The Fabrication of Colored Cellulose-Based Hydrogels for Solar Water Purification

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Pollution and the depletion of clean drinking water sources have made maintaining freshwater supplies a subject of constant concern. Industrial waste dumping within aquatic ecosystems has further compounded this problem and contributed to a rise in infectious waterborne diseases, such as botulism and cholera (Schooner 2015). Therefore, environmentally responsible water purification technology development is essential to ensure a reliable supply of fresh, potable water. One of the most promising emerging technologies for water purification is the hydrogel. Recent studies have shown that hydrogels lower the amount of solar energy needed to evaporate water, thus increasing the efficiency of evaporation-based solar water purification systems (Weerasundara et al. 2021). Although evaporation efficiency rates may vary with the structure and composition of the hydrogel, no study has yet ascertained how hydrogel color affects evaporation efficiency rates. Therefore, in this study, I investigated the impact of different hydrogel colors on water evaporation rates in an experimental solar water purification system utilizing xenon light. The hydrogel colors tested included red, green, and translucent. Consistent with the assumption that hydrogels with the darkest dye would promote the fastest evaporation, red hydrogels performed the fastest, followed by green and transparent hues. This effect may be due to different dyes absorbing different wavelengths of light at unequal rates. Overall, this study provides new insights into the future direction of hydrogels and can help address remaining challenges in the field of water purification.

Keywords: Water Purification, Urbanization, Hydrogels, Pollutants, Potability

Introduction

Amongst the extensive range of negative effects caused by anthropogenic environmental degradation, water pollution is amongst the most urgent (Schnoor, 2015). Several countries have already installed next-generation water purification technologies, such as desalinators, acoustic nanotubes, and photocatalytic systems (Weerasundara et al., 2020). Despite these efforts, next-generation water purification systems are expensive, hard to maintain, and require large amounts of energy, which makes them unfeasible for lower-income communities (Hong et al., 2020).

As an alternative to these overly expensive purification technologies, the hydrogel—a cross-linked hydrophilic polymer with a durable, three-dimensional structure—has gained increasing interest for its affordability and seemingly unlimited potential in purification systems (Xu et al., 2023).

Scientists have incorporated hydrogels into water purification systems to identify key hydrogel properties that can enhance the evaporation process. For example, hydrogel size, composition, shape, and color can all affect the water evaporation rate by affecting the way the hydrogel absorbs light and heat or interacts with particulate matter and water molecules (An et al., 2022). The most commonly studied hydrogels are synthetic hydrogels, which have been manufactured from scratch in a laboratory setting, and hybrid hydrogels, which share features of both natural and artificial hydrogels (Chamkouri et al., 2021). Cellulose-based hydrogels are particularly appealing because they are biodegradable (cellulose is found in the cell walls of green plants, algae, and oomycetes) and highly absorbent, making them ideal for water purification applications (Cao et al., 2022).

Overall, hydrogels have demonstrated enormous potential across the fields of biology, chemistry, and physics, but the vast majority of research has focused on an insufficient range of hydrogel types (van Tran et al., 2018). Because hydrogels remain largely unexplored, scientists are still discovering the full potential of these unique substances, but further research is urgent. By exploring systems in which hydrogels serve as catalysts to accelerate evaporation, scientists can further develop a sustainable alternative to existing water treatment technology and produce a potentially invaluable tool for maintaining access to the vital ingredient of life—clean, potable water. The results of this research have the potential to support future breakthroughs in sustainable, hydrogel-assisted solar water purification technology, with the hope that these technologies can help achieve the United Nations' Sustainable Development Goal of ensuring access to clean water and sanitation for all. Further research could focus on optimizing the composition, structure, and color of cellulose-based hydrogels to improve their efficiency in purification systems. Additional studies should test how other environmental factors, including humidity, room temperature, and solar radiation, may affect the efficiency of hydrogel-based water treatment.

Literature Review

Modern water purification and its problems

It is crucial to take into account previous studies on hydrogels in order to comprehend the distinctive contribution of this study. To begin with, one such study states that the critical issue of a deficit in clean water and basic sanitation is likely to become even more pronounced in the coming years due to population growth, climate change, and urbanization (Shannon et al., 2008). Therefore, to address these issues, scientists and engineers are developing innovative technologies and methods for water purification, desalination, and wastewater treatment. Building on this paper, another related study states the main goal of water purification research revolves around improving water disinfection and decontamination. The authors then go on to explain that traditional methods such as chlorination and ozonation can be effective, but can also create harmful byproducts and have high energy requirements (Mueller et al., 2007). In that same vein, it is also recorded that researchers, in the past, have surveyed disinfection byproducts in the United States and found that many disinfection byproducts are generated during the disinfection process (Lantagne et al., 2006), effectively proving that there are several hazards associated with current systems.

