Advances In 3D-Printed Ultraviolet Light Responsive Hydrogels In Drug Release - A Mini Review

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ABSTRACT - This review digs into how ultraviolet (UV) light-responsive hydrogels, paired with cutting-edge 3D and 4D printing, enable personalized drug delivery. These hydrogels can absorb UV light and shift the structure, so that the hydrogels can release the drug straight to the target site. Photochromic compounds like azobenzene, spiropyran, and spirooxazine give the function of absorbing UV light to activate the release mechanism of the drugs to the target area. These molecules flip back and forth in response to UV light, letting the hydrogel swell, change its pores, and control the movement of drugs through it. Basically, the hydrogel becomes a programmable carrier. By using 3D and 4D printing, these hydrogels can be built with various precision, containing tiny channels, built-in drug reservoirs, and complex, layered shapes. The review lines up UV-responsive hydrogels against traditional drug delivery systems and shows how these hydrogels are better at releasing drugs on demand, limiting exposure to the rest of the body, and cutting down on side effects. To understand on how these hydrogels work, the review also discussing a few tests of the hydrogels: FTIR, UV-Vis spectroscopy, SEM, and rheology. These tests show whether the hydrogels hold up physically, stay chemically stable, and actually respond to UV light according to the wavelength and area of the hydrogel exposed to the UV light. As for the disadvantages affected the hydrogels performance towards manufacturing process—cost, environmental impact, how to scale up production, and whether these materials stay safe in the body for a long term. The review looks at how researchers are tackling these problems, from suggestion of the materials themselves, to mixing in hybrid polymers, to adding nanoparticles for extra responsiveness. The paper points to new frontiers: hydrogels that respond to visible or near-infrared light, platforms that respond to more than one trigger, and smart 4D-printed patches that adapt to patients in real time. Overall, UV-responsive, 3D-printed hydrogels are shaping up to be a big leap forward for safer, smarter, and more sustainable healthcare.

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1.0 INTRODUCTION

Stimuli-responsive hydrogels have been widely developed in many industries, and 3D and 4D printing are the best technologies used in the pharma and medical fields. These hydrogels can change physically or chemically, such as swelling or breaking down, when triggered by ultraviolet light (UV), temperature, or pH levels. These behaviours allow the hydrogel to act reversibly so that the drugs can be released to the target site at a specific time. That makes the hydrogel the perfect pharmaceutical medium in drug release for targeted cancer treatments, healing chronic wounds, or delivering drugs to a specific area (Sadik et al., 2022; Zhao et al., 2023; Firdhaus et al., 2022).

While advancing in 3D printing, these hydrogels can be created with custom shapes, internal structures, and built-in drug reservoirs, which traditional methods cannot do. Techniques like Digital Light Processing (DLP) and Direct Ink Writing (DIW) help in building these structures layer by layer while keeping the tiny details intact (Yu et al., 2021). By using DLP or DIW for customizing the 3D or 4D printing for this UV light hydrogel can help this hydrogel to finely tuned

the hydrogel so that it can release the drugs to the target site easily. Currently, 3D printing is a desired medical tool that, combined with material science, in order to develop good drug delivery systems that give the response required by the body (Qin et al., 2023; Lin et al., 2024).

Adding photochromic molecules like azobenzene, spiropyran, and triphenylethylene into hydrogels has created new possibilities in developing smart, light-responsive materials. When exposed to UV light, these molecules change shape or structure, causing the hydrogel to swell, shrink, or break down. This controlled behaviour allows for regulating drug release precisely, timing it right and controlling the rate, leading to better treatment outcomes with fewer side effects compared to traditional methods (Zhang et al., 2022; Li et al., 2023). However, there is still a lot of researches that need to be done for designing these new systems of using UV light hydrogels as one of the mediums for wound healing (Ma et al., 2023).

The scalability of 3D printing methods can ensure long-term safety and stability inside the body, but using UV light can give potential harm, such as phototoxicity. Currently, many researchers are also working on optimizing material properties, to create hydrogels that can respond to multiple stimuli and designing patient-specific hydrogel structures (Tibbits, 2022; Wang L. et al., 2024; Wang Z. et al., 2021; Mushtaq et al., 2023). All these efforts aim to release the full potential of UV-responsive hydrogels in advanced medical treatments. Finally, by merging UV-sensitive chemistry with 3D printing, a new smart drug delivery system can be developed to design the hydrogels that have adaptability to the environment, can precisely release the drug to the target site and can customize the drug delivery system according to the patients need (Sadik et al., 2022;, Li et al., 2023).

1.1 IMPORTANCE OF 3D PRINTING FOR ULTRAVIOLET LIGHT RESPONSIVE HYDROGEL IN DRUG RELEASE

Merging 3D printing with UV-sensitive hydrogels can change the control of the drugs to be released to the target site. Unlike traditional methods like bulk polymerization, casting, or molding, giving the idea to create the structure of the hydrogel in a 3D printing form that can control the shape, internal details, porosity, and overall size more precisely. That means the hydrogel can be designed to customize localized drug delivery systems, according to the patient's need (Sadik et al., 2022; Zhao et al., 2023; Yu et al., 2021). Creating effective drug delivery systems that can be implemented into the UV light hydrogel, allowing the drug release to the target area, can help to reduce unwanted side effects (Firdhaus et al., 2022; Ma et al., 2023).

There are tools that usually used for 3D printing hydrogel. Most commonly tools used are Digital Light Processing (DLP) and Direct Ink Writing (DIW). These two tools have techniques that adding the layers of the hydrogel one by one, by creating tiny microchannels, reservoirs, and complex 3D shapes which traditional methods cannot do (Qin et al., 2023; Lin et al., 2024). These methods will need to build the data and details for producing the hydrogel that can release the drug loaded by programming the 3D printing methods. The hydrogel can be designed by adding the internal fluid channels and drug reservoirs that respond to UV light which can release the drugs to the target area (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022).

The materials that have good crosslinking with UV light are polymers like Polyethylene Glycol Diacrylate (PEGDA) and Gelatin Methacrylate (GelMA). Those materials are mechanically strong, and are biocompatible for developing the 3D printing UV light hydrogel. To sustain the crosslinking between UV light and the materials, the responsive molecules towards UV light need to be kept inside the hydrogel in an active state, making the drug easily released whenever needed (Lee D. et al., 2023; Lee S. et al., 2023; Alinejad et al., 2022; Tian et al., 2021).

Instead of using UV light materials, multifunctional and hybrid hydrogels can be developed by using the 3D printing method. By adding nanoparticles or other polymers, the strength can be boosted, load more drugs, and can respond to different stimuli like pH, temperature, or enzymes. These hybrid systems open the door to more personalized medicine, responding to various signals and conditions inside the body (Firdhaus et al., 2022; Ye Chan et al., 2025; Bom et al., 2022; Li et al., 2023).

