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Comparative Analysis of Hydrogel Polymer in Smartphone Devices: Thermal Stability Focused

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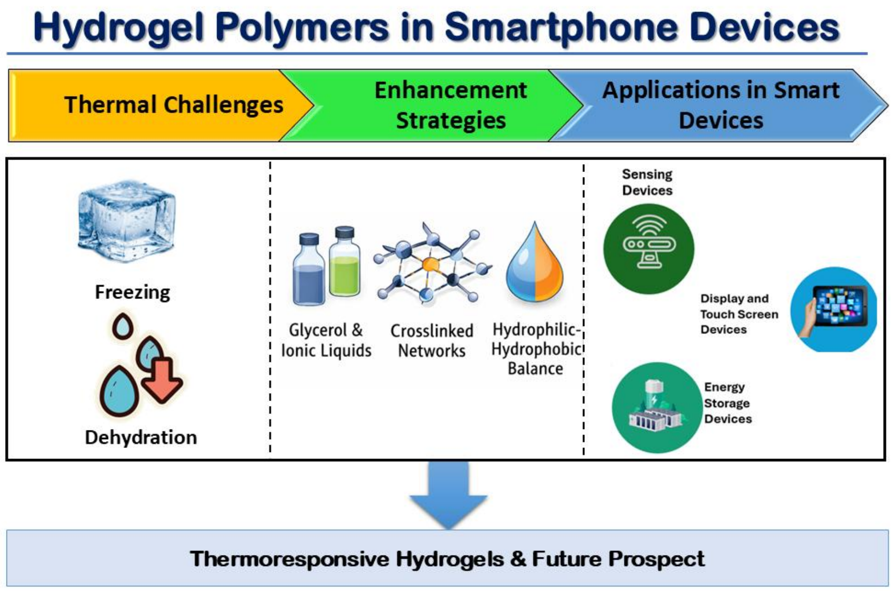
***Abstract*—** Hydrogel polymers have emerged as transformative materials in the field of flexible electronics, offering unparalleled properties such as high water content, mechanical flexibility, and tunable conductivity. This review critically examines the thermal stability of hydrogels and their applications in electronic devices, with a focus on smartphone technology. Despite their inherent susceptibility to thermal fluctuations—ranging from freezing-induced brittleness to dehydration at elevated temperatures—recent advancements have significantly enhanced their resilience. Strategies such as incorporating cryoprotectants (e.g., glycerol, ionic liquids), optimizing crosslinked networks, and balancing hydrophilic-hydrophobic interactions have proven effective in mitigating these challenges. These innovations enable hydrogels to maintain functionality in extreme environments, making them ideal for flexible sensors, energy storage devices, and touch screens. Notably, thermoresponsive hydrogels, which exhibit reversible phase transitions at critical solution temperatures, are paving the way for adaptive cooling systems and dynamic interfaces in next-generation electronics. The integration of hydrogels into electronic devices not only addresses thermal management issues but also unlocks new possibilities for wearable and biodegradable technologies. This review underscores the interdisciplinary potential of hydrogels, highlighting their role in advancing sustainable, high-performance electronic systems while identifying future research directions to overcome existing limitations.

***Keywords*—** Electronic Devices; Hydrogel; Polymer; Thermal Stability; Thermoresponsiveness

***Graphical Abstract*: Schematic illustration of hydrogel thermal stability enhancement strategies and their applications in smartphone devices**



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I. Introduction

Hydrogel is a three-dimensional, crosslinked polymer network characterized by their high water retention capacity, which capable of absorbing and retaining large amounts of water while maintaining its structure. Hydrogels can be made from natural materials, such as cellulose, chitosan, or gelatin, or from synthetic polymers like polyvinyl alcohol (PVA) or polyethylene glycol (PEG) [1]. Hydrogel has unique properties, such as good mechanical flexibility and high adsorption capacity. In recent years, the integration of hydrogels into electronic devices has gained increasing attention due to their ability to couple mechanical adaptability with functional conductivity, allowing it to be used in various applications, such as sensors, and smartphone materials [2]. Hydrogels have applications in energy storage, particularly in supercapacitors and batteries. Their porous structure allows for efficient ion transport, which is critical for energy storage and conversion. Hydrogels have excellent flexibility, electrical conductivity, and mechanical tunability, making them ideal materials for flexible electronic devices. These devices include sensors, energy storage systems, touch panels and other wearable technologies [1]. Therefore, advancing hydrogel formulations with enhanced thermal resistance, anti-freezing properties, and moisture retention is essential for next-generation flexible electronics. Ultimately, thermally stable conductive hydrogels have the potential to revolutionize smartphone technology by enabling adaptive, durable, and energy-efficient systems that seamlessly integrate with both human and environmental dynamics.

