide local hydrogel support for wound healing by controlled release of antimicrobials, direct delivery of chemotherapy within tumor sites, or facilitated ocular drug administration, which could be triggered externally, was successfully demonstrated with several biomaterials. The UV-responsive hydrogel-based personalized care give the benefits of healing due to precise, controlled drug release, compatibility with biological environments, and sensitivity to environmental indicators. By containing context-specific adhesive systems, these UV light hydrogel has increase its function to wearable and implantable platforms that give result to the competence in small invasive and adaptive drug delivery in the future.

3.0 CHARACTERIZATIONS OF ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS

The development of UV-responsive hydrogels for drug delivery demands a multiple approach that consist of analytical techniques to determine structural, mechanical, and functional properties. These characterization strategies are important for validating the hydrogel's performance and ensuring its suitability for controlled drug release applications.

3.1 SWELLING BEHAVIOR ANALYSIS

The swelling test is to measure the absorption of the hydrogel towards water. The swelling property is important in drug delivery because the higher rate of a hydrogel to swell, the higher rate of the drugs to pass through to the target site. For UV-responsive hydrogels, the swelling characterization depends on how the material reacts to light. For example, when azobenzene is exposed to UV light, it changes shape from a straight form (called trans) to a bent one (called cis). That phenomena will gives more space inside the gel, making it easier for water and drugs to pass through [1]. Similar with spirooxazine. This material will act as water-hating form, making the structure or the pores of the hydrogel to keep closed not exposed to light. But once the hydrogel is expose to UV light, the structure will change and becomes water-friendly, increases the swelling property [13]. In one study by Zou et al. [13], the hydrogels were tested with different amounts of spirooxazine (SO-DB). As a result, the swelling happened fast during the first few hours and then leveled off after about 25 hours. To clarify this test, the hydrogel is added with SO-DB, resulting the hydrogel decreasingly swells, dropping from 106.5% to 82.5%. This is because SO-DB makes the gel more hydrophobic (less water-loving) when it is not exposed to UV light. Another paper by Abu Bakar [19] showed that swelling could also change after UV exposure. Hydrogels with groups like spiropyran swelled more after being exposed to UV light, proving that light helps in expanding the pores and lets more water in. Overall, the swelling test is one of the tests that shows how well a UV-responsive hydrogel reacts to light and how well it is at controlling drug movement through its structure [10, 13].

3.2 FOURIER-TRANSFORM INFRARED SPECTROSCOPY (FTIR)

FTIR spectroscopy helps determine certain functional groups are light-sensitive when the material is added to the hydrogel. It works by shining infrared light onto the material and measuring how the bonds inside absorb that light. Each type of bond vibrates at a specific frequency, which shows up as peaks on the FTIR graph. In UV-responsive hydrogels, scientists often use FTIR to prove that compounds like azobenzene or spirooxazine are bonded into the gel, not just floating around. For example, in azobenzene-based systems, a clear N=N stretching signal around 1400–1500 cm^{-1} shows that the azo group is there and ready to respond to UV light [10].

For hydrogels made with spirooxazine, FTIR can detect other materials. Researchers found a few signature peaks:

- One broad peak at 3380 cm^{-1} for the -OH (hydroxyl) and -NH (amine) groups,
- A sharp C=O peak at 1724 cm^{-1} showing ester or carboxylic bonds,
- And importantly, a C=N peak at 1650 cm^{-1}, which confirms the spirooxazine structure is there [13].

When there was no C=C peak near 1600 cm^{-1}, that means all the monomers had reacted properly, showing a good result for the hydrogel to form a good structure of gel. After exposing the hydrogel to UV light, the FTIR peaks shifted or changed in intensity. This shows the light is causing real chemical changes inside the gel, like the isomerization of azobenzene or ring-opening in spirooxazine. These changes are the reason the gel can respond to light by swelling or releasing drugs [1,10]. Since water can interfere with the signals, the samples need to be dried before testing. That way, the differences before and after UV light exposure can be tracked, confirming whether the hydrogel is truly responsive.

