POLYVINYL ALCOHOL-POLYETHYLENE GLYCOL/GLYCERIN HYDROGEL ENHANCED PHYSICOCHEMICAL CHARACTERISTICS: STATISTICAL COMPOSITION

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ABSTRACT: Polyvinyl alcohol (PVA) hydrogels are widely recognized for their potential in biomedical applications, particularly as wound dressings, due to their biocompatibility and water retention properties. However, their performance can be enhanced through modifications in composition and cross-linking with other polymers. This study aims to improve the properties of PVA hydrogels by incorporating polyethylene glycol (PEG) and glycerin through the freeze-thaw method. Central composite design (CCD) and response surface methodology (RSM) were employed to investigate the effect of PEG and glycerin concentrations on moisture retention capability (MRC). The optimized composition, with 6% (w/v) PEG and 4% (w/v) glycerin, achieved the highest MRC at 46.82 ± 0.54%. The hydrogel exhibited a swelling capacity of 143.24 ± 1.66%, a gel fraction of 58.06 ± 1.65%, and a porosity of 42.17 ± 0.94%. Field-emission scanning electron microscopy (FESEM) confirmed the surface features and porosity, while Fourier transform infrared (FTIR) spectroscopy analysis verified the cross-linking within the PVA-PEG matrix with glycerin. These findings highlight the potential of the hydrogel for wound dressings due to its favorable properties.

KEY WORDS: *Polyvinyl Alcohol, Polyethylene Glycol, Glycerin, Hydrogel.*

1. INTRODUCTION

Hydrogels are water-absorbing polymers composed of hydrophilic chains that swell in water while maintaining structural integrity [1]. Despite their excellent water absorption and biocompatibility, polyvinyl alcohol (PVA) hydrogels face limitations when used as stand-alone wound dressings, particularly due to their limited moisture retention capability [2, 3]. Effective wound dressings must maintain a moist environment for optimal healing; however, PVA hydrogels often dehydrate quickly, resulting in a dry wound bed and hindering the healing process [2, 4].

To overcome these obstacles, hydrogel compositions can be enhanced by cross-linking with other polymers or incorporating reinforcing agents, which may potentially improve their performance as wound dressings. Adjusting the polymer composition affects the properties of hydrogels [5, 6]. Incorporating biodegradable components, such as polyethylene glycol (PEG) and glycerin, into PVA hydrogels enhances their swelling capacity, gel fraction, porosity, and moisture retention, resulting in more effective wound dressings [7, 8].

Polyethylene glycol (PEG), a synthetic polymer, offers excellent water solubility, biocompatibility, flexibility, and low toxicity [9]. Integrating PEG with PVA hydrogel addresses issues like limited water retention and absorption. As a cross-linker, PEG enhances water retention and hydrophilicity, which are crucial for maintaining moisture for wound healing [10, 11]. Its flexibility and swelling capacity make it ideal for wound dressing applications [12].

Glycerin, or glycerol, is a versatile compound derived from animal or vegetable fats. With multiple hydroxyl groups, it is highly soluble in water and acts as a humectant [8]. The incorporation of glycerin into PVA hydrogels enhances their flexibility and softness, effectively overcoming the limitations commonly associated with conventional wound dressings [12, 13]. Additionally, glycerin increases the hydrogel's water absorption capacity, maintaining a moist wound environment and mitigating the brittleness and dryness typically observed in traditional PVA hydrogels [14].

Hydrogels, formed by cross-linking polymer chains through methods such as radiation, chemical processes, and freeze-thaw cycles, have gained considerable attention for their diverse applications in biomedical fields [11, 15]. The freeze-thaw method is particularly advantageous due to its simplicity, cost-effectiveness, and eco-friendliness, as it avoids the need for harmful chemicals or radiation [16, 17]. This technique enhances hydrogel structure by subjecting a precursor solution to freezing and thawing cycles, where ice crystal formation rearranges polymer chains, creating a more robust network upon thawing [18, 19].

Extensive research has been conducted on PVA and PEG hydrogels individually, due to their biocompatibility and desirable properties, such as moisture retention, particularly in wound dressing applications [1, 6]. Moreover, there has been growing interest in the combination of PVA and PEG for hydrogel production, as this combination enhances mechanical strength, swelling capacity, and biocompatibility [4, 7, 11]. Some studies have focused on optimizing the formulation of PVA-PEG hydrogels for specific biomedical applications such as drug delivery and wound healing [6, 7]. However, most research on PVA-PEG hydrogels has concentrated on the use of these two polymers without exploring the synergistic effects of incorporating additional plasticizers such as glycerin. This study addresses a gap in literature by examining the incorporation of glycerin into PVA-PEG hydrogels. This modification has been underexplored despite glycerin's potential to enhance flexibility, moisture retention, and swelling properties of hydrogels [3, 8]. While PVA and PEG hydrogels have been studied separately, the combination with glycerin remains limited.

