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# Hyaluronic Acid-Enriched Pectin-Based Hydrogel Films for Wound Healing

Ö. Zeynep Güner Yılmaz[1], F. Seniha Güner[1,2]

[1] Istanbul Technical University, Department of Chemical Engineering, Maslak 34469 Istanbul, Turkey
[2] Sabancı University Nanotechnology Research and Application Center (SUNUM), Tuzla 34956 Istanbul, Turkey

**Corresponding Author**: F. Seniha Güner, guners@itu.edu.tr; seniha.guner@sabanciuniv.edu

**Abstract:** Wound healing research is always looking for approaches to improve patient care. Advanced wound dressings are critical in this process. In this context, the article focuses on the comprehensive examination of the potential of hyaluronic acid-enriched pectin-based hydrogel films to advance wound healing. For comparative analysis, two formulations were prepared: a pectin matrix and a film containing fifty percent hyaluronic acid and pectin. Both formulations were cross-linked using calcium ions. The hydrogels underwent thorough characterization, including Fourier-transform infrared spectroscopy analysis for chemical composition, differential scanning calorimetry for thermal properties determination, and scanning electron microscope imaging for morphological examination of cross-sections. We thoroughly examine their fluid-handling capacities, dehydration rates, and water vapor permeability through meticulous inspection. These characteristics have a significant impact on elasticity, moisture retention, and overall effectiveness throughout the healing process. To demonstrate the transformative potential of HA-enriched pectin-based hydrogel films, we compare their properties to those of pectin hydrogel and a commercial alginate-based wound dressing. As a result, the investigation revealed a notable enhancement in the transparency of the wound dressing, a crucial factor for facilitating continuous monitoring of the wound site without necessitating frequent removal of the dressing. The improvement in water vapor permeability suggests an optimized moisture balance, fostering an environment conducive to efficient wound healing. Moreover, the smoother film contributes to the overall comfort for patients and potentially minimizes skin irritation and discomfort during prolonged wear. The innovative features identified in this study collectively point towards the prospect of these hydrogel films not only as effective wound dressings but also as a step forward in addressing the practical aspects of patient comfort and convenience.

**Keywords:** Pectin, Hyaluronic acid, Hydrogel, Wound treatment

# Yara İyileşmesi için Hiyalüronik Asitle Zenginleştirilmiş Pektin Temelli Hidrojel Filmler

**Özet:** Yara iyileşmesi araştırmaları her zaman hasta bakımını iyileştirecek yaklaşımlar arar. Gelişmiş yara örtüleri bu süreçte kritik öneme sahiptir. Bu bağlamda makale, hiyalüronik asit ile zenginleştirilmiş pektin bazlı hidrojel filmlerin yara iyileşmesi sürecini hızlandırma potansiyelinin kapsamlı bir şekilde incelenmesine odaklanmaktadır. Karşılaştırmalı analiz için iki formülasyon hazırlanmıştır: pektin matrisi ve yüzde elli hiyalüronik asit ve pektin içeren bir film. Her iki formülasyon da kalsiyum iyonları kullanılarak çapraz bağlanmıştır. Hidrojeller, kimyasal bileşim için Fourier dönüşümü kızılötesi spektroskopi analizi, termal özelliklerin belirlenmesi için diferansiyel taramalı kalorimetre ve kesitlerin morfolojik incelemesi için taramalı elektron mikroskobu görüntüleme dahil olmak üzere kapsamlı bir karakterizasyona tabi tutulmuştur. Ayrıca sıvı taşıma kapasitelerini, dehidrasyon oranlarını ve su buharı geçirgenliği incelenmiştir. Bu özellikler iyileşme süreci boyunca elastikiyeti, nem tutmayı ve genel etkinliği önemli ölçüde etkiler. Hiyalüronik asit ile zenginleştirilmiş pektin bazlı hidrojel filmlerin potansiyelini göstermek için, pektin hidrojelin yanında ticari aljinat bazlı yara örtüsüyle karşılaştırılmıştır. Sonuç olarak araştırma, yara örtüsünün şeffaflığında gözle görülür bir artış olduğunu ortaya çıkarmıştır; bu, yara örtüsünün sık sık değiştirilmesini gerektirmeden yara bölgesinin sürekli takibini kolaylaştırmak için çok önemli bir faktördür. Su buharı geçirgenliğindeki iyileşme, optimize edilmiş bir nem dengesine işaret ederek etkili yara iyileşmesine olanak sağlayan bir ortam sağlamaktadır. Dahası, katkı ile daha pürüzsüz olan film hastalar için genel konfora katkıda bulunur ve uzun süreli kullanım sırasında cilt tahrişini ve rahatsızlığını potansiyel olarak en aza indirir. Bu araştırmada belirlenen özellikler, sadece etkili bir yara bandı olmanın ötesinde, aynı zamanda hasta konforu ve kullanım kolaylığına yönelik pratik gelişmeleri ele alarak bir adım öteye taşıyabilir.