3.3 UV-VISIBLE (UV-VIS) SPECTROSCOPY

UV-Vis spectroscopy is used to measure the light-sensitive hydrogels behave under UV exposure. It helps tracking the reaction between the materials by time especially when the hydrogel contains molecules like azobenzene or spirooxazine that react to light. For example, azobenzene usually in a stable “trans” form, which absorbs light around 350 nm. But when expose to UV light, the molecule changed into a “cis” shape, and its absorbance shifts to about 440 nm. That shift shows that the molecule has changed shape, confirming that the hydrogel is reacting to UV light [1,4,2]. Spirooxazine behaves a bit differently but follows a similar idea. It will stay closed when no exposure to the light which can be seen in colourless form. But once UV light is applied, the structure changed and can be seen as a colourful structure that absorbs light at around 624 nm. The more intense the colour (or absorbance peak), the more spirooxazine has reacted, making it a useful signal that the hydrogel is light-responsive [13]. These materials also have a reversibility property. Some hydrogels, like those made with azoPEGMA, can switch “on” with UV light and “off” again with visible light. That means the drug release can be turned on and off with light, offering precise control over when and where the drug gets delivered [10].

3.4 MORPHOLOGICAL ANALYSIS (SEM)

Scanning Electron Microscopy (SEM) is a tool to examine the pore structures inside hydrogels. These pores act like small tunnels or pathways for the water and drugs to move through the material. This study shows that the reaction between the materials, the drugs, and the properties of these hydrogels when delivering the drugs over a period of time. The chemical reactions will trigger when the hydrogel is exposed to the UV light, making it reshape the physical structure of the material. As a result of the exposure to UV light, the pores will expand making the orientation shift or partially collapse. These changes will influence pf swelling behaviour of the hydrogel so that the drug release can be pass through to the target site immediately.

Li et al. [18] provided an example of this phenomenon. The study showed that azobenzene-based hydrogels transformed from smooth surfaces into well-organized porous structures after being exposed to UV light and solvents. This finding shows that UV light can physically reshape the hydrogel and then alter the rate of drug release [1]. Due to that, the light acts as a switch to start or stop the drug delivery, but at the same time, it can also fine-tune the material’s structure while increasing the control of drug release.

A lase light have been used to examine the structural change or reshaping of the material in hydrogel that can cause the changes of direction pores in colloidal hydrogels. This means that the hydrogel can not only trigger drug release but also design the pathways through which the drugs travel. For example, a hydrogel could be developed to release the drugs more quickly in one area of the body while slowing down release in another, simply by adjusting how the pores are arranged.

This ability to reorganize the structure of hydrogels with light makes UV-responsive systems valuable in drug delivery research. The flexibility for the UV light hydrogel making it one of the high demands for drug delivery system compared to that traditional hydrogel. Instead of relying only on passive diffusion or gradual breakdown, UV-responsive hydrogels can be actively reshaped and controlled, helping in to design the tools for treatments that are more personalized, efficient, and adaptable [1].

3.5 RHEOLOGY AND THERMAL BEHAVIOUR

Rheology is the behaviour of the hydrogels to move and respond to force. In one study, researchers used rotational viscometry to see how the gel behaved when stirred or pushed. Both types—one with and one without azoPEGMA—showed shear-thinning, meaning they became thinner and flowed more easily under pressure, like during injection. Once the pressure stopped, the gel thickened again. This behaviour can be functioned well for injectable treatments or 3D printing, where the material needs to be soft during use but stable afterward [10]. To test how much the hydrogel could stretch before breaking down, an amplitude sweep was done. A strain of 10% was found to be safe—it did not damage the gel's structure, which is important for future UV light experiments. This was especially relevant for mixtures with water-to-DMSO ratios of 80:20 or 95:5, which affect how the gel reacts to light [10].