The study employed the freeze-thaw method to fabricate a PVA-PEG/glycerin hydrogel specifically designed for wound dressing applications. The focus was on enhancing the hydrogel's swelling behavior and moisture retention capabilities to create a more effective material for wound care. To optimize the hydrogel's performance, varying concentrations of PEG and glycerin were investigated for their impact on moisture retention capability (MRC). Response surface methodology (RSM) with a central composite design (CCD) was employed to assess the influence of these concentrations on the hydrogel's moisture retention capacity (MRC), aiming to improve the hydrogel's ability to maintain an optimal moisture environment for enhanced wound healing.

The initial and final concentrations of PEG and glycerin were selected based on previous research. A study on PVA/PEG hydrogel demonstrated that a composition with 5% PEG concentration and five freeze-thaw cycles resulted in a gel fraction of 63.7%,

indicating promising hydrogel properties [20]. Similarly, another investigation examined the impact of glycerin content on sodium alginate/PVA-based hydrogel, testing concentrations ranging from 0 to 3.4% (v/v). Findings indicated a decline in gel fraction with increasing glycerin content, suggesting an optimal range for glycerin concentrations to enhance hydrogel performance [8]. Furthermore, the optimized PVA-PEG/glycerin hydrogel was characterized by its swelling behavior, gel fraction, and porosity, with its morphology and functional groups analyzed using field emission scanning electron microscopy (FESEM) and Fourier transform infrared spectroscopy (FTIR).

2. MATERIALS AND METHODS

2.1. Materials

Polyvinyl alcohol (PVA; MW 89,000-98,000; 99% hydrolyzed), polyethylene glycol (PEG; MW 3350), dimethyl sulfoxide (dMSO; ≥99.5%), and glycerin (≥99.5%) were obtained from Sigma-Aldrich (St. Louis, MO, USA). All chemicals were of analytical grade and used without further purification.

2.2. Synthesis of PVA-PEG/Glycerin Hydrogel

First, a 20% (v/v) dMSO solution was prepared by mixing it with deionized water at 45 °C for 15 minutes. Then, a 15% (w/v) PVA solution was made in the dMSO solution, heated to 90°C for 1 hour with constant stirring until it became translucent. Various concentrations of PEG were added, and the mixture was agitated for one hour at 90°C to form a uniform PVA-PEG solution. Next, varying amounts of glycerin were added, and the mixture was stirred for an additional hour at 90°C. To crosslink the polymer, the prepared PVA-PEG/glycerin solution was transferred into a petri dish and subjected to three freeze–thaw cycles, where each cycle involved freezing the sample at –20°C for 18 hours, followed by incubation at room temperature for 2 hours. The freeze-thaw method facilitated the crosslinking of the PVA-PEG/glycerin polymer, resulting in the formation of a hydrogel suitable for wound dressing applications.

2.3. Experimental Design and Optimization

The experimental design aimed to enhance the moisture retention capability (MRC) of the hydrogel. Independent variables, PEG and glycerin concentrations, were varied, with MRC as the dependent variable. Response surface methodology (RSM) using central composite design (CCD) determined the optimal hydrogel composition (see Table 1). Each variable was tested at three levels: low (-), basal (0), and high (+1). Thirteen trials were conducted, including five replications at the central location, to assess experimental errors.

Table 1: CCD design of each variable with its corresponding ranges

Variables	Levels		
	-1	0	+1
PEG concentration [A] (% w/v)	1	3.5	6
Glycerin concentration [B] (% w/v)	1	2.5	4

2.4. Field Emission Scanning Electron Microscope

The hydrogel's surface morphology was analyzed using a field emission scanning electron microscope (FESEM) (Model Supra 55VP, Carl Zeiss AG, Germany) at 50 kV magnification. Before examination, the sample was coated with a thin layer of platinum.

2.5. Fourier Transform Infrared Spectroscopy

The chemical composition of the hydrogel was analyzed using Fourier Transform Infrared Spectroscopy (FTIR) (Spectrum RX spectrophotometer, PerkinElmer, USA). Spectra were recorded across a wavenumber range of 400 to 4000 cm^{-1} with a resolution of 4 cm^{-1}. Each sample was analyzed in triplicate to ensure consistency and accuracy.