**Anahtar Kelimeler:** Pektin, Hiyalüronik asit, Hidrojel, Yara tedavisi

**RESEARCH PAPER**

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## 1. Introduction

Wound healing represents a fundamental and ever-evolving piece of medical research and healthcare, continually striving to enhance the recovery process and elevate patient care. A pivotal component in this domain is the development of advanced wound dressings, which play a crucial role in shaping the trajectory of wound healing. In the existing literature, extensive research has been carried out on hydrogel-based wound dressings, utilizing materials that encompass both synthetic polymers and biopolymers (Chauhan et al., 2022; Divyashri et al., 2022). Among the diverse array of hydrogel wound dressing materials, pectin, a natural polysaccharide, has risen to prominence for its remarkable properties. Pectin-based wound dressings have garnered considerable attention due to their inherent biocompatibility, moisture-retention characteristics, and flexibility. Within the spectrum of wound care, pectin-based hydrogel wound dressings offer a versatile platform, welcoming various additive materials to enhance their performance (Güner et al., 2021; Kumar et al., 2013; S. Bin Wang et al., 2004). The incorporation of diverse additives has led to the development of innovative wound dressings that are tailored to specific clinical needs.

One of the notable additives in this context is hyaluronic acid (HA), which has emerged as a frontrunner for its distinctive properties and compatibility with wound dressing materials (Mero & Campisi, 2014). HA, a naturally occurring biopolymer, is renowned for its ability to bind with water molecules, thereby maintaining an optimal moisture balance—a crucial factor in wound healing (Liao et al., 2018; Price et al., 2005). Its unique molecular structure makes it an ideal candidate for integration into wound dressings, where the preservation of a moist wound environment is imperative. Numerous studies conducted over the years have consistently underscored the advantages of HA-enriched wound dressings such as chitosan, gelatin, alginate, pectin, or a combination of two or more (Bozer et al., 2023; Tarusha et al., 2018; Yang et al., 2019; Zhou et al., 2014) . These findings underscore HA's potential as a key component in innovative wound dressings tailored to meet diverse clinical needs.

In this context, this article focuses on the comprehensive investigation of HA-enriched pectin-based hydrogel films and their potential to advance wound healing. In contrast to the commonly used inter-chain cross-linking method in the literature, we adopted a simpler film preparation process that did not involve cross-linking the chains. Through a rigorous examination of their mechanical attributes, fluid-handling capabilities, dehydration rates, and water vapor permeability, this study seeks to evaluate their suitability for wound healing applications. This study embarks on a comprehensive exploration and evaluation of HA-enriched pectin hydrogel films as prospective wound dressings. The inquiry encompasses an array of critical parameters, spanning mechanical attributes, fluid-handling capacity, dehydration kinetics, and water vapor permeability. The study covers a wide range of critical factors, all of which have a significant impact on the pliability and capacity of wound dressings to maintain an optimal moisture environment during the healing process.

## 2. Materials and Methods

### 2.1. Chemicals

41% amidated low-methoxy citrus pectin provided by Herbstreith & Fox KG (Neuenbürg, Germany) was used as the polymer matrix. Hyaluronic acid (HA) with a molecular weight of 3000-5000 was provided from HD Uluslararası Ticaret ve Ambalaj Sanayi Ltd. Sti. (Kocaeli, Turkey). In addition, glycerol (Labkim, Istanbul, Turkey) was used as a plasticizer. The calcium chloride used as a crosslinker was in analytical purity. The structure of pectin and HA are given in Figure 1.