II. Method

This review was conducted using a systematic approach to identify and analyze the existing literature on hydrogel polymers applied in electronic devices, with a particular focus on their thermal stability in smartphone applications. The search was limited to peer-reviewed articles published between 2013 and 2025 to ensure the iclusion of recent advancements.

The findings from the eligible studies were synthesized thematically, highlighting performance characteristics and comparative thermal behavior using various methods. This approach enabled the identification of current research trends, technological challenges, and potential future directions for the application of hydrogel polymers in smartphone thermal management systems.

III. Results and Discussion

III.1 Enchancing the Thermal Stability of Hydrogels using Various Methods

Hydrogels, characterized by their highwater content, are inherently vulnerable to thermal fluctuations, which significantly impact their mechanical properties and functional stability. At subzero temperatures, the internal water phase crystallizes, resulting in increased brittleness and a loss of flexibility. Conversely, at elevated temperatures, water evaporation leads to dehydration, causing structural shrinkage and mechanical failure. Additionally, these thermal instabilities compromise other essential properties, including electrical conductivity, optical transparency, and self-healing ability, thereby limiting the practical applications of hydrogels in advanced materials and devices [3]. To overcome these limitations, researchers have developed various strategies to enhance the thermal stability of hydrogels. One approach involves the incorporation of hygroscopic and antifreeze agents, such as glycerol and ionic liquids, which effectively lower the freezing point and reduce water [4]. Another method focuses on optimizing polymeric crosslinking networks, where double-network and supramolecular structures improve mechanical resilience under extreme temperatures [5]. Furthermore, the introduction of hydrophilic-hydrophobic balance modifications has demonstrated significant potential in regulating water retention, thereby prolonging hydrogel functionality in diverse environments [6]. By employing these innovative methods, hydrogels can achieve enhanced resistance to freezing and dehydration, making them more suitable for applications in flexible electronics, biomedical engineering, and soft robotics. Continued research in this field is essential for developing next-generation hydrogels with superior thermal stability and long-term durability.

(a) Anti-Freezing Properties

One of the major challenges in the application of hydrogels is their tendency to freeze at subzero temperatures due to their high water content. When water crystallizes within the hydrogel matrix, it disrupts the polymeric network, leading to increased brittleness, loss of flexibility, and a significant decline in mechanical performance. Moreover, the formation of ice can compromise other essential hydrogel properties, such as conductivity, transparency, and self-healing capability, thereby limiting their usability in extreme cold environments [7]. To enhance the anti-freezing properties of hydrogels, researchers have explored several effective strategies. One widely adopted approach is the incorporation of cryoprotectants such as glycerol, ethylene glycol, and ionic liquids, which reduce the freezing point of water and inhibit ice crystal formation [8]. These substances function by disrupting hydrogen bonding between water molecules, preventing them from organizing into ice structures. Additionally, the use of hydrophilic polymers with strong water-binding capacity, such as polyvinyl alcohol (PVA) and polyacrylamide (PAM), helps retain water in an unfrozen state by forming stable hydration shells around polymer chains [9]. Another promising method involves designing anti-freezing double-network hydrogels, which integrate strong covalent crosslinks with reversible supramolecular interactions. This structural enhancement not only improves mechanical robustness at low temperatures but also facilitates energy dissipation, preventing hydrogel fracture under frozen conditions [10]. By implementing these advanced anti-freezing strategies, hydrogels can maintain their functionality in extreme cold environments, expanding their potential applications in flexible electronics, biomedical implants, and soft robotics operating under subzero conditions. Table 1 summarizes the general methods proposed by researchers to enhance the anti-freezing properties of hydrogels, outlining key approaches, mechanisms, and materials used to improve their freeze resistance. Continued research and optimization in this area will further advance the development of next-generation freeze-resistant hydrogel materials.