2.6. Gel Fraction

Hydrogel samples, sized 2 cm × 2 cm and 0.3 cm thick, were dried in a 40 °C oven for 24 h until a constant weight (W_o) was achieved. They were then immersed in deionized water at room temperature for 48 h to reach equilibrium swelling. Afterward, the samples were dried again at 40 °C for 24 h to obtain a constant weight (W_e). The gel fraction (GF) percentage was calculated using Eq. (1).

$$\% GF = (W_e/W_o) \times 100 \quad (1)$$

In the equation, W_o is the mass of the samples after 24 hours of drying at 40 °C, and W_e is the mass of the dried samples after submersion in deionized water.

2.7. Swelling Ratio

The hydrogel samples, cut into uniform pieces (2 cm × 2 cm) with a thickness of 0.3 cm, were weighed (W_d) to measure the swelling ratio. They were then soaked in deionized water at room temperature for 24 h. After removal, excess water was wiped off with tissue paper, and the samples were reweighed (W_s) to calculate the swelling ratio using Eq. (2).

$$Swelling\ ratio\ (\%) = \frac{(W_s - W_d)}{W_d} \times 100 \quad (2)$$

Where, W_s represents the weight of swollen hydrogels and W_d represents the weight of dried hydrogels.

2.8. Moisture Retention Capability

The hydrogel samples were cut into uniform dimensions of 2 cm × 2 cm with a thickness of 0.3 cm, weighed, and heated in a 40°C oven for 6 h. After removal from the oven, they were reweighed to calculate the swelling ratio using Eq. (3).

$$MRC\ (\%) = (W_f/W_i) \times 100 \quad (3)$$

Where W_i and W_f are the weights of hydrogel samples before and after heating at 40 °C for 6 h, respectively.

2.9. Hydrogel Membrane Porosity

The hydrogel samples were cut into uniform 2 cm × 2 cm pieces with a thickness of 0.3 cm, then immersed in ethanol at room temperature until fully saturated. The samples were evaluated before and after ethanol absorption, and the volume of ethanol at each stage was measured. The hydrogel membrane porosity (φ) was subsequently determined using Eq. (4).

$$\varphi\ (\%) = (W_f - W_i)/(\rho V_f - \rho V_i) \times 100 \quad (4)$$

Where, W_i and W_f represents the initial and final sample weights, respectively, while ρ denotes the density of ethanol at ambient temperature. In contrast, V_i and V_f indicates the initial and final ethanol volumes before and after absorption, respectively.

3. RESULTS AND DISCUSSION

3.1. Statistical Analysis and Response Optimization of Hydrogel Composition

The study investigated PEG concentrations ranging from 1% to 6% (w/v) and glycerin concentrations from 1% to 4% (w/v), as outlined in Table 1. The combined effects of these concentrations were analyzed using Central Composite Design (CCD) within Response Surface Methodology (RSM), as detailed in Table 2. The experimental data were modeled using a linear equation for moisture retention capability (MRC), as shown in Eq. (5).

$$Y = +44.78 + 4.52A + 2.97B + 4.62AB \quad (5)$$

Here, Y represents the moisture retention capability (MRC), while A and B represent the independent variables of PEG and glycerin concentrations, respectively.

Positive coefficients in the polynomial equation signify that increasing PEG and glycerin concentrations enhance the hydrogel composition, resulting in higher MRC values. This mathematical model elucidates the relationship between these variables and the response (MRC), reflecting findings consistent with previous studies [20,21].

Table 2: CCD for hydrogel composition and experimental results

Run	PEG concentration [A] (% w/v)	Glycerin concentration [B] (% w/v)	MRC (%)
1	1	2.5	28.24
2	3.5	2.5	34.79
3	3.5	4	36.59
4	3.5	2.5	36.25
5	6	1	31.15
6	3.5	2.5	36.47
7	6	4	46.24
8	1	4	29.46
9	3.5	1	30.43
10	1	1	32.86
11	6	2.5	40.30
12	3.5	2.5	35.64
13	3.5	2.5	33.73

ANOVA was used to assess the model's effectiveness and significance, as depicted in Table 3. It displays the model's significance, characterized by a low p-value ($p < 0.0001$) and an F-value of 44.66, indicating minimal noise contribution. All terms (A, B, and AB) exhibited p-values below 0.05, emphasizing the influence of variables such as PEG and glycerin concentrations on the hydrogel's MRC. The high R^2 value (0.9370) suggested a good fit, supported by the close alignment of predicted R^2 (0.8452) with adjusted R^2 (0.9161), validating accurate predictions [2]. The Lack-of-Fit was insignificant, affirming the model's adequacy and the strong correlation between the variables and the output response.