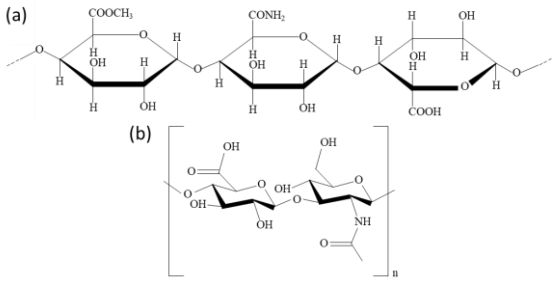


Figure 1. Chemical structure of (a) low-methoxy amidated pectin, (b) hyaluronic acid.

### 2.2. Preparation of hydrogels

Hyaluronic acid-loaded hydrogels were prepared with a similar method used in our previous studies (Güner et al., 2018, 2021). The experimental procedure to prepare hydrogels is shown in Figure 2. In brief, pectin and HA were dissolved in ultrapure water at 1% w.w$^{-1}$, then 15 mL of each solution was mixed. Then glycerol solution (5% w.w$^{-1}$) was added and mechanically stirred at 150 rpm for 2 h. After preparing a homogeneous mixture, %0.7 $CaCl_2$ solution (10 mL) is added to a Petri plate to form a crosslinked hydrogel (Pe-HA). The hydrogel is left to dry in an orbital shaker at 25°C. As a comparison, a pectin hydrogel (Pe) is prepared with pectin, glycerol, and $CaCl_2$ without the hyaluronic acid addition.

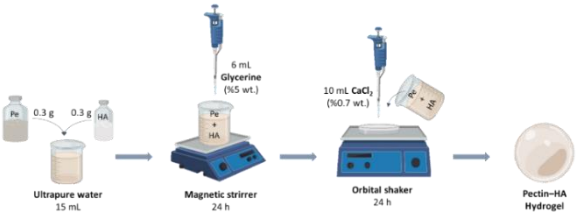


Figure 2. Preparation of hyaluronic acid-pectin hydrogel.

### 2.3. Characterization of hydrogels

Fourier-transform infrared (FT-IR) spectroscopy analysis was performed on a Perkin Elmer Spectrum 100 spectrometer model between 650 and 4000 cm$^{-1}$ using the ATR mode.

Thermal properties of the hydrogels were determined with a Perkin Elmer 4000 differential scanning calorimeter (DSC) under a nitrogen atmosphere. Analyzes were performed between -50 and 300°C with a scan rate of 10°C/min.

Scanning electron microscope (SEM) images of cross-sections of hydrogel samples were produced for morphological examination using Jeol JSM-6390LV. Samples were fractured in liquid nitrogen and then coated with platinum using a sputter coater.

### 2.4. Swelling behavior of hydrogels

The evaluation of the hydrogel films' swelling behavior involved a systematic procedure. Initially, dried samples were cut to a 10 mm diameter each, and their weights were recorded as $W_1$. Subsequently, these samples were immersed in a 10 mL buffer solution, and data points were collected at different time intervals. After removal from the buffer solution, excess water was efficiently absorbed using filter paper, followed by weighing the samples denoted as $W_2$. The swelling ratio of the hydrogels was then accurately calculated utilizing Equation 1.

$$\text{Swelling} = \frac{W_2 - W_1}{W_1} \quad (1)$$

### 2.5. Wound dressing properties of hydrogels

To obtain information about the behavior of the prepared hydrogels in the wound environment, the wound dressing properties were examined under in vitro conditions.

The Shore A hardness of the samples was determined with a durometer according to ASTM D2240. The Shore A hardness scale measures the hardness of flexible rubbers and semi-rigid plastics (American Society for Testing and Materials, 2015).

The flexibility of the samples was measured according to the ASTM-D-522 standard with an Erichsen Model 266S bending tester with 14 stainless steel cylinders from 2 to 32 mm in diameter (Methods, 2001). The test determines the smallest cylinder diameter at which a sample does not show cracking after bending.