Currently, patient-specific devices like implants, wound dressings, and tissue scaffolds that can deliver drugs in a controlled, programmable way can possibly design by using 3D printing with UV-sensitive light hydrogels. This 3D printing UV light hydrogel helps improving the result of wound healing, reducing the time of the treatment by adding materials that has flexibility and structural hydrogels. The outcomes of using this hydrogel for wound healing can create opportunity of drug delivery system where the drug loaded into the hydrogels can be release at maximum state without damaging the physical of the hydrogel. This helps narrowing down the negative side effects occur from using the UV light hydrogels (Zhao et al., 2023; Ye Chan et al., 2025; Wang L. et al., 2024; Wang Z. et al., 2021).

1.2 COMPARISON OF BASIC ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS WITH 3D-PRINTED ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS IN DRUG RELEASE

UV-responsive hydrogels are widely developed due to the release of drugs when exposed to ultraviolet light, making it easier to control when and how much drug is released. Depending on the properties of the polymer used to create the UV-sensitive hydrogel, there are some properties that is important to be considered. The drug release from the hydrogel is influences by the crosslinked between the polymer and the material, the porosity and the swelling behaviour of the hydrogel (Sadik et al., 2022; Zhang et al., 2022). The reaction between the hydrogels and the UV light will create a structure that predictably for drug release. Currently, 3D printing methods will give ways for the drugs loaded to be

released easily to the target site compared to the traditional manufacturing methods of the hydrogel that used polymerization or straightforward molding (Firdhaus et al., 2022; Mushtaq et al., 2023).

Due to that, controlling the rate of drug released within the hydrogel can be hard. By using techniques like Digital Light Processing (DLP) and Direct Ink Writing (DIW), customizing the 3D-printed UV-responsive hydrogels giving precise rate of drug release into the target area. Therefore, a complex shape, microchannels, and specific drug reservoirs of UV light hydrogels can be created (Zhao et al., 2023; Yu et al., 2021; Qin et al., 2023). The precision in drug release means that the specific parts of a 3D-printed hydrogel can create a function activation of UV light, making targeted delivery in areas like tumors, wounds, or implants much more doable (Ma et al., 2023; Ye Chan et al., 2025).

These 3D-printed hydrogels also the hydrogels that incorporate multiple triggers and carry different drugs that can be released in a sequence or when meet certain conditions, like pH or temperature, and changing or adding its flexibility compared to basic hydrogels cannot offer (Li et al., 2023; Bom et al., 2022; Ye Chan et al., 2025). The choices of 3D printing material also can be optimized. Photo-crosslinkable polymers like PEGDA and GelMA are used due to their behaviour that can harden nicely under UV light and are good at holding onto drugs (Firdhaus et al., 2022; Tian et al., 2021; Lee D. et al., 2023; Lee S. et al., 2023). The 3D printing process helps these hydrogels to increase the strength, keep their shape, and distribute drugs evenly, making the hydrogel more reliable and effective than simple UV-responsive hydrogels. Overall, 3D printing changes UV-responsive hydrogels from just light-sensitive drug carriers into smart, customizable systems personalized for individual patients, making them a perfect fit for modern personalized medicine.

Table 1: Summary of Comparison between Basic Ultraviolet Light-Responsive Hydrogels with 3d-Printed Ultraviolet Light-Responsive Hydrogels In Drug Release

Feature / Aspect	Basic UV-Responsive Hydrogels	3D-Printed UV-Responsive Hydrogels	References
Fabrication Method	Bulk polymerization, simple molding	Additive manufacturing techniques such as Digital Light Processing (DLP) and Direct Ink Writing (DIW)	Sadik et al., 2022; Zhao et al., 2023; Yu et al., 2021; Qin et al., 2023
Structural Control	Limited uniformity, less precise geometry	High-resolution, customizable geometries, microchannels, and drug reservoirs	Ma et al., 2023; Lin et al., 2024; Ye Chan et al., 2025
Drug Release Control	Mainly passive diffusion or basic UV response; less predictable	Precise spatiotemporal control; programmable on-demand release using UV light	Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Li et al., 2023
Multi-Drug Capability	Usually single drug system	Supports multi-drug delivery and sequential release; can combine with other stimuli (pH, temperature)	Bom et al., 2022; Li et al., 2023; Ye Chan et al., 2025
Material Optimization	Standard polymer networks; limited customization	Uses photo-crosslinkable polymers (PEGDA, GelMA) optimized for 3D printing and UV responsiveness	Firdhaus et al., 2022; Tian et al., 2021; Lee D. et al., 2023; Lee S. et al., 2023
Precision and Reliability	Less precise, homogeneous drug distribution	Highly precise, patient-specific structures with controlled drug localization	Zhao et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021; Ye Chan et al., 2025
Applications	Simple localized drug delivery; limited to basic therapies	Advanced localized therapy, multi-drug systems, wound healing, tissue engineering	Ma et al., 2023; Khan A. H. et al., 2023; Khan M. S. et al., 2023; Li et al., 2023

1.3 ADVANTAGES AND LIMITATIONS OF 3D-PRINTED ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS

Combining 3D printing with UV-responsive hydrogels is a pretty exciting development in drug delivery. Due to the techniques like Digital Light Processing (DLP) and Direct Ink Writing (DIW), researchers can design hydrogels with tiny channels, pores, and reservoirs that control exactly when and where drugs are released (Zhao et al., 2023; Yu et al., 2021; Qin et al., 2023). This precision helps make treatments more effective and reduce the side effects (Ma et al., 2023; Ye Chan et al., 2025). Photo-responsive molecules like azobenzene, spiropyran, and triphenylethylene are suitable to be used in the development of 3D printing UV light hydrogel. These molecules respond to UV light by changing shape via swelling, shrinking, or breaking down the structural bond to release the drugs into the target area (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Li et al., 2023). A controllable and reversible systems of drug systems that respond to the UV light can be produced and more strengthen by combining with 3D printing. 3D printing also create the systems that deliver multiple drugs or respond to more than one trigger. By designing layered or compartmentalized hydrogels, different rate of drug release can be controlled according to its response towards pH, temperature or UV light (Bom et al., 2022; Ye Chan et al., 2025; Li et al., 2023). Scalability is one of the limitations that occur when developing the 3D printing UV light hydrogel. High-res 3D printing can be slow, making it tough to produce large amounts of these

hydrogels for clinical use (Tibbits, 2022; Li et al., 2023). Another concern is how well these hydrogels hold up in the body over time. It is important to sustain the effectiveness of the hydrogel when applied to the skin. Having strong, stable, effective and safe usage of this hydrogel can create more eco-friendly hydrogels that can be implemented in clinical, hospital or in pharmaceutical field (Firdhaus et al., 2022; Wang L. et al., 2024; Wang Z. et al., 2021). To trigger the reaction of the drug release, the amount of UV light is important. Using the correct amount of UV light and its wavelength can create safer and suitable reaction between the hydrogel towards the target area. But, implementing wrong wavelength of the UV light can cause bad effect especially reducing the emission of the drugs to the target area. The drugs can be damaged if there are too much exposure of UV light and messing up the hydrogel structure. Due to that cause, considering the UV light parameters such as the UV light intensity, the exposure time, and the wavelength of the UV light can keep a safe condition of the hydrogel in development process (Tian et al., 2021; Zhao et al., 2023). Overall, 3D-printed UV-responsive hydrogels obtain a good control and flexibility in drug delivery which can be used for developing the hydrogels that have multi-drug therapies, can be personalized and easy to reach the specific target area. But, producing these hydrogels for healthcare use, the scaling up production, durability property of the hydrogel and also managing the safety of patient while using UV light need to be (Ma et al., 2023; Ye Chan et al., 2025; Khan A. H. et al., 2023; Khan M. S. et al., 2023).