Table 3: ANOVA of hydrogel composition

Source	Sum of squares	DF	Mean square	F-value	p-value	
Model MRC (Y)	261.25	3	87.08	44.66	<0.0001	Significant
A-PEG concentration	122.67	1	122.67	62.91	<0.0001	
B-Glycerin concentration	53.10	1	53.10	27.23	0.0006	
AB	85.47	1	85.47	43.83	<0.0001	
Residual	17.55	9	1.95	-	-	
Lack of Fit	12.47	5	2.49	1.96	0.2667	Not significant
Pure Error	5.08	4	1.27	-	-	
Cor Total	278.80	12	-	-	-	
R^2	0.9370		Adequate Precision		23.61	
Adjusted R^2	0.9161		C.V. %		4.01	
Predicted R^2	0.8452		Standard Deviation %		1.40	

With a precision of 23.61%, the model demonstrated adequate signal strength for navigating the design space. Its standard deviation of 1.40% fell below the 3% threshold, indicating close alignment between predicted and actual responses [6]. The low coefficient of variation, below 10%, affirmed high accuracy and validity. Three-dimensional response surface plots (Fig. 1) depicted the influence of PEG and glycerin concentrations on the hydrogel's MRC.

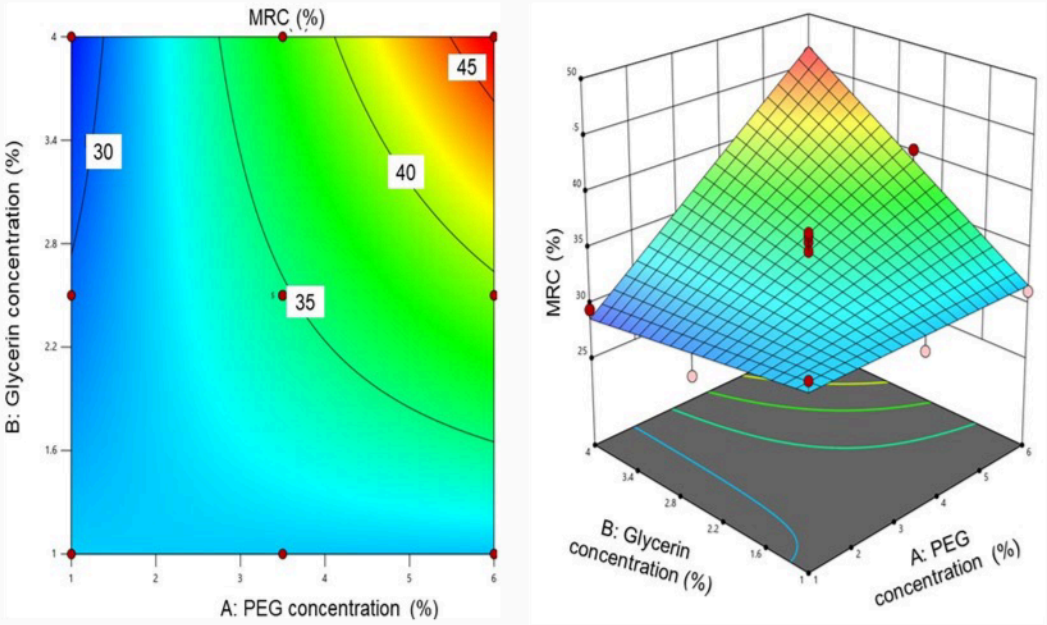

Fig. 1. Impact of PEG and glycerin concentrations on the MRC of the hydrogel shown in (a) the contour plot and (b) the response surface graph.

In Fig. 1(b), a noticeable downward curve and non-elliptical forms reveal a significant relationship between PEG and glycerin concentrations and the hydrogel's MRC. This implies that variations in PEG and glycerin concentrations significantly impact MRC, highlighting an optimal combination that maximizes moisture retention. While the graph

illustrates the hydrogel's sensitivity to these parameters, it may not pinpoint a single optimal point due to system complexity.

Through Response Surface Methodology (RSM) optimization, the ideal hydrogel composition for the PVA-PEG/glycerin system was determined to be 6% (w/v) PEG and 4% (w/v) glycerin, yielding a moisture retention capacity (MRC) of 46.24%. Validation experiments confirmed the optimized composition with an MRC of 46.82 ± 0.54%, closely matching the predicted value of 46.90%, demonstrating the accuracy of the RSM model and the effectiveness of the optimization process.