While many past studies emphasize developing new technologies for water treatment, their focus remains on developing the existence of such systems rather than ways to accelerate evaporation. Additionally, a majority of this research focuses on expensive and high-energy consumption technology. Therefore, this study differs from past studies considering it uses an accessible, transferable, and biodegradable substance. Inclusive and improved clean water access and sanitation provide immeasurable benefits to human society, including public health, economic development, and sustainability.

What is a hydrogel?

The term 'hydrogel' encapsulates a group of hydrophilic polymers that can hold or absorb a large amount of water (Nie et al., 2020). Hydrogels can be produced from either natural or synthetic materials, although synthetic hydrogels have become increasingly popular because of their superior water absorption capacity and longer lifespan (Ahmad et al., 2o22). Additionally, the raw materials needed to produce synthetic hydrogels are also more readily available than natural materials—therefore, due to their unique physicochemical properties, hydrogel-based products are now widely involved in various industrial and environmental applications (Jayakumar et al., 2020). Nevertheless, these studies fail to examine the physical characteristics that deter hydrogel's ability to purify. This paper will thereby address this gap in existing literature by exploring changes in external color impact of water purification.

Advantages of cellulose-based hydrogels

Cellulose-based hydrogels offer several benefits over conventional hydrogels. Among some of these advantages include (but are not limited to) them being biodegradable, biocompatible, and made from readily available raw materials (cellulose) (Kabir et al., 2018). Cellulose-based hydrogels also have good mechanical strength, high water-holding capacity, and can be easily modified to control their properties.

Water purification using hydrogels

The polymeric networks in a hydrogel can be tailored to regulate the water state and incorporate solar absorbers, making hydrogels a promising platform for efficient solar water purification. Hydrogel-based water purification has the potential to demonstrate improved performance, scalability, stability, and sustainability relative to traditional water treatment systems. For example, Zhao et al. fabricated a floatable composite hydrogel using squid ink nanoparticles, silica aerogel, poly(vinyl alcohol), and acrylamide. This hydrogel was then used to increase the efficiency of solar evaporation-based desalination. Yu et al. showed that their experimental solar water purification system, based on a hybrid hydrogel evaporator, effectively removed heavy metal ions from contaminated water. Their system operated with a high evaporation rate and exhibited a natural anti-salt-fouling function, making it a promising solution for sustainable solar-driven water purification systems.

Solar water purification using differently colored, cellulose-based hydrogels

Despite these many advances in the use of hydrogels for water purification, few studies have focused on *how* hydrogels absorb the solar energy necessary for solar-powered water purification or how this process could be further optimized. I thereby synthesized cellulose-based hydrogels and used watercolor dyes to color them. By testing these colored hydrogels in an experimental solar water purification system, I was able to experimentally determine which hydrogel color is most efficient for solar water purification.

Comparative analysis of double-degradable hydrogels and cellulose-based hydrogels

Numerous experiments have investigated potential hydrogel features that make it appropriate for environmental applications. As reported by Zhang et al. (2020), a novel double-degradable hydrogel synthesized using yeast, polyvinyl alcohol (PVA), and carboxymethyl cellulose (CMC) tends to have both excellent physical and mechanical properties that make it suitable for environmental application. More specifically, per the research findings, these hydrogels exhibited superior biodegradability and swelling capabilities, making it an appropriate reagent for water purification.

Zhang et al. (2020) developed double-degradable hydrogel through the freeze-thaw method. Mc Gann (2009) defines freeze-thaw as the freezing and thawing of a hydrogel solution at room temperature, which results in the creation of ice that produces a void inside the structure of the hydrogel, whereas thawing causes the ice crystals to collapse. A porous hydrogel will be generated when this procedure is repeated numerous times. Additionally, using scanning electron microscopy (SEM) and tensile strength testing, Zhang et al. (2020) categorized the double-degradable hydrogel's physical and mechanical properties. The thermal stability of a novel double-degradable hydrogel was determined using thermogravimetric analysis (TGA) which, according to Kubiski et al. (2023), is a procedure that involves weighing a hydrogel while it is heated and cooled in an experimental environment. The study reveals that the weight of a hydrogel with great thermal properties will grow as its temperature rises and decrease as it cools, primarily as a result of the release of volatile components. In contrast to my study, in which the hydrogel was manufactured using cellulose biopolymer and the Zhang et al. (2022) production approach. For the evaluation of the optical and thermal properties of the synthesized cellulose-based hydrogel, I applied watercolors dyes to the hydrogel. This step would assist in determining the ideal hydrogel concentration for the water purification process while exposed to solar radiation. The evaporation rate of the synthesized hydrogel was then determined by measuring the rate of water evaporation under a xenon lamp every six hours for 24 hours to determine the water-retention capacity of cellulose-based hydrogel compounds.