TABLE 1.
GENERAL METHODS FOR ENHANCING THE ANTI-FREEZING PROPERTIES OF HYDROGELS

Method	Additives/ Materials	Advantages	Limitations	Ref
Utilizes electrolyte hydrogel (EH) surface infused with salted water to enhance freezing resistance	Polyelectrolyte hydrogels, NaCl solutions, zwitterionic osmolytes	Durable antifreezing performance, ultralow ice adhesion, and rapid self-deicing within 10 seconds at -10°C	Requires periodic replenishment of salted water to maintain anti-icing efficacy and has reduced performance at extreme subzero temperatures.	[11]
The method employed to enhance freeze resistance in hydrogels involves the incorporation of inorganic salts, which effectively lower the freezing point and maintain mechanical properties at sub-zero temperatures	Dimetil sulfoksida (DMSO), ethylene glycol, and ionic liquids, which form hydrogen bonds with water molecules to prevent ice crystallization	Dimetil sulfoksida (DMSO), ethylene glycol, and ionic liquids, which form hydrogen bonds with water molecules to prevent ice crystallization	Limitations include the potential environmental impact of some organic fluids like DMSO and ethylene glycol, which are not as eco-friendly as water	[12]
The method employed to enhance freezing resistance involves a solvent displacement strategy, where water molecules in hydrogels are partially replaced by cryoprotectants, inspired by the cryopreservation of biological samples	Cryoprotectants such as glycerol, glycol, and sorbitol are used in the method	This method offers a simple and reliable approach that does not require complex polymerization conditions, allowing for the rational tuning of freezing and drying tolerance in a variety of water-based hydrogels	Challenges remain in achieving long-term stability and addressing the limitations of single cryoprotectants, and there are safety concerns regarding the potential toxicity of some cryoprotectants, although these can be mitigated by using non-toxic options like glycerol and sorbitol	[13]
The method employed involves the fabrication of ionic conductive organohydrogels using a one-pot sol–gel synthesis approach, incorporating a DMSO/H_2O binary solvent system to enhance freezing tolerance.	The materials used include polyvinyl alcohol (PVA), 2,2,6,6-tetramethylpyperidine-1-oxyl (TEMPO) oxidized cellulose nanofibrils (CNFs), and dimethyl sulfoxide (DMSO) as a cryoprotectant.	The primary advantage of this method is the impressive freezing tolerance, allowing the organohydrogel to remain flexible and conductive even at temperatures as low as −70 °C.	A limitation of this approach is the potential decrease in ionic conductivity due to reduced ion dissociation and mobility in the presence of organic solvents and enhanced crosslinking density.	[14]
The approach involves designing an anti-freezing hydrogel polyelectrolyte that maintains ionic conductivity and mechanical properties at subzero temperatures.	Low molecular vicinal alcohols such as glycerol and ethylene glycol (EG) are used as nontoxic inhibitors for water freezing.	The method provides excellent energy-power density, stable cycling performance, and remarkable flexibility at subzero temperatures.	The introduction of alcohols can degenerate the mechanical properties of physically cross-linked hydrogels, posing a challenge in material design.	[15]

III.2 Application of Hydrogels Based on Thermal Stability in Electric Device

Hydrogels were designed for use in flexible sensors that can detect mechanical stimuli such as compression and stretching [16]. Hydrogels with thermal stability are increasingly being used in electric devices due to their unique properties such as flexibility, high water content, tunable conductivity, and ability to respond to external stimuli (like heat or electricity). These properties make thermally stable hydrogels ideal for various advanced applications in electronics [17].

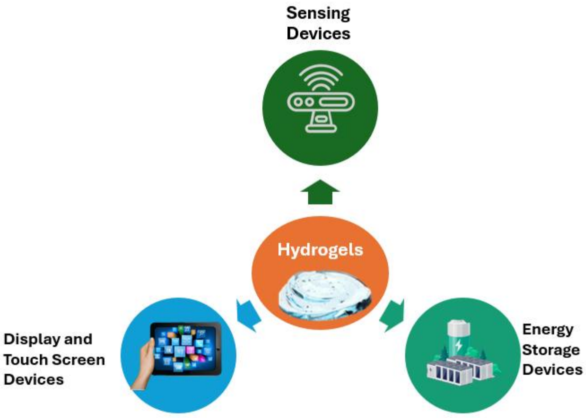

Figure 1. Schematic view of hydrogels used in various application in flexible electronics and devices

(a) Application in Flexible Sensors

Flexible sensors are devices designed to detect and measure physical parameters such as temperature, pressure, strain, humidity, and biological signals while being bendable or stretchable. Unlike traditional rigid sensors, flexible sensors can conform to curved or irregular surfaces, making them ideal for applications in environments where flexibility, stretchability, or adaptability are required [18]. Based on the [19] research that discussed the development of a double network (DN) hydrogel made from chitosan and poly (acrylic acid-co-acrylamide). The study aims to address the challenges in creating hydrogels that are both highly conductive, mechanically strong, and resistant to freezing, which are key features for flexible strain sensors. The hydrogel sensor is freeze-resistant, maintaining its function even at temperatures as low as −20°C, making it ideal for applications in extreme environments. The hydrogel sensor has been tested for detecting human body movements, showing potential for wearable devices and flexible electronics.