Photorheology was then used to measure the gel when it turns solid due to exposure to UV light. Two key values were measured: storage modulus (G') for stiffness, and loss modulus (G'') for liquid-like behavior. When G' becomes higher than G'', the gel has solidified. This shows the material responds well to light and can form a stable structure for drug delivery or tissue support [10]. Thermal stability was also tested using DSC and TGA. These methods helped identify the glass transition temperature (Tg) and the point where the gel starts to degrade. Hydrogels made with PEGDA stayed stable even at high temperatures, making them suitable for body heat, storage, or sterilization. This makes them a reliable option for medical use, particularly in injectable systems and UV-cured implants [10].

3.6 DRUG RELEASE AND DEGRADATION KINETICS

Controlling drug release for specific use is important especially for wound healing. These materials react to signals from their surroundings, like they are listening for instructions, in contrast with typical drug carriers that allow the drug to be released. Light can be used as a signal. This signal can 'switch on' the release of drugs when expose to UV light and 'switch it off' again with visible light. This signal helps to reduce the time consume by the drugs to be released and penetrate into the skin and the capacity to easily modify delivery is like having a remote control for the drug [2, 4, 18].

UV-Vis spectrophotometry is used to understand how this release happens. This tool functioned to measure how much light is absorbed as molecules leave the hydrogel while tracking both the speed and the total amount of drug released. In azobenzene-based systems, the process is almost like a lock and key mechanism at work. When UV light at around 365 nanometers shines on the hydrogel, the azobenzene molecules change shape, loosening the network and opening pathways for the drug to escape. When visible light at about 450 nanometers is applied, the molecules return to their original form, tightening the structure again and slowing or even stopping the release.

One example consists of azoPEGMA micelles filled with Nile Red, a visible color that acts well for drug molecules. The micelles behaved effectively in solution, opening to release the dye when exposed to UV light and then reassembling to trap it once more when exposed to visible light. However, when converting the micelles into hydrogel, the process of release was no longer reversible since the light-triggered changing of form and was still effective, but the micelles were unable to rebuild. This highlighted a major problem: how to maintain reversible behaviour once the material solidifies. Researchers have offered innovative methods, such as splitting the stages of photopolymerization and photo-switching or creating materials that have flexibility even after adding gelatin [10].

Other studies show that hydrogels modified with spirooxazine showed that UV light could expand their pores, speeding up drug release [17]. Another approach using the light except for UV radiation is using near-infrared (NIR) light instead. By combining micelles with a heat-sensitive hydrogel, a system where NIR irradiation controlled drug delivery can be created. This shift is important because NIR light penetrates deeper into tissues than UV light, making it more practical for clinical use [20]. Whether UV light or NIR light, the goal remains the same: to use light as a gentle, precise tool for deciding when and where drugs are released.

Release process is important for the drug delivery system, same as degradation of the drugs, or how long the hydrogel stays inside the body and how stable it is throughout treatment. To determined whether the drugs degrade fastly or not in the body, the material distribute the drugs is consistently over time by conducting degradation trials. The period of time the hydrogel is exposed to UV light is the form of polymer utilized, and the quantity of photo-initiator that affects how quickly it degrades. A hydrogel that breaks down too rapidly might not be able to deliver the entire amount of the drugs, while the drugs that stays too long might be dangerous [10].

4.0 MECHANISM OF PHOTORESPONSIVE HYDROGELS UNDER ULTRAVIOLET LIGHT

The hydrogels that have light-sensitive changeable properties and accurate control drug release is widely used in biomedical research. That is why, most hydrogel that use or exposed to UV radiation, the photo-responsive molecules such as azobenzene, spiropyran, and spirooxazine will undergo structural or chemical changes. These hydrogels can be regulated according to the expansion and contraction of the hydrogel, or the release of drugs due to the different reactions between the molecules.