BS EN 13726-1:2002 standard was used to determine the fluid handling of the samples (Updated et al., 2016). Briefly, a hydrogel film was cut into a 5 cm × 5 cm square, weighed ($W_{D1}$), and placed in a Petri dish. Then, a salt solution prepared by adding 2.298 g NaCl and 0.368 g $CaCl_2.2H_2O$ in 1 L of deionized water was heated to 37±1°C and added to the Petri dish at a ratio of 1:40 (wt.volume$^{-1}$). The Petri dish was placed in the incubator at 37±1°C for 30 minutes and then removed from the incubator. The hydrogel was held in one corner using tweezers and allowed to drip off excess water for 30 seconds. The hydrogel was reweighed to calculate the mass of the solution absorbed by the hydrogel (Ww). Equation 2 was used to calculate the fluid handling.

$$\text{Fluid handling} = \frac{W_w - W_{D1}}{W_{D1}} \quad (2)$$

To determine the in vitro dehydration rate, the sample (5 cm x 5 cm) was first dried at 37±1°C for 24 hours. Then, it was kept in deionized water at 37±1°C, taken out of the water after 30 minutes, held from one corner with tweezers for 30 seconds to remove excess water, and weighed again ($W_W$). The sample was then dried again at 37±1°C for 24 hours (T = 1440 min) and weighed ($W_{D2}$). The dehydration rate was calculated according to Equation 3.

$$\text{Dehydration Rate (g.min}^{-1}) = \frac{W_w - W_{D2}}{T} \quad (3)$$

The water vapor permeability of the synthesized samples was determined according to ASTM E96-00 standards (Conshohocken, 1996). For this purpose, the sample was cut with a round mold with an area (a) of 3.14 cm$^2$, masked with aluminum foil, and glued to the mouth of sample containers filled with silica. The sample container was weighed ($W_1$) and placed in a desiccator containing saturated NaCl solution. It was reweighed ($W_2$) at regular intervals from the beginning on a daily basis, and water vapor permeability was calculated according to Equation 4. Simultaneously, the corresponding day of each measurement from the start was recorded (T).

$$\text{Water Vapor Permeability (g.m}^{-2}\text{day}^{-1}) = \frac{W_2 - W_1}{a \,.\, W_1 \,.\, T} \quad (4)$$

The average mass per unit area (g.m$^{-2}$) of hydrogels was determined according to the BS EN 12127:1997 standard (BS EN 12127:1997). The dry sample was cut into 5 cm x 5 cm dimensions, weighed and the resulting value was divided by area.

The water contact angle was measured using a Biolink Scientific Attension Theta Flex goniometer at room temperature by placing 4 µL of distilled water on the hydrogel surface using the sessile drop method.

Additionally, the change in the transparency of the film by adding HA to the matrix was examined. For this purpose, the transparency test was carried out using a UV-Vis spectrophotometer (LAMBDA 1050) as in the literature (Andriotis et al., 2020; Farahnaky et al., 2018; Martucci & Ruseckaite, 2010). The films were cut into a rectangular shape and placed on the outside of the spectrophotometer cell, and measurements were made at 550 nm, which is the wavelength at which the human eye perceives colors. transparency was calculated using Equation 5, where A is the absorbance.

$$\text{Transparency} = 10^{(2-A)} \quad (5)$$

The dispersion properties of wound dressings are an indicator of their mechanical strength when interacting with fluid during wound healing. Therefore, the dispersion property of the sample was measured according to the BS EN 13726-2:2001 standard (Updated et al., 2016). A 5 cm x 5 cm sample was cut from the hydrogel and placed in a 250 ml conical flask. To determine the liquid holding capacity, 50 mL of the prepared salt solution (NaCl and $CaCl_2.2H_2O$) was added and rotated gently for 60 seconds so as not to create a vortex. The integrity of the hydrogel was then visually categorized as “dispersible” or “non-dispersible”.

## 3. Results and Discussion

In this section, we discuss the key findings from our in vitro characterization studies on the prepared hydrogels and their wound dressing properties. The results shed light on the potential of these hydrogels for wound healing applications.