Even though Zhang et al. (2020) study on the application of hydrogels in water purification yielded encouraging findings, further research is required. First, Zhang et al. (2020) did not investigate the level of toxicity of double-degradable hydrogel when discarded into the environment. My research addresses this issue by manufacturing a hydrogel composed of cellulose, a naturally occurring polymer that does not emit any type of hazardous substance into the environment. According to Sannino et al. (2009), not only is the freeze-thaw procedure time-consuming, but polyvinyl alcohol (PVA) is also not a naturally occurring substance, unlike cellulose, which is abundant and cost-effective in large-scale implementation.

The optimization of hydrogel matrices' design and performance for solar-powered water purification

The increased interest in hydrogels for solar-powered water purification is attributable to their high water absorption capacity and elastic properties. Researchers Guo and Yu (2021) delved into the synthesis of solar water purification systems utilizing hydrogels. Their study focused on thermal properties and how they can be optimized to enhance hydrogels' solar energy absorption and heat transfer rate for a more efficient water purification system. However, in contrast to my study, Guo and Yu's (2021) research centered on optimizing the hydrogel structure and structure for a solar water purification system.

In their study, Guo and Yu (2021) employed various methods to increase the solar absorption of hydrogels, such as the incorporation of light-absorbing materials like carbon black, graphene, and metal nanoparticles into the hydrogel structure. By increasing the light absorption properties of the hydrogel, the rate of solar-driven water evaporation will also improve. This can be achieved by incorporating carbon black and graphene into the Hydrogel matrices. According to the study, including silver and gold nanoparticles can improve hydrogel matrices' solar absorption and antimicrobial properties. In addition, Guo and Yu (2021) found that combining light-absorbing materials into hydrogels improves their swelling and mechanical properties. These characteristics are essential to hydrogel matrices because they preserve the hydrogel's structural integrity and water absorption capacity during solar desalination and water purification. Zhang et al. (2022) show that cross-linking density and chemical composition can enhance hydrogel's swelling and mechanical properties. In addition, the study demonstrates that the material's swelling and mechanical properties can be optimized by using a suitable hydrogel matrix. For example, synthesizing hydrogel based on the research of Song et al. (2023) can improve its swelling properties and biocompatibility.

In contrast, my research aims to investigate hydrogels' synthesis and potential applications in solar-powered water purification systems. As previously mentioned, Guo and Yu's (2021) research aimed to optimize the structure of hydrogels by improving their thermal and optical properties. Even though the study presented an efficient hydrogel for water desalination and purification, it needed to fully account for the solar energy absorption required for the purification process. The study conducted by Guo and Yu (2021) focuses on using graphene and carbon nanotubes to optimize the structure of their hydrogels. Nevertheless, Xiao et al. (2023) study reveals several drawbacks to incorporating these light-absorbing materials into hydrogel matrices. Carbon black harms aquatic organisms, which is a significant disadvantage. Similarly, gold and silver used as metal nanoparticles in optimizing the hydrogel matrices can have toxic effects on marine and terrestrial organisms and contribute to the accumulation of toxic metals in the environment.

Moreover, as shown by Xiao et al. (2023), incorporating these materials into research affects the mechanical properties of the hydrogel. For instance, incorporating gold nanoparticles into a hydrogel structure can reduce its elasticity and increase its fragility. As demonstrated by Song et al. (2023) study, a hydrogel with diminished mechanical strength is not viable for water purification systems due to its increased disintegration potential in an aqueous solution. Cellulose is highly eco-friendly and cost-effective compared to the light-absorbing material used in Guo and Yu's (2021) research. Contrastingly, for gold and silver production, significant amounts of energy and resources are used, and their disposal may result in metal accumulation in the environment. In addition, carbon blacks can also pose potential harm to the environment because they are derived from fossil fuels.

In summary, adding a light-absorbing material to optimized hydrogel matrices raises water temperature, hence increasing the efficiency of solar water purification. However, their use has environmental consequences like accumulation and can drive up the price of hydrogel production. Therefore, using cellulose from natural sources mitigates these drawbacks. Furthermore, the mechanical strength of the hydrogel is also reduced by these light-absorbing materials. However, when the hydrogel is synthesized from cellulose, the mechanical and structural properties are not tampered with, increasing the hydrogel's water absorption capacity.

A comparative analysis of the synthesis and applications of hydrogels in solar water purification and environmental remediation

One such study run by Song et al. (2023) focuses on hydrogel synthesis and its possible applications in environmental remediation and antimicrobials. This particular experiment examined the use of hydrogels for water purification by eliminating heavy metals, dyes, and organic contaminants from water. Song et al. (2023) used chitosan, alginate, and polyvinyl alcohol to synthesize their hydrogel; however, due to its abundance and eco-friendliness, my study employed cellulose as the basis material for hydrogel synthesis.