2.0 OVERVIEW OF MECHANISMS OF ULTRAVIOLET LIGHT-TRIGGERED DRUG RELEASE IN 3D-PRINTED HYDROGELS

Ultraviolet (UV) light-responsive hydrogels are useful when it comes to control drug release. The hydrogels work mainly because of the photo-responsive properties built into the hydrogel. These hydrogels often include molecules like azobenzene, spiropyran, or triphenylethylene, which change shape or structure when exposed to UV light. These molecules are used in 3D-printed hydrogel structures due to their behaviour that can absorb UV light and release the drug while absorbing the UV light. This cause the hydrogel to swell, shrink, or even break down. The drug release then can be controlled precisely according to the time and target area of the (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Sadik et al., 2022). One of the mechanisms is photoisomerization. This mechanism allows molecules like azobenzene to change between two configurations, trans and cis, when exposed to UV light. This changes of structure making the hydrogel act as water-loving (hydrophilic) molecules that can hold the bond of the structures tightly when is crosslinked. So, the hydrogel will expands or contracts, affects the movement of the drug to diffuse out quickly (Li et al., 2023; Ye Chan et al., 2025). The hydrogels can be triggered exactly when it is needed, using light, with no need for chemicals or heat, giving a really tight control over the dosage.

These hydrogels also undergo photodegradation where, the UV light breaks specific light-sensitive links, called photocleavable linkers, inside the hydrogel. The drugs stored in the hydrogel will leaked out when photocleavable linkers occur, releasing the drugs to the target site (Firdhaus et al., 2022; Tian et al., 2021). Using 3D printing to make these hydrogels gives better control over how these hydrogels work. By building them layer by layer, creating the hydrogel with the shapes consist of tiny channels or pockets hydrogels can tune the drug release. For example, loading the drugs into specific zones that only get exposed to UV light means the medicine is released exactly where it needs to be, helping to avoid side effects that might happen if the drug spreads all over the body (Ma et al., 2023; Zhao et al., 2023; Lin et al., 2024).

Combining two features of wound healing hydrogel such as UV-triggered, pH or temperature changes has levelled up the pharmaceutical field. These hybrid systems let hydrogels react to the natural conditions inside the body as for instance, the more acidic environment of a tumor, by controlling the UV light outside the body, can control the conditions of the target area (Bom et al., 2022; Li et al., 2023; Ye Chan et al., 2025). Using UV light to trigger drug release giving the hydrogels to use light-sensitive molecules, having specific designed structures, and having precision of drug release by using 3D printing (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Wang L. et al., 2024; Wang Z. et al., 2021).

2.1 MATERIALS AND MECHANISMS IN 3D-PRINTING ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS FOR CONTROLLED DRUG RELEASE

When it comes to UV-responsive hydrogels used for controlled drug delivery, using the right materials and how the hydrogel will be processed with 3D printing will give the difference towards its property. These materials need to be biocompatible and biodegradable, but also have to be photo-crosslinkable, where the hydrogel can solidify when exposed to UV light during printing, while remaining sensitive to that UV light afterward (Firdhaus et al., 2022; Zhao et al., 2023; Ma et al., 2023).

Materials Used for 3D Printing

1. Photo-crosslinkable polymers

   Polyethylene Glycol Diacrylate (PEGDA) and Gelatin Methacrylate (GelMA) are mostly use for 3D printed UV-responsive hydrogels. PEGDA's can be crosslinked layer by layer with UV light, which helps create the structures with specific shapes and porosity. One of the polymers that is naturally compatible with the body is GelMA. This

polymer is made from gelatin and can be modified to be photo-crosslinkable. It is suitable to be used for 3D printing due to the solid form of the gelatin, making it easy for customizing a drug delivery system (Firdhaus et al., 2022; Tian et al., 2021; Lee D. et al., 2023; Lee S. et al., 2023). These polymers are very suitable for printing methods like Digital Light Processing (DLP) and Direct Ink Writing (DIW) that create complex microstructures and control how drugs are released (Zhao et al., 2023; Yu et al., 2021).

2. Photochromic molecules

Molecules like azobenzene, spiropyran, and triphenylethylene used in the hydrogel can respond to UV light exposure. This condition is called photoisomerization, where the process includes the changing of the structure of the materials, causing the hydrogel to swell, shrink, or even partially break down. This change affects the rate of drug release, making it deliver the drug precisely to the target area (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Sadik et al., 2022).

3. Hybrid polymer systems or nanoparticles

To make the hydrogel stronger, like silica, gold, or hybrid polymer systems, adding nanoparticles can enhance the strength of the hydrogel. Multiple stimuli can enable a response, such as light, heat, or magnetic fields. The rate of drug release can be controlled depending on the body's conditions, making the hydrogel more effective for clinical applications (Li et al., 2023; Zhao et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021).

Mechanisms in 3D-Printed Hydrogels

1. Photoisomerization

When a 3D printed UV light hydrogel is exposed to UV radiation, it triggers photoisomerization. This makes the molecules like azobenzene changing its shape between trans and cis structures. The interactions between water and the hydrogel cause the bond in the hydrogel to shift. Once the hydrogel is exposed to the UV light, the crosslinking between the molecules will be disrupted. Developing the hydrogels by using 3D printing can make the layered structure more effective. Due to the arrangement of polymer chains and the shifting of the structure, making the molecular change in the hydrogel's size and pores. Besides, controlling the time, UV light radiation, temperature, and pH will release the drugs loaded inside these hydrogels at a specific target site precisely (Li et al., 2023; Ye Chan et al., 2025). By designing the internal function of hydrogel that can adjust the amounts of photo-responsive molecules, the rate of swelling or shrinking can be controlled, creating a great drug delivery system that is available for customizing the hydrogel according to the function needed. Combining the molecular photoisomerization process with the structures achieved through 3D printing creates a reliable hydrogel to overcome the drug release process.

2. Photodegradation

Some UV-sensitive hydrogels made with 3D printing will include the photocleavable linkers that can break the bond of the hydrogel when expose to UV light. The 3D printing process will allow these linkers to be placed at the target area for degradation process, making the drug to be released only in targeted areas. Photodegradation shows the drug release over the time including the release patterns of the drug delivery such as quick burst drug delivery depending on the arrangement of the linkers and the location of the UV light is exposed. This process is ideal for treatments that need specific dosing schedules like cancer therapy, wound healing, or delivering sensitive biological molecules right to the target area. By combining photodegradation with the spatial control of 3D printing, these hydrogels can deliver drugs efficiently and safely, decreasing the widespread exposure and boosting treatment effectiveness (Firdhaus et al., 2022; Tian et al., 2021). However, by finalizing the properties of the hydrogel that use certain amount of UV light, the flexibility and a tunable system use for personalized drug delivery applications.