### 3.1. Characterization of Hydrogel Structure

The FT-IR spectra of the hydrogels are presented in Figure 3. Spectrum analysis revealed the incorporation of HA into Pe film, as evidenced by the characteristic peaks of HA (de Oliveira et al., 2017; Grkovic et al., 2015) and Pe film in Pe-HA film, indicating a high degree of compatibility between the two components. Specifically, the C-O-C (1094 $cm^{-1}$), sp3 C-H (1420 $cm^{-1}$), and N-H (1619 $cm^{-1}$) peaks are observed in HA, Pe, and Pe-HA. In conjunction with these, the O-H peak (3200-2900 $cm^{-1}$), primarily arising from the carboxylic acid in Pe, and the C-H aliphatic stretching band (2900 and 2800 $cm^{-1}$) are specific to Pe and Pe-HA.

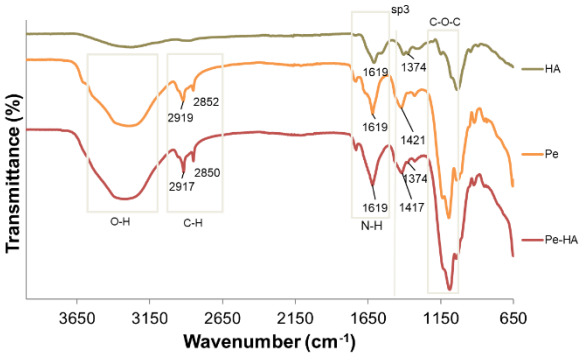


Figure 3. FT-IR Spectra of HA, Pe, and HA-Pe.

DSC analysis provides insights into the thermal characteristics of HA and Pe-HA hydrogels. (Figure 4) The glass transition temperatures ($T_g$) of Pe, and HA-Pe were found to be 40.1, and 38.6°C, respectively. Additionally, the significant sharp exothermic peak suggested that a thermal degradation occurred at around 226 °C for HA and 240 °C for Pe-HA (Kafedjiiski et al., 2007). Modification of HA by pectin caused the exothermic peak to shift to higher decomposition temperatures compared to HA. The difference is about 14 °C. On the other hand, an endothermic peak was observed in the DSC curve of pectin indicating the presence of water, hydrogen bonding among the galacturonic acid units, and conformational changes of the galacturonan ring (Taufiq & Saiffullah, 2019; W. Wang et al., 2016).

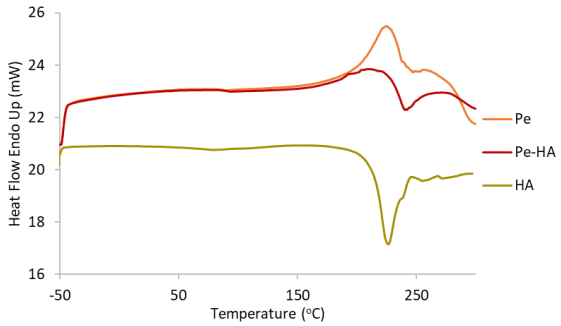


Figure 4. DSC curves of Pe, HA, and Pe-HA

For morphological analysis, images of cross-sections of hydrogel samples were obtained using SEM. According to SEM images given in Figure 5, it was determined that the pectin film structure became smoother with the addition of HA. This is an indication that HA-Pe hydrogels will create a more comfortable environment when placed on the wound, which is a crucial feature for wound healing applications.

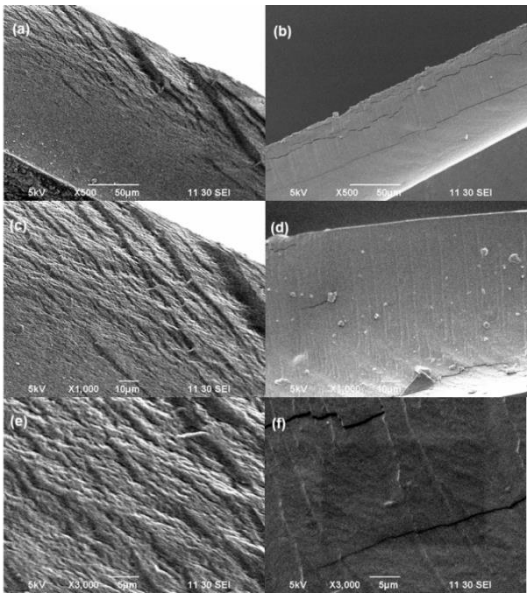


Figure 5. SEM images at different magnifications: (a, c, and d) Pe and (b, d, and f) HA-Pe.