By combining chemical reagents like chitosan, alginate, and polyvinyl alcohol, Song et al. (2023) were able to develop hydrogels used in water filtering. The chemical and physical qualities of each of these materials determined whether or not they would be preferable in hydrogel synthesis. For instance, chitosan possesses various advantages, including biocompatibility, biodegradability, and antibacterial characteristics that make it suitable for hydrogel synthesis. However, due to chitosan's chemical makeup, it is not suitable for an environmental application. This is due to chitosan being insoluble in water without the presence of an acid, making its incorporation into water filtering systems exceptionally challenging. However, A.L. Samman and Sanchez's (2021) research indicated that alginate hydrogels expand and degrade in water, and thereby their poor mechanical qualities would rule them out as a viable water purification option. The study also indicated that alginate degraded rapidly when subjected to mechanical stress from compounds like chitosan. Lastly, Song et al. (2023) employed the use of synthetic polymer polyvinyl alcohol to synthesize hydrogel, which is frequently utilized in hydrogel synthesis due to it being biocompatible, biodegradable, and very water-soluble. However, Wang et al. (2018)'s recent study differs from other studies. It indicates that polyvinyl alcohol has poor solubility and weak mechanical strength in water, which makes it unsuitable for use in water purification processes.

In contrast to Song et al. (2023), I opted for cellulose as the hydrogel synthesis foundation material, mainly due to the quantity and eco-friendliness of cellulose. According to a study by Patchan (2013), cellulose is the most prevalent biopolymer on earth. In addition, Patchan's (2013) study reveals that cellulose has high water solubility, is biocompatible, non-toxic, and possesses outstanding mechanical strength, making it a suitable material for water purification systems.

In summary, as presented above, materials used by Song et al (2023) study have their own unique chemical properties that make them suitable for water-purification. Additionally, cellulose-based hydrogels exhibit exemplary mechanical strength and solubility even in aqueous solution as presented in Zainal et al. (2021) study as compared to chitosan, which has both poor solubility and requires acid to increase solubility, and alginate, which has poor mechanical strength and disintegrate in aqueous solution.

Materials and Methods

This experiment was designed to quantify the rate of water purification across a suite of differently colored hydrogels. Solar-powered water purification is a natural water purification technique in which fresh water is separated from contaminant molecules by evaporating the water molecules using solar heat (Altherr et al., 2008). The point of this type of method was to analyze and compare the performances of the differently colored hydrogels using their rate of evaporation, so observing the phenomena with direct laboratorial experimentation was the easiest way to analyze the data. Furthermore, the method applied allowed for direct observation of any possible changes to the appearance of the hydrogel and clarity of water produced (Zhou et al., 2019).

The hydrogel synthesis technique was also essential to the success of my experiment. The chosen approach had to guarantee that the hydrogels possess the proper swelling and mechanical properties. It required the aforementioned properties for my synthesized hydrogel to maintain its structural integrity and water-absorption capacity during solar desalination and water purification. The choice of watercolor dyes was also crucial, as it was based on the fact that none of the stains interfered with the hydrogel's properties, resulting in accurate and timely results.

Fabrication of cellulose-based hydrogels

Materials

The components utilized in synthesizing cellulose-based hydrogel were meticulously chosen based on their compatibility and capacity to form a stable hydrogel structure with desirable mechanical and swelling properties. Due to their biocompatibility, non-toxicity, and biodegradability, cellulose and epichlorohydrin (ECH) were used to synthesize cellulose-based hydrogel. I utilized NaOH as a crosslinker to form a three-dimensional network within my hydrogel. Therefore, the objective of the three-dimensional network was to give hydrogel mechanical strength and prevent its dissolution in water. Urea was utilized to optimize the swelling characteristics of my hydrogel, which will increase hydrogel capacity of retention.

Different natural and synthetic tinting techniques were employed to produce various hydrogel colors. I decided to use watercolor dye, methylthioninium chloride, and graphite powder to create multiple shades due to their compatibility with hydrogel synthesis materials. Watercolor dye was also used due to its abundance in producing a vast array of colors. This enabled me to increase the light-absorption properties of the hydrogel, hence improving the efficiency of solar water purification. I purchased all of my reagents from Sigma Aldrich, a reputable online vendor of laboratory chemicals and reagents, to ensure accurate and reliable experimental results.