3. Structural Control Using 3D Printing

When the 3D printing UV light hydrogel is exposed to the UV light, it helps in controlling the structure of the hydrogel to be changed. Using microchannels and layered structures of the hydrogel will allow the drug to diffuse into the skin to the target area and release the loaded drug from the hydrogel to the target area. This behaviour is more effective when used in treatments while reducing the waste exposure (Ma et al., 2023; Lin et al., 2024; Yu et al., 2021). Custom microchannel layouts can control flow speed, diffusion routes, and how drugs are distributed. The layered designs can load multiple drugs and release them sequentially.

2.2 FABRICATION AND FUNCTIONAL MECHANISMS OF 3D-PRINTED UV-RESPONSIVE HYDROGELS FOR DRUG RELEASE

3D printing is one of the tools used in the fabrication of UV-responsive hydrogels for drug delivery, providing precision drug release that cannot be matched and customized compared to conventional methods. In traditional hydrogel fabrication, drug-loaded hydrogels are typically produced by bulk polymerization, casting, or molding, which limits the control over porosity and drug delivery. Using 3D printing in developing UV light hydrogel, it enables layer-by-layer deposition, allowing the fabrication of hydrogels by changing the behaviour of the hydrogel that directly influences drug release kinetics (Zhao et al., 2023; Yu et al., 2021; Qin et al., 2023).

3D Printing Techniques

Digital Light Processing (DLP) is one of the 3D printing techniques used for UV-responsive hydrogels. In DLP, a liquid hydrogel containing photo-crosslinkable polymers (e.g., PEGDA, GelMA) and photochromic molecules (e.g., azobenzene, spiropyran) is selectively polymerized using UV light. Each layer is cured in a precise pattern, creating solid microstructures with high resolution. This technique allows the absorption of drugs loaded within the hydrogel, enabling controlled spatial and temporal drug release (Firdhaus et al., 2022; Zhao et al., 2023). Direct Ink Writing (DIW) is a technique that extrudes a hydrogel through a nozzle under controlled pressure. The hydrogel must exhibit thinning properties, allowing it to flow during extrusion and rapidly solidify after deposition. DIW can produce hollow structures, and layered designs, which can encapsulate multiple drugs or enable staggered release profiles (Yu et al., 2021; Ye Chan et al., 2025). Photopolymerization and stereolithography (SLA) are additional methods used in pharmaceutical manufacturing. These methods use light to cure the wound area, allowing for precise microstructural fabrication and incorporation of multiple drugs in a single hydrogel construct (Qin et al., 2023; Lin et al., 2024).

Mechanisms of UV-Triggered Drug Release

In 3D-printed UV-responsive hydrogels, the primary mechanisms of drug release include photoisomerization and photodegradation:

- Photoisomerization: molecules such as azobenzene change structure between trans and cis configurations under UV light, altering the hydrogel's crosslink density and hydrophilicity. This changing structure of the molecule enables spatiotemporal release, resulting in controlled swelling or deswelling, which modulates drug diffusion (Li et al., 2023; Ye Chan et al., 2025).
- Photodegradation: relies on photocleavable linkers embedded into the hydrogel bonds. When exposed to UV light, these linkers break, causing partial hydrogel degradation and subsequent drug release. These linkers can be positioned to control the time and the target area at which the drug is released when using 3D-printed hydrogels (Firdhaus et al., 2022; Tian et al., 2021).

3D printing enhances these mechanisms by enabling microchannels, reservoirs, and layered architectures, which allow targeted, localized drug release with minimal systemic exposure (Ma et al., 2023; Lin et al., 2024; Yu et al., 2021).

Applications in Pharmaceutical Manufacturing

1. Personalized medicine
   3D printing allows the fabrication of patient-specific hydrogel implants and patches. Drugs can be embedded according to the patient's needs, enabling personalized dosing and treatment schedules (Ma et al., 2023; Ye Chan et al., 2025).

2. Multi-drug delivery
   3D printing creates layered or compartmentalized hydrogels, where different drugs are released at different times or can respond to multiple stimuli. This is useful for combination therapies and complex treatment regimens (Bom et al., 2022; Li et al., 2023; Ye Chan et al., 2025).

3. Rapid prototyping and scale-up
   3D printing enables rapid prototyping of new hydrogel designs and testing of drug release kinetics. Once optimized, these structures can be replicated consistently, which is beneficial for small-scale clinical trials and specialized drug delivery systems (Zhao et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021).

4. Tissue engineering and regenerative medicine
   3D-printed UV-responsive hydrogels are applied in manufacturing scaffolds for tissue engineering. They can release growth factors, antibiotics, or anti-inflammatory drugs controlled to support tissue regeneration while minimizing the side effects of the drugs (Firdhaus et al., 2022; Tian et al., 2021).

5. Targeted therapy
   In pharmaceutical production, 3D-printed hydrogels can be designed to release drugs at specific disease sites, such as tumors or wounds, by combining UV responsiveness with precise structural design. This targeted delivery reduces systemic toxicity and improves treatment efficacy (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Li et al., 2023).

2.3 APPLICATIONS OF 3D-PRINTED ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS IN DRUG RELEASE

The combination of 3D printing and UV-responsive hydrogels is currently used in the pharmaceutical field. Due to the accuracy of 3D printing, hydrogels can be designed to load the drugs and release them at the target area. When expose to the UV light radiation, the reaction between the materials and the hydrogels can control the time and the rate of the drug release at the target area. The circulation of the drugs can effectively minimize the side effects due to the enhanced precision of the drug release (Zhao et al., 2023; Ma et al., 2023; Ye Chan et al., 2025). For example, cancer treatment that uses 3D-printed UV-responsive hydrogels can deliver chemotherapy drugs straight to tumor locations, which helps reduce the exposure of healthy tissues to harmful compounds. This method reduces negative side effects and improves the ability of the drugs to deal with the cancer cells (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Li et al., 2023). The 3D printing design of UV light hydrogel also allows the flexibility of complex features, like microchannels and drug reservoirs, where it can fine-tune both rate and location of drug release (Lin et al., 2024; Yu et al., 2021). UV-sensitive hydrogels can be loaded with antibiotics, giving the growth factors, or anti-inflammatory characteristics when applied to the wound area. The 3D printing UV hydrogel can be fit to a wound by customizing the shape and porosity during the printing process, enabling deeper drug penetration and quicker healing. This is especially important for chronic wounds or diabetic ulcers, where consistent, localized delivery can really impact recovery (Firdhaus et al., 2022; Tian et al., 2021).