### 3.2. Wound Dressing Properties of Hydrogels

The pH of a wound environment plays a crucial role in the healing process. It is well accepted that as a wound heals, the pH of the wound milieu falls. Our study investigated the swelling behavior of Pe-HA hydrogels at pH levels of 4.6, 6.4, and 8.0 within the initial 24 hours. The data shown in Figure 6 show that the swelling of both samples increases in time as expected. Furthermore, the addition of HA improves the hydrogels' ability to retain water at pH 4.6 and pH 6.4. The ionization of -COOH groups in pectin(Gałkowska et al., 2003) and hyaluronic acid within the release medium promotes polymer swelling, driven by osmotic pressure until an equilibrium is reached. Given the gradual decrease in wound pH during healing, these findings highlight the suitability of HA-Pe hydrogels for maintaining an optimal moist wound environment.

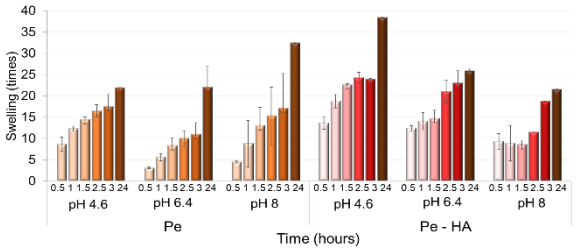


Figure 6. Swelling behavior of Pe and Pe-HA films at pH 4.6, 6.4, and 8.

Due to the hyaluronic acid addition, the pectin hydrogel's contact angle increased by 30 degrees (Figure 7), indicating a considerable increase in surface hydrophobicity. Pectin hydrogels, when enhanced with hyaluronic acid, exhibit a significant increase in contact angle, indicating improved surface hydrophobicity. In the context of wound dressings, this heightened hydrophobicity can help to repel excess

moisture, maintaining the vital moist environment required for effective wound healing.

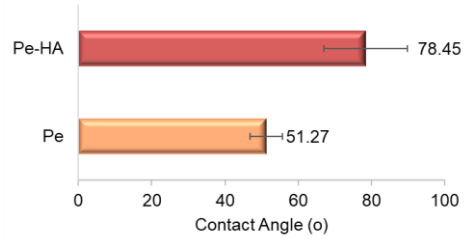


Figure 7. Water contact angle measurements of Pe and Pe-HA.

In the context of wound dressings, some properties of the hydrogels are given in Table 3. The Shore A hardness values may be an indication of protecting the wound against external physical forces. The Shore A value for Pe-HA is approximately twice that of Pe. A higher Shore A value, such as in Pe-HA, indicates greater rigidity, making it suitable for wound dressings that require structural support and stability, which could be essential for wounds needing protection. Conversely, the lower Shore A value of PE suggests increased flexibility, which can be advantageous in dressings designed for areas where adaptability and comfort are prioritized, like sensitive or curved body contours. This flexibility may enhance patient comfort during the healing process. Therefore, the choice between Pe-HA and Pe for wound dressings should depend on the specific requirements of the wound and the level of support and comfort needed.

The results of various experiments demonstrating the performance of wound dressings are presented in Table 3. In this context, a comparison is made with Kaltostat, a commercially available alginate-based wound dressing widely used for wound care. There is a wide variety of wound dressing matrices available. Due to Kaltostat being alginate-based, our film, which is pectin-based and shares a mirrored chemical structure in terms of carbohydrate composition, is selected for comparison in this study. This choice is made to provide a suitable basis for comparison due to the chemical similarities between the two materials.