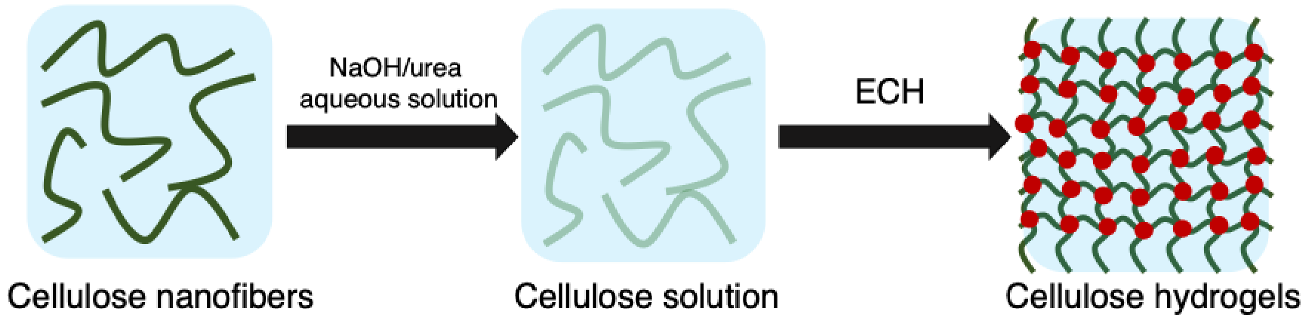
Fabrication process

Firstly, to produce environmentally friendly hydrogel disks, I chose cellulose as the base material; because it comprises most plant tissue, cellulose is the most widely distributed organic compound and is extremely affordable (Aziz et al., 2022). Furthermore, cellulose hydrogels are biodegradable, thus giving them a clear environmental advantage over other polymers that may contain harmful synthetic chemicals or pollutants (Motloung et a., 2019).

To synthesize the hydrogels, the cellulose was first dissolved in water to create a base solution. Because cellulose is not easily soluble, 3.5 g NaOH and powdered urea were added to 40.5 g of water to help the cellulose dissolve. These two substances release large amounts of heat when dissolved in water and thereby accelerate the solubilization of cellulose. Once the cellulose was fully dissolved, ECH was added to solidify the hydrogel mixture from a liquid to solid. This process, known as gelation, produces chemical cross-links between the polymers in the structure. Subsequently, watercolor dyes and graphite powder were added after gelation to produce different tints in the gel matrix.

This hydrogel fabrication procedure was based on the procedure described by Zhang et al., who used NaOH and urea to fully solubilize the cellulose before adding ECH as a cross-linking agent. Zhang states that the ECH-induced gelation step is necessary because hydrogels are hydrophilic solids that must hold their shape during the water purification process. In that same vein, if the hydrogel was used as a non-gelatinized liquid, the solution would simply be diluted when water was added and the impure water would not be effectively evaporated.

Once ECH was added to the NaOH-urea-cellulose solution, the solution was evenly distributed between six labeled petri dishes and baked in an oven for four hours, as baking induces gelation and the consequent formation of hydrogel disks (Peidayesh



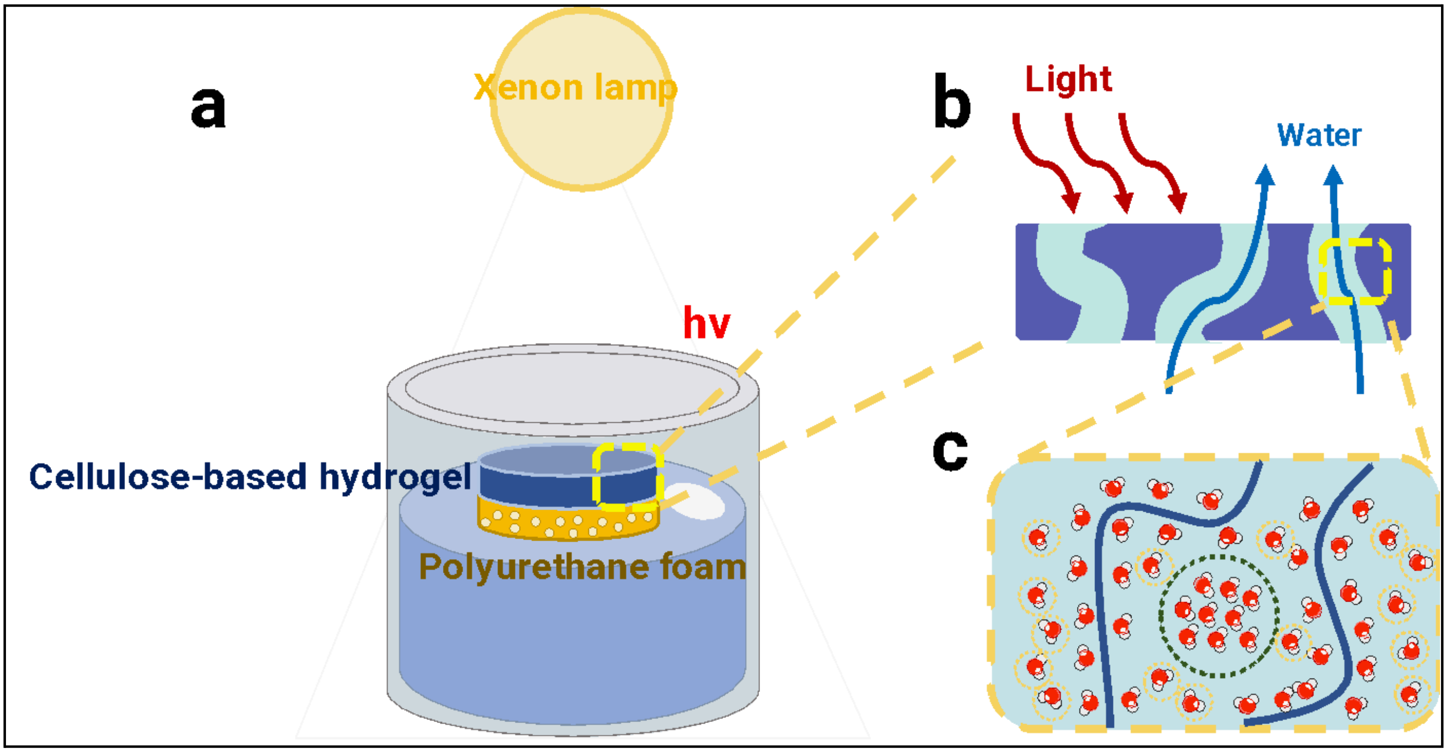
Scheme 1: A schematic diagram demonstrating the fabrication of differently-colored, cellulose-based hydrogels.