Table 2: Applications of 3d-Printed Ultraviolet Light-Responsive Hydrogels In Drug Release

Application	Description	References
Localized drug delivery	3D-printed UV-responsive hydrogels can deliver drugs directly at the target site, allowing precise control over drug release with minimal systemic side effects.	Zhao et al., 2023; Ma et al., 2023; Ye Chan et al., 2025
Cancer therapy	Drugs are released specifically at tumor sites using UV-triggered mechanisms, reducing exposure to healthy tissues and enhancing treatment efficacy.	Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Li et al., 2023
Wound healing and tissue regeneration	Hydrogels can deliver antibiotics, growth factors, or anti-inflammatory agents to conform to the wound or tissue defect, promoting healing.	Firdhaus et al., 2022; Tian et al., 2021
Multi-drug delivery systems	Layered or compartmentalized hydrogels allow sequential or simultaneous release of multiple drugs, triggered by UV or combined stimuli (pH, temperature).	Bom et al., 2022; Ye Chan et al., 2025; Li et al., 2023
Hybrid systems with nanoparticles	Nanoparticles incorporated into the hydrogel improve mechanical strength, responsiveness, and drug-loading capacity; can add multi-stimuli responsiveness.	Li et al., 2023; Zhao et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021
Personalized medicine	Customized 3D-printed hydrogel structures can be tailored for individual patients, enabling precise, on-demand, and patient-specific therapeutic delivery.	Ma et al., 2023; Ye Chan et al., 2025; Khan A. H. et al., 2023; Khan M. S. et al., 2023

3.0 CHARACTERIZATIONS OF 3D-PRINTING ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS FOR DRUG RELEASE

Characterization of 3D-printed UV-responsive hydrogels is paramount for their effectiveness in controlled drug delivery. Characterization offers researchers the information needed regarding physicochemical properties, mechanical strength, drug release profile, and biological compatibility of the hydrogels. Without characterization, the hydrogels will not ensure the specific, demand-controlled drug release necessary for therapeutic application (Firdhaus et al., 2022; Zhao et al., 2023; Khan A. H. et al., 2023; Khan M. S. et al., 2023).

Physical and Structural Characterization

The morphology and structure of 3D-printed hydrogels are typically using the techniques such as scanning electron microscopy (SEM) and confocal laser scanning microscopy (CLSM). SEM provides good-resolution images of the surface and internal pores of the hydrogel, which are impotant in drug diffusion pathways identification and mechanical strength (Ma et al., 2023; Lin et al., 2024). CLSM allows fluorescently labeled drugs to be seen in the hydrogel, exposing the drug distribution and storage of drugs in specific microchannels or reservoirs (Ye Chan et al., 2025; Zhao et al., 2023). Other structural analysis like micro-computed tomography (micro-CT), can measure the porosity, layer thickness, and global 3D architecture of printed hydrogels. Accurate thickness of layers and porosity have a direct influence on drug release rates and UV light responsiveness (Li et al., 2023; Yu et al., 2021).

Mechanical Characterization

Mechanical properties of 3D-printed hydrogels are identified through rheological characterization, compression, and tensile testing. Rheology is particularly important in predicting the printability of hydrogels in such a way that shear-thinning hydrogels used in direct ink writing extrude freely but not following deposition (Yu et al., 2021; Ye Chan et al., 2025). Tensile and compressive tests measure the print strength and elasticity of printed structures, which should withstand handling, implantation, and stresses in vivo without collapse (Firdhaus et al., 2022; Tian et al., 2021).

UV Responsiveness and Drug Release Characterization

Photoresponsive nature is the character of UV-responsive hydrogels. Characterization involves testing the hydrogel's response to UV irradiation, for example, swelling or deswelling or degradation rate, by techniques such as UV-Vis spectroscopy or photomechanical testing (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Sadik et al., 2022). Drug release is typically characterized via cumulative release profile under controlled UV exposure conditions. Through correlation of UV exposure time, strength, and hydrogel topology, scientists are able to calibrate the hydrogel for particular on-demand experience drug delivery (Li et al., 2023; Ye Chan et al., 2025; Ma et al., 2023).

Chemical and Molecular Characterization

Chemical characterization, photo-crosslinking, and photochromic reactions occur between hydrogels and the materials. By using techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Nuclear Magnetic Resonance (NMR), and X-ray diffraction (XRD), the chemical structure, crosslinking efficiency, and molecular structure of the hydrogel can be confirmed (Firdhaus et al., 2022; Zhao et al., 2023; Tian et al., 2021). To maintain the UV responsiveness, drug-loading ability, and structural integrity, the chemical reactions between the compounds are important in order to avoid any bad effect influences the function of the hydrogels.

Biological and Cytocompatibility Evaluation

Biocompatibility is an important aspect of any hydrogel utilized for biomedical purposes. Cytotoxicity tests, such as MTT or live/dead staining, are used to evaluate cell viability upon exposure to the hydrogel (Firdhaus et al., 2022; Lee D. et al., 2023; Lee S. et al., 2023). Performing the in vitro drug release tests can help to inspect the hydrogel releases sufficient therapeutic amount of drugs to initiate the biological response without killing the surrounding cells. These tests help for the scaling-up of laboratory-scale hydrogels into clinically acceptable drug delivery systems (Ye Chan et al., 2025; Ma et al., 2023).

4.0 CHARACTERIZATION TECHNIQUES FOR 3D-PRINTED UV-RESPONSIVE HYDROGELS IN CONTROLLED DRUG DELIVERY

To ensure the effectiveness of controlled drug delivery, 3D-printed UV-responsive hydrogel characterization is important. To develop a high-quality 3D printed UV light hydrogel, the physicochemical properties, mechanical strength, drug release behaviour, and biological compatibility of these hydrogels can be considered. Without proper characterization, the hydrogels fail to achieve the precise, on-demand drug release necessary for therapeutic applications (Firdhaus et al., 2022; Zhao et al., 2023; Khan A. H. et al., 2023; Khan M. S. et al., 2023).

1. Physical and Structural Characterization

Physical and structural characterization focuses on evaluating the structure, porosity, and internal microarchitecture of 3D-printed hydrogels, which directly affect drug diffusion and release kinetics.

Methodologies:

- Scanning Electron Microscopy (SEM): Provides high-resolution images of the hydrogel surface and internal structure. SEM helps determine the pore size, distribution, and interconnectivity, which are critical for drug diffusion pathways (Ma et al., 2023; Lin et al., 2024).
- Confocal Laser Scanning Microscopy (CLSM): Visualizes fluorescently labelled drugs within the hydrogel, showing how the drug is distributed in microchannels, allowing uniform encapsulation and potential release of the drugs (Ye Chan et al., 2025; Zhao et al., 2023).
- Micro-Computed Tomography (Micro-CT): Provides a 3D view of the internal structure, including layer thickness, porosity, and overall architecture, ensuring the printed design is suitable for drug delivery (Li et al., 2023; Yu et al., 2021).

Purpose: Structural characterization ensures that the 3D-printed hydrogel structure can control localized drug release and maintain structural integrity during handling and implantation.

2. Mechanical Characterization

Mechanical characterization ensures the hydrogel has the strength and elasticity required for handling, implantation, and in vivo application.

Methodologies:

- Rheology: Measures hydrogel flow behaviour for thinning hydrogels used in direct ink writing. This determines printability and how well the hydrogel maintains its shape post-extrusion (Yu et al., 2021; Ye Chan et al., 2025).
- Tensile and Compression Testing: Assesses the elasticity, stiffness, and structural integrity of the printed hydrogel. This ensures the hydrogel can withstand physiological forces without collapsing (Firdhaus et al., 2022; Tian et al., 2021).

Purpose: Mechanical testing to maintain the hydrogel structure and drug release function under mechanical stress.

3. UV Responsiveness and Drug Release Characterization

UV-responsive hydrogels are designed to change structure and release drugs upon UV exposure.