1. Spiropyran and Spirooxazine Hydrogels

   These molecules are commonly used for light-responsiveness hydrogels. Normally, there is no colour spotted and their rings are closed. But when hit with UV light, their rings open up and turn into more polar, often colored forms like merocyanine in spiropyran. This opening influences the internal forces inside the gel, making it swell more and release more drugs [10,17]. As for azobenzene, these molecules can go back to their original shape when exposed to visible light or when UV is removed. That means it can repeatedly trigger drug release with light, perfect for on-demand or pulsatile therapy [2,18].

2. Azobenzene-based Hydrogels

Azobenzene acts like a switch inside the hydrogel structure. When UV light is expose or absorb (around 365 nm) to the hydrogel, azobenzene flips from a straight 'trans' shape to a bent 'cis' shape. This change makes the hydrogel more water-friendly, causing it to absorb more water, expand, and let drugs pass through more easily. When switched to visible light (around 450 nm), azobenzene reverts to its original form, tightening the gel and slowing down drug release [1,10,18]. Due to this reversible behaviour, the drug release can be controlled to where the area of the drugs needed by adjusting the light precisely. By changing the time and the wavelengths of the UV radiation, the hydrogel can fine-tune the gel’s properties, especially when azobenzene is combined with polymers like PEGDA [1,2].

3. Tunable Response via Light Wavelengths

Some light wavelengths stimulate the optimum responses from each of these substances. Spiropyran and spirooxazine mostly react to UV light, but azobenzene reacts to both UV and blue light. Based on this behavior, hydrogels can have layered or unique zones that react to various kinds of light [1,13]. Cool materials, such as scaffolds whose structure can be adjusted with light or wound dressings that only react when exposed to UV light, have already been created using this wavelength specificity. These developments offer up the path to adaptive, highly customized biomedical systems with great potential in clinical use [2,18].

5.0 INFLUENCE OF PH ON ULTRAVIOLET LIGHT RESPONSIVE HYDROGEL PROPERTIES

UV light can trigger the drug release of the hydrogels to filtrate into the body, by having various pH values either in human body or surrounding, using pH variations also needs to be considered. Different tissues consist of different pH values. Healthy tissues usually have a neutral pH 7.4, while areas affected by infection or cancer tend to be more acidic. By combining UV responsiveness with pH sensitivity, hydrogels with good drug release rates and the precision of drug delivery to the target site can be developed.

One example comes from hydrogels that use spirooxazine as its UV light material. Spirooxazine molecules can change shape from a close-ring shape to an open shape when exposed to UV light making it more polar form. This transformation becomes more effective in acidic environments where at lower pH, the open form is more stable, which causes the hydrogel to swell and speeds up drug release. This makes the hydrogels particularly effective in tumor sites or infected wounds, where the environment is naturally acidic [13].

Collagen-based hydrogels provide another behaviour of this dual sensitivity. In one study, researchers observed that pH levels influenced how the gel swelled and degraded, especially when UV light was added. Under slightly acidic conditions, around pH 5–6, the gel absorbed more water and softened, which made rate of drug release increases. These hydrogels were crosslinked using riboflavin and UV light, and their behavior shifted depending on the surrounding pH [8].

Xu et al. [2] developed a hydrogel that responded to both UV light and pH in a coordinated way. When placed in an acidic environment at about pH 5.5 and exposed to UV light, the gel became more porous and released drugs at a faster rate. The acidity loosened the structure, while UV light triggered internal changes, creating a dual-trigger system that only released the drugs to the target area according to the pH and wavelengths of the UV light.

Instead of using UV light to release the drugs from hydrogel, to increase the rate of drug release by time, pH variations are important to be ideal towards human body. This approach reduces side effects, improves targeting, and enhances treatment outcomes for patients dealing with conditions such as cancer or chronic wounds [2, 8, 13].