MRC is a key factor in hydrogel performance, playing a vital role in moisture absorption and retention, which is essential for wound healing by maintaining hydration and preventing fluid accumulation [15, 17]. While hydrogels typically aim for an MRC range of 80% to 95% [1, 16, 22], the PVA-PEG/glycerin hydrogel achieved an MRC of 46.82 ± 0.54%. For comparison, a PVA-PEG/CNF-curcumin hydrogel exhibited an MRC of 44.84% [23], while a PVA/starch hydrogel with clove oil reached 95.50 ± 0.48% [16]. Although the MRC remains below the 50% threshold, this formulation demonstrates significant potential and underscores the need for further optimization. Achieving higher MRC values typically requires a careful balance of factors such as crosslinking density and plasticizer content [1, 6]. Although it does not surpass the 50% MRC threshold, the PVA-PEG/glycerin hydrogel's performance falls within the expected range, suggesting opportunities for further improvement.

The lower MRC observed may be attributed to the saturation effect of glycerin. Although effective as a humectant, glycerin likely reaches its optimal concentration at 4% (w/v), beyond which increasing the glycerin concentration may not significantly enhance water retention capacity, as higher levels may not yield further improvements [8]. Similarly, while PEG positively contributes to moisture retention, it may not be sufficient alone to increase the MRC beyond the observed value of 46.82%, as reported in other PVA-based hydrogel systems [4, 7].

This suggests that further optimization of the hydrogel composition is necessary, potentially through the incorporation of reinforcing agents or adjustments in crosslinking density, to achieve higher MRC values for enhanced wound healing. The inclusion of reinforcing agents, such as cellulose nanocrystals, could further improve the MRC. Future adjustments to the hydrogel composition are required to enhance its suitability for wound care [1, 13]. While the optimized formulation with 6% PEG and 4% glycerin does not exceed the 50% MRC threshold, it shows promising potential for wound dressing applications. This formulation offers a balanced approach to moisture retention, which is essential for maintaining an optimal moist wound environment [3]. To further improve the MRC, future research could explore variations in crosslinking conditions or investigate other biopolymers to optimize the performance of the hydrogel.

3.2. Swelling Behavior Assessment

Controlled swelling, typically ranging from 100% to 1000%, maintains a moist wound environment, fostering healing [20]. Fig. 2(b) illustrates the swelling behavior of the hydrogel. The optimized PVA-PEG/glycerin hydrogel, consisting of 6% (w/v) PEG and 4% (w/v) glycerin, demonstrated a remarkable swelling capacity of 143.24 ± 1.66%, surpassing both the PVA hydrogel (54.4 ± 0.46%) and the PVA/PEG hydrogel (118%) reported by Ahmed et al. (2018) [20]. This significant improvement in swelling capacity highlights the role of glycerin in enhancing the PVA-PEG hydrogel system, particularly in its ability to

retain moisture, which is essential for wound dressing applications. The addition of glycerin, known for its humectant properties, enhances the hydrogel's ability to absorb and retain a large amount of water, thereby promoting a moist environment crucial for wound healing [8, 24].

A swelling capacity exceeding 100% signifies high absorbency, a desirable feature for hydrogels used in wound care [8, 24]. Notably, this hydrogel formulation outperformed the PVA-PEG/CNF-curcumin hydrogel (26.44%) in terms of absorption capacity [23]. The incorporation of PEG and glycerin not only softens the typically rigid PVA hydrogel but also increases its pliability, significantly improving its moisture absorption properties. The hygroscopic nature of glycerin and PEG allows them to form hydrogen bonds with water molecules, thus enhancing the water uptake capacity of the hydrogel. This increased swelling capacity is critical in maintaining a moist wound environment, which is conducive to faster healing. Glycerin, acting as a plasticizer, helps prevent gel cracking, ensuring that the PVA-PEG/glycerin hydrogel maintains its structural integrity during swelling. Additionally, both glycerin and PEG improve the hydrogel's ability to interact with water, further enhancing its swelling behavior and moisture retention [2, 17]. As a result, this hydrogel formulation demonstrates great potential for use in wound dressing applications, offering improved moisture retention and structural stability compared to traditional hydrogels.

3.3. Gel Fraction

Gel fraction measures the proportion of a hydrogel that has cross-linked into a stable network, indicating its resilience and durability. Typically ranging from 60% to 90% in wound dressing hydrogels, a higher gel fraction signifies enhanced stability [8, 24]. While the PVA hydrogel exhibited a gel fraction of 36.99 ± 0.34%, the optimized PVA-PEG/glycerin hydrogel showed a higher value of 58.06 ± 1.65%, indicating significant cross-linking and stability. Although slightly below the standard range, this value still supports moisture retention and structural integrity. Similar findings were observed in PVA/starch hydrogels with oregano oil [8, 16].