Methodologies:

- UV-Vis Spectroscopy: Measures drug concentration in the medium over time to generate release profiles under UV exposure.
- Photomechanical Testing: Evaluates hydrogel swelling, shrinking, or degradation when exposed to UV light.
- Drug Loading Efficiency Testing: Determines how much drug is retained within the hydrogel and available for controlled release.

Purpose: These characterizations of the hydrogel respond to UV light and can be programmed based on UV exposure for drug release (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Sadik et al., 2022).

4. Chemical and Molecular Characterization

Chemical and molecular characterization ensures the photo-crosslinking and photochromic mechanisms function by maintaining the hydrogel's responsiveness and drug release capabilities.

Methodologies:

- Fourier Transform Infrared Spectroscopy (FTIR): Confirms the presence of functional groups and crosslinking efficiency.
- Nuclear Magnetic Resonance (NMR): Analyzes the molecular structure of the hydrogel and incorporated molecules.
- X-Ray Diffraction (XRD): Determines the crystallinity of the hydrogel, which can affect drug diffusion and mechanical stability.

Purpose: Chemical characterization ensures that the hydrogel has stable, reproducible UV responsiveness, maintaining drug release performance (Firdhaus et al., 2022; Zhao et al., 2023; Tian et al., 2021).

5. Biological and Cytocompatibility Evaluation

Biocompatibility is important for any hydrogel for drug delivery.

Methodologies:

- MTT Assay or Live/Dead Staining: Assess cell viability in contact with the hydrogel to confirm it is non-toxic.
- In Vitro Drug Efficacy Studies: Test the hydrogel to deliver drugs at sufficient concentrations to produce the biological effect without harming surrounding cells.
- Hemocompatibility Testing: Ensures the hydrogel does not induce unwanted blood reactions when implanted.

Purpose: These studies confirm that the hydrogel is safe for in vivo applications and that the UV-triggered drug release is effective and non-toxic (Firdhaus et al., 2022; Lee D. et al., 2023; Lee S. et al., 2023; Ye Chan et al., 2025).

5.0 SUITABLE CONDITIONS THAT INFLUENCE DRUG RELEASE USING 3D-PRINTED ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS

Accuracy and performance of UV-sensitive hydrogels 3D printed depend upon very intricate interaction between environmental conditions, drug characteristics, UV light illumination conditions, printing conditions, and material morphology. All provide reproducible, homogenous, and therapeutically targeted drug release. All these parameters need to be optimized to meet incredibly stringent demands of biomedical and drug applications, i.e., target therapy, personalized medicine, and controlled wound healing (Sadik et al., 2022; Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022).

1. Material Properties

Structural and material composition are most important to control drug release volume and functional activity. Polyethylene Glycol Diacrylate (PEGDA) and Gelatin Methacrylate (GelMA) are employed as the polymers to organize the hydrogel skeleton morphology and must balance mechanical properties, biocompatibility, and UV sensitivity (Firdhaus et al., 2022; Tian et al., 2021; Lee D. et al., 2023; Lee S. et al., 2023). The photochromic azobenzene and spiropyran molecules' matrix is doped in a hydrogel to impart UV-induced sensitivity. Crosslink density, swelling, and UV exposure sensitivity depend on dispersion, concentration, and intermolecular interaction, and therefore, drug diffusion rate. In nanoparticle hybrid hydrogels, there is an enhancement of multisensitivity towards stimuli, drug loading, and mechanics, and accordingly designing them and multiscale release profiles (Li et al., 2023; Zhao et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021). Optimal material is obtained by homogeneous delivery of the drug and structural stability.

2. Hydrogel Architecture

Intrachannel hydrogel 3D-printed architecture, porosity, microchannel networks, and geometry are some of the most crucial contributory factors towards drug release profiles. Additive manufacturing possesses it with gigantic potentiality for channel development, layered geometries, and reservoirs for drugs to be problematized by traditional

methods (Ma et al., 2023; Lin et al., 2024; Yu et al., 2021). Porosity controls drug diffusion and permeation of fluids, whereas drug delivery to the region of interest may be controlled by microchannels. Rates of drug release can be tailored to therapeutic requirements by controlling direction, connectivity, and channel size. Patient-specific hydrogel geometries for wound healing, tumor therapy, or implantation can also be printed with high-resolution printing.

3. UV Exposure Parameters

UV-illumination controls the release of the drug from UV-sensitive hydrogels by changing UV-illumination intensity, wavelength, and time, which govern the response of the hydrogel (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022). Structural change of UV-illuminated photoisomerization or photodegradation swells or shrinks the hydrogel or partially degrades it to release the drug. Overexposure to UV will degrade the drug or destabilize the hydrogel matrix, or underexposure will result in ineffective drug release. Proper calibration of UV conditions and effective microchannel design needs to be adopted for optimal drug release effectiveness without concomitant loss or systemic exposure.

4. Drug Characteristics

Physicochemical properties of the drug, such as molecular weight, solubility, and UV stability, are playing a major role in the regulation of release behavior (Firdhaus et al., 2022; Tian et al., 2021). Hydrophobic drugs will possess specialties either for the formulation of hydrogel or in microchannel shape to release properly, and hydrophilic drugs will diffuse freely. Bio-molecules like peptides or growth factors that are sensitive may, in normal conditions, require UV degradation protection by nanoparticle encapsulation or polymeric protection.

5. Environmental Conditions

Physical properties like pH, temperature, and ionic strength regulate hydrogel swelling, matrix degradation, and drug release (Li et al., 2023; Ye Chan et al., 2025; Bom et al., 2022). Multi-stimuli responsive hydrogels can be designed responsive to physiologic microenvironments, i.e., acidic tumor microenvironment or site-specific hyperthermia, and have even better release time and site regulation for maximal therapeutic advantages.

6. 3D Printing Parameters

Printing parameters like nozzle diameter, layer thickness, printing speed, and curing time will decide structural precision and functionality of hydrogel (Yu et al., 2021; Zhao et al., 2023; Ma et al., 2023). Printing microchannel, reservoir, and layered structure, high-precision fabrication should be achieved. Channel collapse or uneven layers due to inefficient printing parameters affect drug release precision and reproducibility.

7. Integrated Considerations

Control of all parameters is required to achieve maximum release of the drug from 3D printed UV-sensitive hydrogels. Optimized formulation of drug, morphology of hydrogel, duration of UV exposure, properties of drug, environment, and printing conditions are required for reproducible, successful long-term performance. Optimized hydrogels have unlimited potential for site-specific therapy delivery and future drug delivery and customized medicine (Sadik et al., 2022; Ma et al., 2023; Ye Chan et al., 2025).

6.0 CHALLENGES IN DRUG RELEASE USING 3D-PRINTED ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS

Despite the remarkable advances in 3D-printed UV-responsive hydrogels, multiple challenges exist and affect their performance in controlled drug release. These are material limitations, fabrication limitations, UV-triggered responsiveness, drug stability, and clinical translation, and must be addressed to maximize their potential in pharmaceutical applications (Sadik et al., 2022; Khan A. H. et al., 2023; Khan M. S. et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021).