6.0 CHALLENGES IN DRUG RELEASE CONTROLLED BY UV LIGHT-RESPONSIVE HYDROGELS

Even though UV-responsive hydrogels have a lot of benefits for drug delivery, there are still quite a few challenges that researchers need to overcome before the hydrogels are used widely in everyday treatments. One big problem is that UV light cannot penetrate deeply into the body. For wound that appear only on the skin or under the surface, this UV light hydrogel can be used to treat the wound due to the distance of the drug release into the wound area only take shorter time for the drug to be reached. But, as for a deeper wound inside the organ or tissues, the drug release will take longer time to reach the infected area. Due to the time taken for the drugs to reach the target area, UV light hydrogels is not suitable to be used for deeper wound. That makes it tricky to use UV hydrogels for things like internal tumors or deep muscle treatments because the light cannot get through [1,2]. Another concern is safety. While UV light helps trigger the hydrogel, using UV light hydrogel will need the UV light sources to activate the drug release mechanisms. Once the UV light sources are expose for a long duration time, it can harm healthy tissues. Repeated or long-term use might cause skin damage or even DNA mutations. While using these hydrogels, the usage of the UV light needs to be carefully used to avoid the risk of light-induced tissue damage, or phototoxicity [1,18]. The issue with the problem materials used also need to be considered. Some of the molecules, like azobenzene or spiropyran, can lose effectiveness. After several cycles of switching on and off, these materials might not work well, which could mess with the reliability of the drugs released

[10,13]. Plus, when these molecules are being a solidified hydrogel, the ability to reverse the structure of the material can decrease, making it harder to stop the release of the drugs once the drugs are release [10]. Designing these hydrogels needs to follow the procedure. The right balance between the strength of the gel, the responds of the gel towards light, the volume of the drug that can be carried, the safety of the body while using the hydrogel need to be determined. If any one of those behaviour is not work right, this means the exposure of the light is not enough or the gel is built too soft. That is why coming up with a system that is consistent and reliable is challenging [2,18]. Lastly, scaling up production is one of the biggest challenges that is not easy to overcome. A functional hydrogels that work well in the lab practically, need to consider for few aspects like high costs, navigating regulatory tests, and ensuring they can be stored properly over time if these hydrogels want to produce on a large scale production [1,7].

6.1 SOLUTIONS AND STRATEGIES FOR OVERCOMING CURRENT CHALLENGES

There are some limitations in the development of UV light-responsive hydrogels. Researchers are finding ways to overcome the limitations and making these hydrogels more effective, safer, and easier to use in real-world medical. One big challenge is that UV light can not penetrate deep into the body. To overcome this, scientists are exploring the benefits and compatibility in using the visible or near-infrared (NIR) light. These types of light can travel further through tissues and are gentler on the skin. Some studies made by the researchers regarding the use of special materials—like up-conversion nanoparticles—that absorb deeper-penetrating light and convert it into UV light inside the tissue. So, UV-responsive materials can still be used without shining UV rays directly on the skin [7]. To reduce the risk of skin damage, a small amount of UV light with suitable wavelength is added to the hydrogel. This can be achieved by making the light-sensitive molecules more efficient and can react even at lower light levels. Plus, the molecules like spiropyran, can be activated with safer types of light, such as blue light, instead of UV light [13,18]. Durability properties is needed in developing these hydrogels. To produce long term of usable applications of hydrogel on the skin over the time, a durability behaviour of hydrogels is important to. Some photo-responsive materials tend to weaken after repeated use, which can make drug release less predictable. To overcome this issue, a more flexible polymer is used to combine with the material, as to keep the hydrogel can reversibly use in many cycles. Combining UV responsiveness with other triggers, like pH or enzymes, adds extra control, so the gel only releases drugs when multiple conditions are met. That makes the hydrogels more compatible and useful in wound dressing [2,10]. In terms of materials, mixing natural and synthetic polymers is a good combination to develop a flexible UV light hydrogel. Natural materials like gelatin and collagen are gentle and safe for the body, while synthetic polymer add strength and responsiveness. When combined, both biocompatible and durable hydrogels are created and suit the behaviour to be implemented for injections or 3D printing [7,18]. Some manufacturing methods are being studied to make the production easier and more scalable. One example is light-controlled 3D printing, which allows hydrogels to be shaped and hardened in real time without using dangerous compound or chemicals. These practical improvements are helping UV-responsive hydrogels in the applications of wound dressing or wound healing use in clinics and hospitals [2, 10].