The optimized PVA-PEG/glycerin hydrogel, comprising 6% (w/v) PEG and 4% (w/v) glycerin, demonstrated robust cross-linking among PVA, PEG, and glycerin, resulting in a high gel fraction. The hydrophilic nature of PEG and glycerin promoted water retention within the hydrogel, fostering an ideal environment for cross-linking reactions. This hydration facilitated more effective bonding between polymer chains, resulting in stronger physical and chemical bonds, significantly increasing the gel fraction [12]. Additionally, their hydrophilic properties enhanced water absorption into the polymer matrix, reinforcing bonds between polymer chains and augmenting cross-linking density, further enhancing the hydrogel's resilience for wound dressings [8, 16].

3.4. Hydrogel Porosity

Porosity, the measure of empty spaces or voids within the hydrogel structure, is crucial for wound dressings [16]. In Fig. 2(c), the porosities of PVA hydrogel and PVA-PEG/glycerin hydrogel are displayed. PVA hydrogel exhibited 27.42 ± 0.65% porosity, whereas the optimized PVA-PEG/glycerin hydrogel showed a higher porosity of 42.17 ± 0.94%. This porosity level of 42.17 ± 0.94% compares favorably with that of a PVA/starch

hydrogel incorporating oregano oil, which had 41% porosity [16], but falls below that of a PVA-PEG/CNF-curcumin hydrogel with 48% porosity [23]. Ideal wound dressing hydrogels typically aim for porosity levels between 30% and 40% to balance moisture retention without over-saturation [24, 25].

The addition of glycerin and PEG to the PVA-PEG/glycerin hydrogel enhances porosity through multiple mechanisms. Firstly, both glycerin and PEG are hydrophilic compounds with hydroxyl (-OH) groups, which exhibit a strong affinity for water molecules, resulting in increased water uptake by the hydrogel. This swelling creates more void spaces, thereby increasing overall porosity [16, 24]. Secondly, the hydrophilic properties of glycerin and PEG facilitated efficient cross-linking between the polymer chains, resulting in a more interconnected network within the hydrogel matrix [16, 20]. This improved structural integrity, along with enhanced water retention, contributed to the observed increase in porosity. The swelling tests, porosity measurements, and FESEM confirmed this enhancement. The swelling tests and porosity measurements demonstrated increased water uptake and the formation of void spaces. At the same time, FESEM imaging revealed a more interconnected polymer network, supporting the hypothesis that glycerin and PEG enhance cross-linking and porosity in the hydrogel.