et al., 2020). However, because a strong base was used to dissolve the cellulose, the newly formed hydrogel disks were washed with distilled water three times over twelve hours. This would prevent excess hints of leftover dye or particulate matter, which may have been picked up during the baking stage.

Measuring the effect of hydrogel color on evaporation rate

To determine the efficacy of water evaporation, a xenon lamp was utilized. Unlike natural sunshine, which varies in intensity and duration, the xenon lamp gave me greater control over experimental settings without extraneous mistakes. Secondly, according to Sharshir et al. (2020)'s study on the effect of temperature and humidity on hydrogel-based solar water evaporation, all hydrogel systems should maintain an environment of 15 °C and 30% relative humidity during the experiment. This is owing to the sensitivity of hydrogel to variations in temperature and humidity, which might lead to incorrect experiment results. The work done by Pan et al. (2022) also supports using xenon lamps because they generate sun-like conditions that make them dependable and accurate light sources for replicating solar water purification systems.

Due to research time limits and the need for accurate data, the evaporation rate was recorded every six hours as it would not be expected to shift drastically over short periods. As illustrated in Scheme 2a, this measurement frequency was employed to determine an accurate measurement of the water evaporation rate in each hydrogel disk. A beaker containing 150 mL of water and hydrogel was placed beneath the xenon light. The water evaporation rate was then determined by dividing the water lost from the beaker by the period that passed.



Scheme 2: Schematic diagram showing (a) the experimental system, with a hydrogel resting on polyurethane foam in a beaker underneath a xenon lamp; (b) the enlarged hydrogel, and (c) the enlarged pores of a hydrogel.

Water evaporation efficiency across differently colored hydrogels
I suspended cellulose-based hydrogels on a layer of polyurethane foam to ensure direct exposure to the xenon lamp, since they tend to settle in water. I monitored evaporation rates every six hours for 24 hours to better understand hydrogel's efficacy in water purification. This was achieved by taking measurements at the intervals specified in scheme 2a. As a comparison standard, it was decided to include a beaker devoid of the hydrogel. This would allow me to calculate how much faster the hydrogels evaporated water than the baseline.

Results and Discussion

Water evaporation efficiency across differently colored hydrogels
The control beaker exhibited a low evaporation rate, with only 8 mL of water evaporating in the first 6 hours (Figures 2a, 3). In the three subsequent 6 h periods, evaporative water loss was 8 mL, 12.5 mL, and 11.5 mL, respectively. Thus, the evaporation rate remained constant for the first 12 hours but then increased by 56% for the subsequent 6 hours, presumably because the water temperature was increasing with longer-term exposure to the xenon lamp. The evaporation rate then decreased slightly for the final six hours, potentially because continuous evaporation had increased the saturation vapor pressure.

The addition of hydrogels to the beaker was expected to increase the evaporation rate relative to the control. As described in the literature review, hydrogels can absorb solar energy and convert it into heat, thereby increasing the temperature of the surrounding water and thus the rate of evaporation. Moreover, due to the porous structure of hydrogels, water molecules can move freely from the interior of the hydrogel to its surface, where they can evaporate into the surrounding environment. This porous structure also facilitates the diffusion of water vapor out of the hydrogel, further increasing the rate of evaporation. Additionally, evaporation enthalpy intermediate water in hydrogels is much lower than free water (Scheme 2).