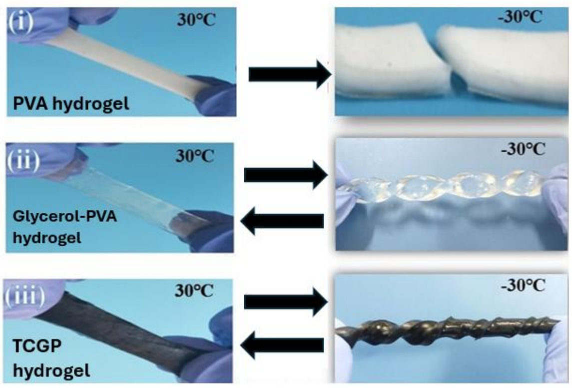

Figure 2. Anti-freezing and moisturizing properties of hydrogel (Source: [20] with modification)

Based on the [20] study that discusses the development and use of a highly sensitive strain sensor based on a specially designed hydrogel. The strain sensor that made from a TCGP hydrogel, which includes a polyvinyl alcohol (PVA) matrix embedded with tannic acid (TA) and carbon nanotubes (CNTs) in a water-glycerol solution. This hydrogel formulation can stretch and compress without losing structural integrity, allowing it to function in environments where it must conform to moving surfaces like skin. The CNTs within the hydrogel impart excellent conductivity, making it ideal for detecting changes in resistance caused by strain. The inclusion of glycerol lowers the freezing point of the hydrogel, allowing it to function even at temperatures as low as -30°C. On the [16] research that discussed hydrogels with enhanced flexibility and functionality at low temperatures. These hydrogels, made from LiCl and poly(HEAA-co-BD), possess abundant hydrogen bonding, which helps prevent freezing and maintains their flexibility, conductivity, and stretchability even at extreme temperatures as low as -40°C.

(b) Application in Energy Storage Devices

Polymers known as hydrogels has the amazing capacity to absorb significant volumes of water while retaining their structural integrity. Ion transport allows ionic hydrogels to transmit electricity, which is advantageous when interacting with biological tissues. Their high dielectric constants are essential for their use in dielectric elastomer actuators and capacitive sensors because of their water content [21]. Energy storage hydrogels are polymer-based materials with the ability to store and release electrical energy, making them useful in devices such as supercapacitors and batteries. These hydrogels are often modified with conductive materials like carbon nanotubes (CNTs), graphene, or metal ions to enhance their electrical conductivity and energy storage capabilities. Hydrogels for energy storage combine the unique properties of hydrogels such as flexibility, high water content, and stretchability, with the electrochemical functionality needed for energy applications. The study of [22] highlights the potential of these hydrogels in energy storage, specifically as electrodes for supercapacitor. The addition of carbon nanotubes (CNTs) and gum arabic (GA) to the hydrogel matrix significantly enhances its mechanical and electrochemical properties, making it ideal for use in flexible energy storage devices. The characteristics of hydrogel make the hydrogel suitable for soft, flexible electronic devices, particularly supercapacitors, which require materials that combine high capacitance, durability, and flexibility. The porous structure created by the CNT and GA allows efficient ion and electron transport, crucial for energy storage performance.

(c) Application in Display and Touch Screen Devices

Hydrogels can be used in ionic touch screens. For instance, lithium-containing polyacrylamide hydrogels have been developed for touch panels that are elastic and can withstand significant deformation. This enables hydrogels to function as flexible touch interfaces that are more durable under strain, such as bending up to 1000% without loss of functionality [1] Based on [23] study that discussed how hydrogels are utilized in touch screen devices due to their flexible, conductive, and self-healing properties. Hydrogels, with their ability to conduct electrical signals, are integrated into touch-sensitive applications, where they serve as the core material for capacitive and resistive touch panels. These hydrogels enable devices to register touch inputs while maintaining mechanical flexibility and sensitivity. The [24] research explains the application of hydrogels in touch screens, particularly focusing on the development of a highly stretchable and transparent ionic touch panel. This touch panel is based on polyacrylamide hydrogel containing lithium chloride (LiCl) salts, which serves as an ionic conductor for detecting touch inputs.