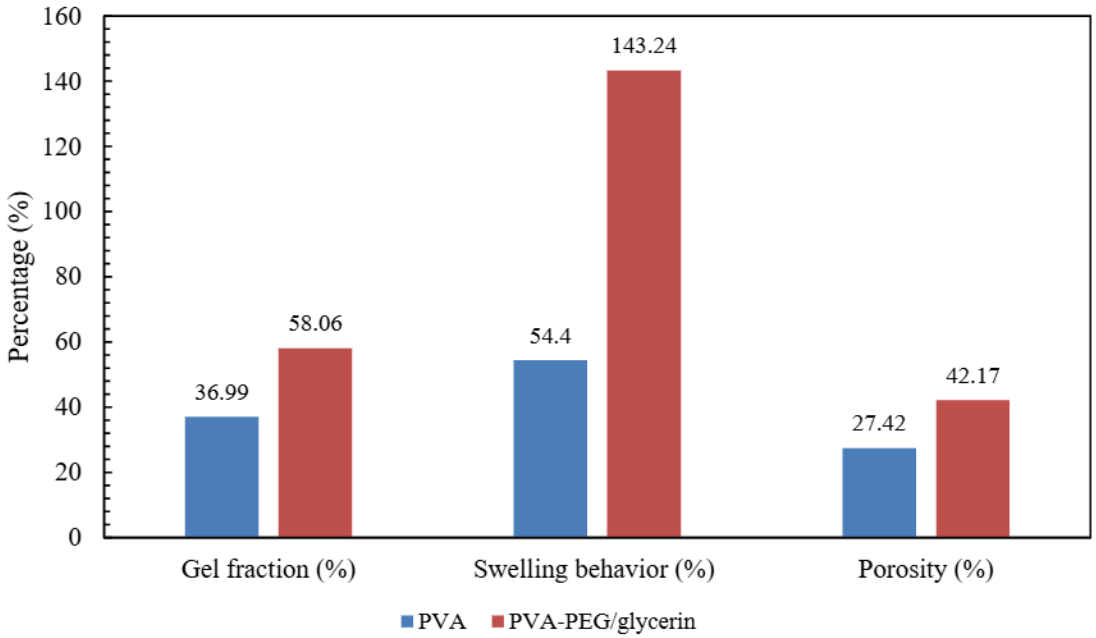

Fig. 2. Physical characterization of PVA hydrogel and PVA-PEG/glycerin hydrogel (a) gel fraction (GF); (b) swelling behavior; and (c) porosity.

3.5. FESEM Analysis

FESEM was employed to analyze the morphology of the hydrogels, as shown in Fig. 3. The surface characteristics varied significantly between the hydrogels due to compositional disparities. Notably, the PVA hydrogel exhibited a compact and non-porous structure, whereas the PVA-PEG/glycerin hydrogel displayed a more porous architecture. These observations are consistent with findings in existing literature [16, 20].

The porous structure observed on the surface of the PVA-PEG/glycerin hydrogel in Fig. 3, resulting from the inclusion of PEG and glycerin, can be attributed to their intrinsic hydrophilic properties and the hydrogel formation process. Both PEG and glycerin feature hydroxyl (-OH) groups in their molecular compositions, which exhibit a strong affinity for water. Upon integration into the PVA hydrogel matrix, these hydrophilic compounds readily interact with water molecules, facilitating absorption and retention. This increased water content prompts polymer chains to swell and separate, forming void spaces and a porous structure [12, 26].

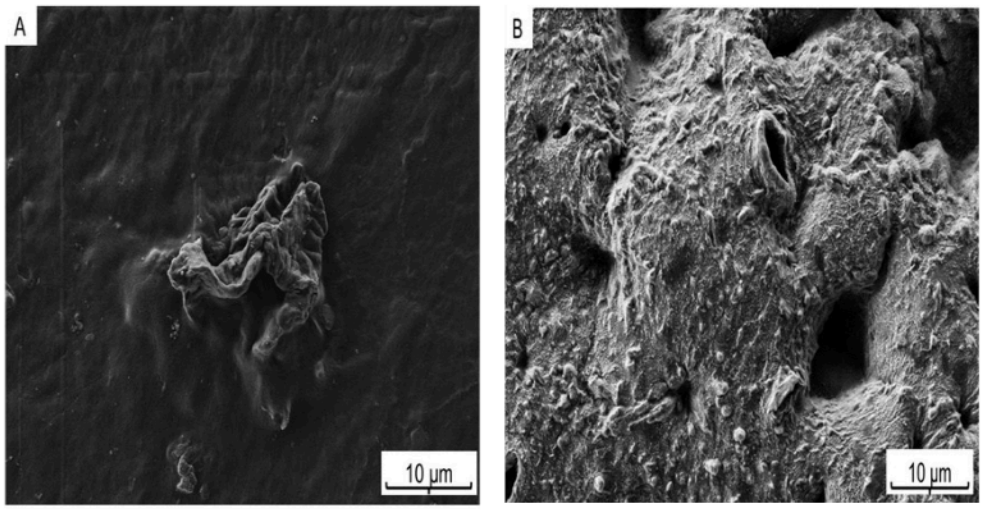

Fig. 3. FESEM images (a) PVA hydrogel and (b) PVA-PEG/glycerin hydrogel.

Additionally, the hydroxyl groups participate in cross-linking processes, promoting the formation of a more interconnected network characterized by numerous open channels on the hydrogel surface [8, 12, 27]. The surface irregularities observed on the PVA-PEG/glycerin hydrogel are a consequence of the freeze-thaw process, a common technique employed to improve hydrogel properties. During freezing, ice crystals form, displacing polymer chains and water molecules to specific regions. Upon thawing, polymer chains reorganize, and water redistributes, resulting in surface ripples and bumps [15, 28].