The experiment findings were in line with the literature review. Transparent hydrogel placed on polyurethane foam in the beaker resulted in faster water evaporation than the control beaker. 20 mL of water evaporated during each of the first two 6-hour measurement periods. Like the control beaker, the initial evaporation rate remained constant for the first 12 hours. However, the rate was noticeably faster than the control. Only 10 mL evaporated in the subsequent 6 hours, and only 13 mL in the final measurement period. Put differently, the evaporation rate decreased by almost 75% after the first 12 hours. These findings significantly differed from the control. Evident from the study, in the control's case, evaporation rate surged after the first 12 hours. Indeed, the low evaporation rates over the second 12-hour period were quantitatively similar to the evaporation rates from the control. The decrease in evaporation rate was likely stemming from the experimental flaw where the hydrogel suspended on the polyurethane foam was no longer in contact with the water after the first 40 mL had evaporated. Nevertheless, despite this flaw, the rapid evaporation rate observed during the first 12 hours of the study matched the results foretold in the presented extant literature.

I then tested the effects of hydrogel color on the evaporation rate. Figures 2c and 3 show the amount of water evaporated from a beaker with a red hydrogel suspended on polyurethane foam. During the first six hours, 25 mL of water evaporated, which is 25% more than with the transparent hydrogel. During the subsequent six hours, 38 mL of water evaporated, which is twice the amount that evaporated from the transparent hydrogel and nearly five times more than the control. An additional 37 mL evaporated over the third six-hour period, and evaporative loss was 41 mL over the final six-hour period. Because this substantially higher evaporation rate was achieved with the simple addition of a red dye, red hydrogels may be a valuable tool in solar water purification systems; indeed, the cost of the dye is considerably lower than the initial cost of making hydrogels or using other energy sources for solar water evaporation. Overall, the red hydrogel was 2-3 times more efficient than the transparent, non-dyed hydrogel, with only a fractional added cost.

Figure 2d shows evaporation over time with a green hydrogel. Only 20 mL of water evaporated over the first six hours with the green hydrogel, which represents no improvement over the transparent hydrogel. However, evaporative loss increased to 28 mL during the second six hours, suggesting that the green dye may nevertheless increase the evaporation rate. Evaporative water loss decreased to 12 mL during the subsequent six hours and then continued to decrease to the end of the experiment, similar to the results observed with the transparent hydrogel.

As expected, the colored hydrogels in this study were more effective at promoting evaporation than the transparent hydrogel. When a colored hydrogel is exposed to a xenon lamp, it absorbs light at wavelengths that correspond to its absorption spectrum. The absorbed light is converted into heat energy, which increases the temperature of the hydrogel and, correspondingly, the surrounding water, and the warmer water then evaporates more quickly. Colored hydrogels may also have a higher surface area than transparent hydrogels due to their porous structure, which can further increase the rate of water evaporation. Conversely, transparent hydrogels are not as efficient at absorbing light and converting it into heat because they lack light-absorbing pigmentation. As a result, the temperature of a transparent hydrogel may not increase as much as with a colored hydrogel, resulting in a lower evaporation rate.

The choice of color also had a significant impact on the hydrogel's ability to absorb and convert light into heat. In this study, I found that red hydrogels exhibited a higher water evaporation rate than green hydrogels when incubated under a xenon lamp. Different dyes have different absorption spectra, meaning they absorb different wavelengths of light. Because red light has a longer wavelength than green light, it can penetrate deeper into the hydrogel and be converted into heat more efficiently, resulting in a higher temperature increase and therefore increased evaporation rate. Conversely, green light has a shorter wavelength and is absorbed less efficiently by the hydrogel, green hydrogels do not cause as pronounced of a temperature increase and are therefore associated with a slower evaporation rate. The choice of color becomes particularly important in applications such as solar-powered water evaporation, where a color that efficiently absorbs and converts light into heat can help optimize the evaporation process and improve its efficiency.

In addition to the effects of color alone, the specific dye molecules used to create the color may also affect the amount of light energy a hydrogel can absorb. The red dye used in the red hydrogel may have a higher absorption coefficient in the red region of the spectrum than the green dye does in the green region of the spectrum, resulting in more efficient light absorption and heat conversion.