7.0 ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

7.1 ENVIRONMENTAL IMPACT OF USING ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS FOR WOUND DRESSING AND WOUND HEALING

UV light-responsive hydrogels are widely developed in wound healing and dressing applications. The development of these hydrogels needs to be considered economically, especially on how these materials might affect the environment. Many of these hydrogels are made from materials that are naturally safe and break down over time. Polymers like PEGDA, gelatin, or collagen have been shown to degrade without causing harm to the environment, especially when used in short-term medical applications like wound [3,18]. This shows that these hydrogels are made to not harm the environment when the hydrogels are thrown out after the treatment. So no harmful chemicals emitted from the hydrogel itself [1,10]. But some of the special compounds used to make the hydrogel light-sensitive—like azobenzene—are not biodegradable. If large amounts of these hydrogels are thrown in soil or wastewater, there is a chance they could break down into by-products that are not environmentally friendly causing the environment to be exposed to the hazardous chemical. One example is aromatic amines, which can form when azobenzene degrades. These compounds may be toxic to fish and microorganisms if they accumulate over time [2, 13].

Using UV light to trigger hydrogels requires special equipment that uses electricity and must be handled carefully. Too much UV light exposure can be harmful, not just to the materials but also to the patient. That is why a deep research done by researchers are finding a safer options of light to be used for these hydrogels like visible or near-infrared (NIR) light. These light uses less energy and is gentler for both patients and the environment [2,7]. To make these systems more eco-friendly, scientists are also working on cleaner production methods. Using natural ingredients and milder crosslinking techniques like solvent-free UV light curing or enzyme-based reactions helps reduce waste and avoid hazardous chemicals [10,18].

7.2 ECONOMIC VIABILITY AND SCALABILITY OF UV LIGHT-RESPONSIVE HYDROGELS IN DRUG RELEASE

Producing UV-responsive hydrogels for everyday medical applications, the hydrogels' performance in the lab must be examined. It is important to find out whether these materials are affordable to produce and whether they satisfy the needs of hospitals and clinics. One of the challenges is the method of developing the hydrogels. Many of these hydrogels rely on specifically constructed polymers and light-sensitive compounds like azobenzene or spiropyran, which must be handled and created carefully. The hydrogels also need specific UV curing techniques, which often need sophisticated equipment and carefully watched conditions. As a result, these procedure takes more time, effort, and money [1,18]. Furthermore, one of the factors that affects the creation of UV-responsive hydrogels is the price of the materials. When purchased in small quantities, as is typical during research periods, some of the compounds used—particularly those that react to UV light—can be pricey. Even though natural materials like collagen or gelatin are more affordable and environmentally harmless, combining them with synthetic photo-responsive chemicals can still increase the cost [10]. Increasing production causes problems. For small, specialized batches, methods like injectable gels or UV-assisted 3D printing are effective. However, if these hydrogels are to be produced on a larger scale, such as for medication patches or wound dressings, many considerations must be taken care of, especially regarding how uniformly the UV light can reach the material, how well the products can withstand storage, and whether each batch is consistent [2,7]. It has become easier to make these materials more economically as UV curing technology becomes more widely available and less expensive, particularly with LED-based systems. That is why ‘plug-and-play’ hydrogels are being developed by some researchers, where the hydrogels can be readily modified for various medications or medical purposes [1,18].