Material Limitations

One of the main challenges is the materials. UV-sensitive hydrogels rely on photo-crosslinkable polymers and photochromic molecules, which must be biocompatible, mechanically stable, and UV-sensitive. However, certain of the polymers may have short degradation time when exposed to UV light causing poor exhibition of mechanical strength, leading to inconsistent drug release. Higher concentrations pf photochromic molecule also affect the structural stability and cell compatibility of the hydrogel (Firdhaus et al., 2022; Tian et al., 2021; Lee D. et al., 2023; Lee S. et al., 2023).

Fabrication Challenges

3D printing allows for precise control of hydrogel structure that may consist of limitations to the condition of printing resolution and performance of the hydrogel. A few parameters like nozzle diameter, layer thickness, or curing time can yield defects in drug reservoirs or microchannels if insufficient parameters amount are applied, resulting in incomplete or uneven drug delivery (Yu et al., 2021; Zhao et al., 2023; Ma et al., 2023). Besides, mass production by scaling up from laboratory scales to industrial quantities is challenging since the speed of printing is slow, and high-resolution 3D printing techniques are costly.

UV-Triggered Release Limitations

UV-catalyzed drug delivery introduces added complexities. The amount of UV exposure, as well as the wavelength and exposure time, must be carefully regulated to ensure consistent release. Higher than optimal UV exposure can be detrimental to the drug and hydrogel matrix, and lower than optimal UV exposure can result in incomplete drug delivery. Further, UV light does not penetrate very far into thick hydrogel structures, limiting uniformity of release in dense or thick structures (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Sadik et al., 2022).

Drug Stability

Stability of the trapped drugs in UV-sensitive hydrogels is also a concern. Some drugs, particularly sensitive biological molecules or proteins, may be degraded by UV irradiation or as a result of the printing process. Stability of the drug with bioavailability and potency while delivering controlled quantities is still a significant technical problem (Firdhaus et al., 2022; Tian et al., 2021; Li et al., 2023).

Environmental and Physiological Factors

Environmental conditions, such as temperature, pH, and ionic strength, influence hydrogel swelling and drug release. Multi-stimuli responsive hydrogels are designed to account for these conditions, but in vivo conditions are multifaceted and dynamic variables, with it being challenging to accurately predict and control drug release (Ye Chan et al., 2025; Bom et al., 2022; Li et al., 2023).

Translation to Clinical Applications

Finally, regulation and safety hinder in bringing of UV-responsive 3D-printed hydrogels to clinics. Long-term biocompatibility, biodegradability, and potential phototoxicity of repeated UV exposure must be thoroughly tested before human use. Reproducibility and patient safety also require standardized protocols for sterilization, testing, and fabrication (Wang L. et al., 2024; Wang Z. et al., 2021; Zhao et al., 2023; Ma et al., 2023).

6.1 SOLUTIONS AND STRATEGIES FOR OVERCOMING CURRENT CHALLENGES IN 3D-PRINTED ULTRAVIOLET LIGHT RESPONSIVE HYDROGELS

3D-printed UV-responsive hydrogels is currently used to controlled drug delivery. Several challenges related to material properties, fabrication processes, UV responsiveness, drug stability, and clinical translation must be considered. Various solutions and strategies to optimize the performance and reliability of these hydrogels have been discuss (Sadik et al., 2022; Khan A. H. et al., 2023; Khan M. S. et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021).

Material Optimization

To overcome limitations in hydrogel materials, tuning the concentration and ratio of photo-cross linkable polymers and photochromic molecules by adjusting polymer composition, crosslinking density, and the amounts of UV-responsive molecules. These help the hydrogel to achieve mechanical stability, controlled swelling, and precise drug release (Firdhaus et al., 2022 [22]; Tian et al., 2021 [27]; Lee D. et al., 2023; Lee S. et al., 2023 [24]). The use of hybrid materials or nanoparticles can enhance mechanical strength, drug loading capacity, and multi-stimuli responsiveness, while improving the drug release control (Li et al., 2023; Zhao et al., 2023; Wang L. et al., 2024; Wang Z. et al., 2021).

Advanced 3D Printing Techniques

Optimizing 3D printing parameters, such as nozzle diameter, layer height, printing speed, and UV curing time, can minimize structural defects and improve drug release uniformity (Yu et al., 2021; Zhao et al., 2023; Ma et al., 2023). Using high-resolution DLP and multi-material printing, allow for precise microchannel fabrication and layer-specific drug loading, enhancing spatial and temporal control of drug delivery.

Controlled UV Exposure

UV-light release can be optimized by calibrating light intensity, wavelength, and exposure duration. Combining UV-sensitive molecules with high photoresponsivity can reduce the required UV light dose, minimizing potential degradation of the drug or hydrogel matrix (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Sadik et al., 2022). To ensure uniform activation throughout the hydrogel, using UV-transparent or thin-layered hydrogels can improve the light penetration.

Drug Formulation Strategies

To control the stability of the drug release, the drugs can be encapsulated in protective carriers such as liposomes, micelles, or nanoparticles before being loaded into the hydrogel. This improves the bioavailability under the UV exposure (Firdhaus et al., 2022; Tian et al., 2021; Li et al., 2023). Selecting drugs compatible with UV light or using photo-stabilizers further reduces degradation.

Environmental Control

Hydrogel performance can be enhanced by designing multi-stimuli responsive systems that respond to environmental triggers like pH, temperature, or ionic strength in addition to UV light. This allows the drug to be released under variable physiological conditions, making the hydrogels more reliable for in vivo study (Ye Chan et al., 2025; Bom et al., 2022; Li et al., 2023).

Regulatory and Clinical Strategies

For clinical practices, standardized fabrication, characterization, and sterilization protocols are necessary to ensure reproducibility and safety (Wang L. et al., 2024; Wang Z. et al., 2021; Zhao et al., 2023; Ma et al., 2023). Long-term biocompatibility, biodegradability, and phototoxicity studies are critical to obtain regulatory approval. Collaboration between material scientists, pharmaceutical researchers, and clinicians can facilitate translation from laboratory research to clinical applications.

Future Directions

Combining 3D-printed UV-responsive hydrogels with artificial intelligence for predictive modeling of drug release (artificial intelligence embedded into the hydrogel) allows the development of multi-drug release hydrogel, compartmentalized systems for advanced therapies, personalized, precise, and reliable drug delivery platforms (Li et al., 2023; Ye Chan et al., 2025; Ma et al., 2023).

7.0 ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

7.1 ENVIRONMENTAL IMPACT OF USING 3D-PRINTED ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS FOR WOUND DRESSING AND WOUND HEALING

Using 3D-printed UV-responsive hydrogels for wound dressing and healing is one of the new strategies that can increase the level of medical applications for wound dressing and wound healing. These hydrogels offer benefits like precise drug delivery, faster healing, and targeted treatment. A good wound dressing applicator that can customise the patient's needs is eligible to be created, but needs to consider the affect towards environment if the wound dressings are being discarded after use (Firdhaus et al., 2022; Zhao et al., 2023; Lee D. et al., 2023; Lee S. et al., 2023).