III.3 Hydrogel Responsiveness In Electronic Devices

Numerous industries have made extensive use of flexible electronic devices that are inexpensive, highly effective, and pliable. The selection of materials plays a crucial role in the development of flexible electronic devices. Hydrogels are three-dimensional polymers that are insoluble in water yet possess a hydrophilic crosslinked network capable of absorbing water while maintaining their structural stability [25]. Crosslinks are present in the majority of hydrogels, both chemically and physically. Hydrogels that have been chemically crosslinked are often reversible. Conversely, dynamic non-covalent connections create physically crosslinked hydrogels. Changes in temperature and pH can be readily adapted to by hydrogels that include physical crosslinking. Due to their high water content, hydrogels can freeze at low temperatures and dry out easily at high temperatures. Certain types of hydrogels are highly sensitive to temperature changes, causing significant alterations in shape, appearance, or size within a narrow temperature range Hydrogels exhibit remarkable responsiveness in electronic devices, particularly in terms of thermoresponsiveness. They can be utilized for electronic cooling by evaporating water within their structure to dissipate heat generated by the device. Consequently, this cooling mechanism enhances the efficiency and performance of electronic devices [17]. Various forms of thermoresponsive hydrogels have been developed to increase the performance and efficiency of smartphones, notably in aspects relating to sensory functions, cooling, and device flexibility. These characteristics enable hydrogels to be employed in the fabrication of multifunctional components for flexible electronic devices.

(a) Hydrogels Thermoresponsivenes with Influential Factors

Water-based hydrogels are highly susceptible to freezing at sub-zero temperatures, which can cause them to become rigid and brittle [26]. Hydrogels can undergo a sol-gel transition at a specific temperature, commonly referred to as the Critical Solution Temperature (CST). Based on their properties, thermoresponsive hydrogels can be categorized into two types: Lower Critical Solution Temperature (LCST) and Upper Critical Solution Temperature (UCST). In LCST-based hydrogels, the polymer remains soluble in water at temperatures below LCST, while upon exceeding the LCST, the hydrogel undergoes phase separation (gel phase). In contrast, UCST-based hydrogels remain soluble in water at temperatures above UCST, and when the temperature drops below UCST, the hydrogel transitions into the gel phase [27]. The following section presents polymers commonly used in thermoresponsive hydrogels:

TABLE 2.
TYPE OF LOWER CRITICAL SOLUTION TEMPERATURE HYDROGELS

Polymer	Abbreviation	Application	Ref
LiCl and Poly (HEAA-co-BD)	Poly (HEAA-co-BD)	Flexible senssor	[16]
Poly (acrylic acid-co-acrylamide) Double Network	DN Hydrogel	Flexible sensor	[19]
Polyvinyl alcohol (PVA) matrix	TCGP hydrogel	Flexible sensor	[20]
Poly(N-isopropylacrylamide)	PNIPAM	Smart sensors, passive cooling, and responsive displays	[21]
Biopolymers gum arabic	Gum arabic-CNT reinforced hydrogels	Supercapacitor energy storage	[22]
Poly(2-hydroxyethyl methacrylate)	PHEMA	Smartphone screen coatings, biometric sensors	[28]
Polyethylene Glycol	PEG	Scratch-resistant protective screen, flexible sensor, antibacterial coating	[29]

Poly(vinyl alcohol)	PVA	Self-healing screen protector, flexible touch sensor, water-and dust-resistant coating	[30]

IV. Conclusion

The scientific advancement of hydrogel polymers represents a significant milestone in modern material science, expanding their potential well beyond traditional boundaries. Recent progress in enhancing thermal stability through advanced crosslinking, cryoprotectant incorporation, and molecular modification has enabled their integration into next-generation electronic systems. These developments have driven major improvements in flexible sensors, energy storage devices, and touch-screen technologies, where hydrogels demonstrate exceptional flexibility, transparency, and durability.

Among these achievements, the thermoresponsive behavior of hydrogels stands out as a key innovation, allowing autonomous adaptation to temperature variations while maintaining structural integrity and functionality. Such intelligent properties position hydrogels as essential materials for adaptive and sustainable electronic systems. Such capabilities position hydrogels not merely as supplementary materials, but as fundamental technological enablers with potential applications spanning medical, industrial, and consumer electronics domains. Looking toward the future, the research landscape presents both extraordinary opportunities and significant challenges.

Future research will rely on interdisciplinary collaboration to optimize performance parameters, including electrical conductivity, mechanical flexibility, and environmental responsiveness. Computational modeling, bio-inspired design strategies, and hybrid polymer systems will play a central role in advancing the next generation of hydrogel-based technologies.

Hydrogels emerge not simply as a material innovation, but as a conceptual bridge connecting rigid, static electronic systems with dynamic, responsive technological ecosystems that can adapt, self-regulate, and interact with unprecedented sophistication. The future of electronic technologies will be increasingly characterized by hydrogel integration, challenging existing paradigms of material capabilities and system design. This convergence of scientific innovation promises transformative changes that extend far beyond incremental improvements, potentially revolutionizing our fundamental approach to technological development and interaction.

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