8.0 FUTURE PERSPECTIVE

8.1 FUTURE RESEARCH DIRECTIONS AND POTENTIAL BREAKTHROUGHS IN DRUG RELEASE CONTROLLED BY ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS

There are many benefits that UV light-responsive hydrogels could give in every application in the medical world. Scientists are trying to create hydrogels that are more efficient, practical, and even safer for long-term use. The potential for practical medical applications is rapidly growing as research continues to enhance hydrogel materials and incorporate more capable control functions. Making these systems more useful, not just for researchers, but also for patients and healthcare professionals. These hydrogels could be developed into common treatments in future studies.

1. Safer light sources beyond UV

   The fact that is, UV light does not penetrate deeply into tissue and can be damaging to healthy cells. Due to the lacking properties of the hydrogels, safer light sources like visible or near-infrared (NIR) light are currently being studied by researchers. These choices can penetrate farther without causing harm and are less harmful [1,7].

2. Hydrogels respond to more than one trigger

   The hydrogels that are being developed can react to other signals, triggering their properties or functions of hydrogels, including variations in pH, temperature, enzymes, or magnetic fields, rather than the UV light itself. More accurate and adaptable drug release is made possible by this type of multi-trigger system [2,13]. It is particularly helpful in complex environments, such as inflammatory tissues or tumors, where the release of the drug may need the fulfillment of multiple conditions. These hydrogels can be designed to function precisely when and where they are required by combining several triggers.

3. Design of more biocompatible and eco-friendly materials

   The hydrogels are being researched by combining with natural polymers like gelatin, collagen, and chitosan, or blended with synthetic materials to balance safety and performance [10,18]. The goal is to develop hydrogels that break down naturally in the body and leave no harmful residues in the body.

4. Miniaturized and wearable delivery systems

   To activate the hydrogels loaded with the drugs by using a wearable LED device or smartphone app, a systems need to be implemented to allow the users to control drug release themselves at home, offering more independence and comfort in managing chronic conditions [2].

5. Improving drug loading capacity and release accuracy

   Balancing the drug that can be loaded into the hydrogel with its reliability to release the drug evenly. The new formulations aim to create the controlled, pulsed, or even multi-phase release patterns depending on patient needs and light exposure cycles [1,13].

6. Greater integration with 3D printing and modular fabrication

   Using 3D printing in UV light curing can be more complex. But future hydrogels could be printed in various shapes tailored according to the sizing of the wound area. A modular hydrogel systems can be introduced like plug-and-play kits with customizable drug and light profiles, reducing manufacturing costs while improving flexibility [10,18].

7. Long-term safety and sustainability research

The hydrogels need to sustain the durability of the structure of hydrogels to make them work well practically. Hydrogels that can last long over the time when applied on the wound area is important to make sure that the drug being released into the target area completely before disposing them. The focus is on eliminating synthetic residues, improving degradation profiles, and ensuring hydrogels do not interfere with ecosystems after use [2,7].

8. Converting the innovation into clinical practice

To solve the problems of research and real-world healthcare such as scaling up the production, cost reduction, regulatory approval, and shelf-life stability, these hydrogels can be designed with various size and functions. With better production methods and standardized protocols, UV-responsive hydrogels can be produced in a large scale of production where it can be a demand clinical, hospital and even home treatments use [1,18].

Even though UV radiation can damage healthy cells and can not penetrate deeply into tissue, these hydrogels are being formulated with a function that use safer light sources with suitable wavelengths to activate them. The UV light sources such as visible or near-infrared (NIR) light can be substituted to make the hydrogel penetrate farther and are less damaging. That is why, researchers are creating new materials that can respond to these softer wavelengths, such as low energy photo-switches and up-conversion nanoparticles, to facilitate this change.

9.0 AUTHORS CONTRIBUTION

F. A. K. M. Suzaki (Writing - original draft, Visualization)

N. Sazali (Conceptualization; Supervision; Resources)

A. Junaidi (Validation, Resources)

M. S. A. Munaim (Supervision; Resources)

N.A. Sidek (Resources)

W. N. W. Salleh (Resources)

N. Sazali (Resources)

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