1. Materials and Sustainability

   Most of these hydrogels are made from synthetic polymers like PEGDA and GelMA. The hydrogels are biocompatible and biodegradable, making them often involves chemicals and solvents that could be harmful if not handled properly (Tian et al., 2021; Li et al., 2023). That is why researchers are now turning to natural materials like gelatin and alginate, which are safer and more eco-friendly while still doing the job well (Firdhaus et al., 2022; Zhao et al., 2023).

2. Manufacturing Energy Use

   3D printing methods like DLP and DIW rely on UV light and precise controls that allow the hydrogel to use a small amount of energy. To reduce environmental footprint and save energy, 3D printed hydrogels that have curing time, layer thickness, and exposure intensity can produce a safer hydrogel for wound dressing (Yu et al., 2021; Ma et al., 2023; Lin et al., 2024). This hydrogel will help in avoiding waste, especially when making custom dressings for individual patients.

3. Waste Management

   3D printing hydrogels can create waste from leftover materials and UV-sensitive chemicals. The environment can be harmed if the hydrogel is not disposed of properly. Using biodegradable hydrogels helps reduce long-term pollution, recycle unused materials, or switch to eco-friendly photo-initiators to make the process greener and safer (Firdhaus et al., 2022; Zhao et al., 2023; Tian et al., 2021).

4. End-of-Life and Biodegradability

   To avoid harming the environment, using natural polymers in developing the hydrogels will produce harmless by-products. But synthetic hydrogels can take longer to degrade and need careful disposal, especially when used widely in hospitals (Lee D. et al., 2023; Lee S. et al., 2023; Li et al., 2023).

5. Less Drug Waste

   3D printing UV hydrogel can reduce drug waste. Compared to traditional dressings, the drug is released all at once, which leads to excess drugs entering the environment through the body. UV-responsive hydrogels can respond quickly to release the drugs to the target area over time. This behaviour will help by cutting down on waste and environmental exposure (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022; Ye Chan et al., 2025).

7.2 ECONOMIC VIABILITY AND SCALABILITY OF 3D-PRINTED ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS IN DRUG RELEASE

The economic viability and scalability of 3D-printed UV-responsive hydrogels are important considerations for their practical application in drug delivery. The production costs, materials, printing efficiency, and reproducibility of this hydrogel can affect the characterization of the hydrogel for drug release (Sadik et al., 2022; Zhao et al., 2023; Ma et al., 2023). The cost of raw materials, including photo-crosslinkable polymers like Polyethylene Glycol Diacrylate (PEGDA), Gelatin Methacrylate (GelMA), photochromic molecules, and nanoparticles, can be pricy depends to the demand. High-purity polymers and specialty UV-responsive molecules contribute to the overall expense when producing patient-specific hydrogels in small batches (Firdhaus et al., 2022; Tian et al., 2021; Li et al., 2023). Optimizing polymer concentrations, reusing unpolymerized material, or developing bio-based alternatives can be cost-effective while maintaining performance (Wang L. et al., 2024; Wang Z. et al., 2021).

3D printing UV-responsive hydrogels involves layers of fabrication and precise curing under UV light, which can be time-consuming, especially for high-resolution structures with complex internal microchannels (Yu et al., 2021; Lin et al., 2024). Techniques like Digital Light Processing (DLP) provide higher speed and resolution than Direct Ink Writing (DIW), but can increase production costs due to the energy consumption and UV exposure time (Ma et al., 2023; Zhao et al., 2023). Scaling up requires automation, parallel printing, and optimized process parameters to reduce manufacturing time while maintaining structural and functional integrity. Scaling 3D printing from laboratory to industrial production by maintaining consistent quality, reproducibility, and UV responsiveness across large batches. The drug release performance will be impacted even if there are slight deviations in printing parameters, polymer formulations, or UV exposure (Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhang et al., 2022).

Large-scale printing requires high-capacity printers, UV curing systems, and precise environmental controls, which increase initial investment and operational costs (Li et al., 2023; Ye Chan et al., 2025). For commercial application, UV-responsive hydrogels must comply with pharmaceutical quality standards, reproducibility requirements, and regulatory approvals before undergoing commercial application. Each batch must be validated for mechanical stability, UV responsiveness, drug loading, and release kinetics (Wang L. et al., 2024; Wang Z. et al., 2021; Zhao et al., 2023; Ma et al., 2023).

8.0 FUTURE PERSPECTIVE

8.1 FUTURE RESEARCH DIRECTIONS AND POTENTIAL BREAKTHROUGHS IN DRUG RELEASE CONTROLLED USING 3D-PRINTING ULTRAVIOLET LIGHT-RESPONSIVE HYDROGELS

The combination of 3D printing and UV-responsive hydrogels can change the rate of stimuli when it comes to controlled drug delivery. There are still plenty of areas where future work could boost performance and help get these technologies into clinical use (Sadik et al., 2022; Khan A. H. et al., 2023; Khan M. S. et al., 2023; Zhao et al., 2023).

1. Developing Multi-Drug and Multi-Stimuli Responsive Hydrogels

   Designing hydrogels that can release multiple drugs is important to determine the rate of response of the drugs towards the wound. If these hydrogels could respond to other triggers like pH changes, changes of temperature, or enzymes, the reaction of UV light between the parameters can avoid complex issues like cancer or tough wounds (Li et al., 2023; Bom et al., 2022; Ye Chan et al., 2025). By using 3D printing, the drugs can be loaded into the hydrogel, allowing it to be released at the target site to where and when needed.

2. Material Innovations for Better Compatibility and Sustainability

   Development of 3D printing UV light hydrogel might include creating bio-based, biodegradable polymers that keep UV-responsive hydrogel to react easier on the environment. Natural materials like gelatin, alginate, or cellulose derivatives could be good replacements for synthetic material, helping improve biocompatibility and the increase the time taken to break down the structure (Firdhaus et al., 2022; Zhao et al., 2023; Tian et al., 2021). Adding nanomaterials or hybrid polymers can increase the strength, drug-carrying capacity, and multi-trigger sensitivity, making the manufacturing process more eco-friendly.

3. Improving 3D Printing Techniques

   Better resolution for faster printing speeds, and scalable methods can give growth towards the development of 3D printing hydrogels. Techniques like Digital Light Processing (DLP) and Direct Ink Writing (DIW) can be fine-tuned to decrease the printing time, save energy, and reduce waste (Yu et al., 2021; Ma et al., 2023; Lin et al., 2024). A more consistent and easier drug delivery system can be produced by inducing multi-material printing and smarter automation on a large-scale.

4. Using Computer Models and AI to Improve Design

   Emerging trends include using computer simulations and AI to better predict and refine drug release patterns. By combining the data about hydrogel characterizations, structure, and UV response in these models, systems that deliver drugs to the target site with specific release time, less trial and error can be created (Li et al., 2023; Ye Chan et al., 2025).

5. Moving Toward Clinical Use and Meeting Regulations

To create the 3D-printed UV light hydrogels, a few tests and characterizations are being run to see the fast response towards the drug released to the target area. In vivo studies show the gap between lab results and real-world medical applications for safety, compatibility, clear manufacturing, sterilization, and quality standards (Wang L. et al., 2024; Wang Z. et al., 2021; Zhao et al., 2023; Ma et al., 2023).

9.0 AUTHORS CONTRIBUTION

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

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