3.5. FTIR Analysis

Fig. 4 illustrates the FTIR spectra of composite hydrogels. Distinguishing between PVA hydrogel and the optimized PVA-PEG/glycerin hydrogel presents a challenge due to their similar Fourier Transform Infrared (FTIR) spectra. Notably, distinctive peaks at approximately 1438 cm^{-1} and 2916 cm^{-1} correspond to the stretching vibrations of -CH and CH_2, characteristic of the aliphatic PVA chain [8, 16, 24]. Peaks at 1600 cm^{-1} and 1800 cm^{-1}, attributed to C=O and C=C bonds, indicate contributions from both PVA and PEG components to the hydrogel structure. The broad band observed between 3200 cm^{-1} and 3400 cm^{-1} in the FTIR spectra indicates the presence of -OH (hydroxyl) groups in PVA, PEG, and glycerin, which are essential for hydrogen bonding interactions. These interactions contribute to the formation of hydrogels and their ability to retain moisture. The FTIR analysis confirms the formation of these hydrogen bonds, with characteristic absorption peaks corresponding to the -OH stretching vibration, supporting the presence of intermolecular interactions between the components of the hydrogel [20].

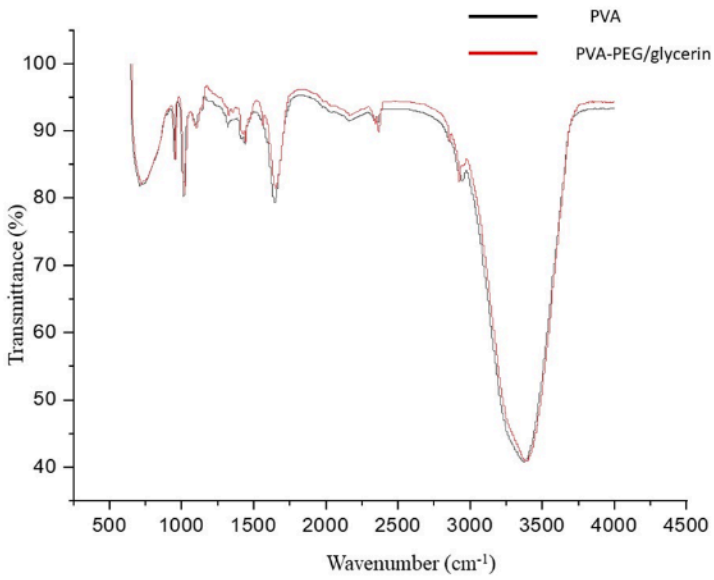

Fig 4. FTIR image of PVA hydrogel and optimized PVA-PEG/glycerin hydrogel.

Furthermore, the analysis of lower wavenumber peaks provides valuable insight into the molecular interactions within the hydrogel structure. The deformation vibrations in the 1430-1450 cm^{-1} region are characteristic of the C-H bonds from the -CH_2- group in the aliphatic PVA chain, indicating that the PVA maintains its structural integrity, with interactions between polymer chains contributing to flexibility and stability [29]. Additionally, vibrations in the 1100-1450 cm^{-1} range correspond to -OH bonds in both PVA and PEG, highlighting hydrogen bonding interactions crucial for forming a stable hydrogel network, which aids in water retention and enhances mechanical properties [29].

The FTIR spectra of the PVA-PEG/glycerin system show distinct peaks between 2916 and 2359 cm^{-1}, attributed to the stretching vibrations of C-H bonds from PEG and glycerin. These peaks are absent in the pure PVA hydrogel spectra, clearly indicating the successful incorporation of PEG and glycerin into the PVA matrix. Their presence suggests that PEG and glycerin interact with the PVA chains, likely enhancing the hydrogel's properties, including increased flexibility, improved water retention, and potentially better biocompatibility [8, 12].

While the FTIR spectra of PVA and the optimized PVA-PEG/glycerin hydrogels may appear similar, a detailed analysis reveals significant differences. These differences indicate the successful formation of the hydrogel and emphasize the role of PEG and glycerin in modifying its structure. The distinct peaks confirm that these additives significantly improve the hydrogel's performance, making it more robust and versatile. In conclusion, FTIR analysis confirms that PEG and glycerin alter the molecular structure of the hydrogel, enhancing its functionality, as supported by previous studies [8, 12].

3. CONCLUSION

In this study, a PVA-PEG/glycerin hydrogel was successfully synthesized using the freeze-thaw method. Through optimization studies, a composition of 6% (w/v) PEG and 4% (w/v) glycerin was determined to be optimal. The resulting hydrogel exhibited a swelling capacity of 143.24 ± 1.66%, a gel fraction of 58.06 ± 1.65%, and a porosity of 42.17 ±

0.94%. FESEM analysis revealed a porous hydrogel structure with a considerable number of pore spaces. FTIR spectra provided evidence of the successful formation of the PVA-PEG polymeric network, although explicit confirmation of cross-linking with glycerin was not observed. These findings highlight the optimized hydrogel's favorable properties, suggesting its suitability for various applications, particularly where high swelling and porosity are beneficial.

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