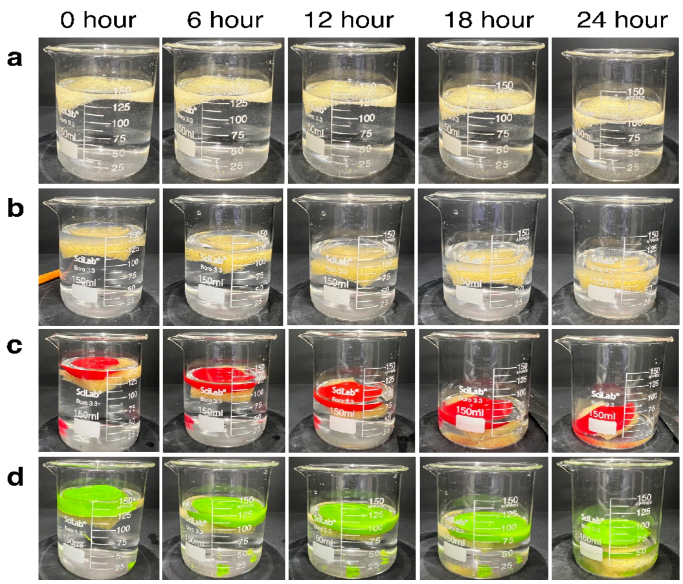


Figure 1: A series of photos capturing the evaporation of water in a beaker under a xenon lamp over time, taken every 6 hours: (a) Only polyurethane foam, (b) transparent hydrogel, (c) red hydrogel, and (d) green hydrogel.

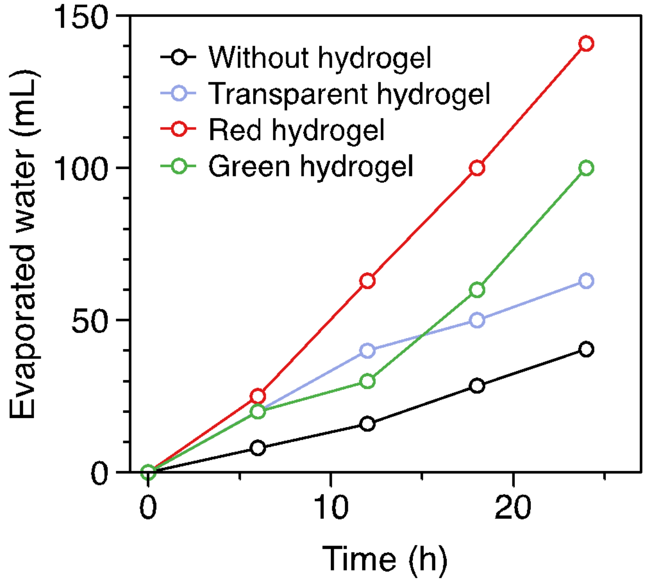


Figure 2: A graph depicting the rate of evaporated water in mL per hour-designated periods.

Conclusion

As the threat of climate change looms closer, the need for innovative, efficient, and sustainable water purification systems has become increasingly urgent. Therefore, in this study, I have demonstrated that the color of hydrogels can have a significant impact on their ability to absorb and transfer light energy, which, in turn, affects their evaporation rate in a water purification system. To be more specific, red hydrogels proved to be the most effective at maximizing evaporation while keeping additional costs of materials to a minimum. By shedding light on the role of hydrogel color in the purification process, this research may help to build awareness about the importance of preserving scarce water resources. The results of this study provide valuable insights into the vast potential of hydrogels as a sustainable and cost-effective solution for water purification in the face of the growing threat of pollution and climate change.

Appendix of Vocabulary

For the purpose of clarification, crucial terms used in this study have been defined. The following terms are:

Carbohydrate. A group of organic compounds that include sugars, starches, and cellulose, all of which consist of carbon, hydrogen, and oxygen atoms and serve as a major source of energy in living organisms.

Cross-linked. The condition of having chemical bonds between two or more polymer chains that are typically formed through a series of chemical reactions or physical interactions, which can modify the physical and mechanical properties of a material.

Gelation. The process of forming a gel that involves the formation of a three-dimensional network of cross-linked molecules that can trap and retain liquid (often water) within its structure.

Hydrogel. A type of cross-linked polymer composed of a network of hydrophilic polymer chains capable of retaining large amounts of water, often with physical properties such as high elasticity, softness, and porosity.

Hydrophilic. Having a strong affinity for water molecules and being able to attract and hold them within a structure for long periods of time without disturbance.

Porous. To have small spaces or pores within a structure that allow liquids or gases to pass through, often used in reference in materials with a high degree of permeability.

Polysaccharide. A large molecule consisting of multiple sugar units linked together, which are commonly found in carbohydrates and serve various functions in biological processes.

Purification. The act of removing impurities, contaminants, or pollutants from a substance to obtain a cleaner, more refined final product.

Soluble. Being capable of dissolving within a particular solvent to form a homogeneous mixture.

Spectra. A range of different frequencies or wavelengths of electromagnetic radiation that are used to describe patterns of light and/or color produced by a specific light source.

Wavelength. The distance between two adjacent points or troughs of a wave, usually in terms of electromagnetic radiation properties, such as light.

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