Table 3. Wound dressing performance of hydrogels.

| Sample Code | Shore A Hardness | Flexibility[b] (mm) | Fluid Handling ($g.g^{-1}$) | Dehydration Rate x 103 ($g.min^{-1}$) | Mass per Unit Area ($g.m^{-2}$) | Transparency | Dispersion |
|---|---|---|---|---|---|---|---|
| Pe | 52 | 2 | 5.06±0.0 | 5.7 | 269.54±29.97 | 16.06 | Non-Dispersible |
| Pe-HA | 96 | 2 | 5.17±1.4 | 3.8 | 354.41±0.94 | 30.53 | Non-Dispersible |
| Kaltostat[a] | - | - | 18.44±1.3 | 350 | 148±4.2 | - | Dispersible |

[a] from reference (Uzun et al., 2013)
[b] the smallest diameter of the cylinder which caused no crack on the film.

The testing method used to determine the flexibility of polymer coating materials was adapted to hydrogels in our study. For this purpose, the pectin hydrogel was first fixed to a rectangular tin plate and rolled on the plate test device to observe whether there were any cracks. The diameter of the smallest cylinder that did not cause cracking in the film was determined. Since both films did not crack after bending with the smallest diameter (2 mm) roller, they were determined to be quite flexible according to the applied test (Table 3). In summary, Pe and Pe-HA are quite flexible for a wound dressing application. These results are an indication that Pe-HA hydrogel films can be used easily during wound healing applications.

The absorbencies (liquid retention amount) of Pe and Pe-HA are given in Table 3, together with the absorbance of Kaltostat. Pe and Pe-HA retained liquid almost five times their dry mass. Their fluid retention capacity is approximately four times lower than that of Kaltostat. On the other hand, typical wound dressings show only 2.3% water absorption. Therefore, the liquid retention capacities of pectin and HA-based hydrogels are acceptable for wound dressing applications.

The rate of dehydration is an indicator of the formation of a moist wound environment along with its fluid retention capacity. As shown in Table 3, the dehydration rate of Pe was found to be 58 times lower than that of the commercial product, and that of Pe-HA was 60 times lower. As mentioned in the previous paragraph, Kaltostat adsorbed four times more liquid than pectin-based hydrogels. This means that Kaltostat adsorbs much more liquid than Pe and Pe-HA films, but also loses much more water by evaporation. Considering the dehydration rate and liquid retention capacity of the samples together, it is predicted that our Pe-HA films will provide a more humid environment than Kaltostat, which is an advantage for wound healing.

While water loss from healthy skin is approximately 204±12 $g.m^{-2}.day^{-1}$, in injured skin, such as first-degree burns, this value varies between 279±26 and 5138±202 $g.m^{-2}.day^{-1}$ (Balakrishnan et al., 2005). An ideal wound dressing should keep water at an optimum level. It should keep the wound environment moist and prevent the removal of large amounts of water from the environment.

When Figure 8 is examined, it is seen that there is no significant change in water vapor permeability with the addition of HA to the matrix. The average water vapor permeability of 6 days for pectin was calculated as approximately 175 $g.m^{-2}.day^{-1}$, and for Pe-HA it was approximately 159 $g.m^{-2}.day^{-1}$. Notably, these values closely resemble the water vapor permeability of healthy skin. This finding underscores the potential of HA-Pe hydrogel films as

promising candidates for applications where maintaining an ideal moisture balance is crucial, such as wound healing and skin care.

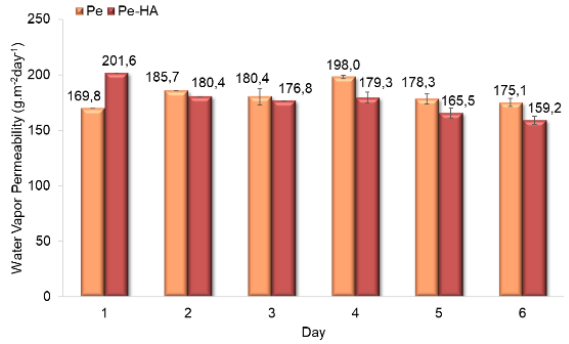


Figure 8. Average water vapor permeability of Pe and Pe-HA for 6 days.

As a result of adding HA to the Pe film, the average mass per unit area increased in Pe-HA films (Table 3). This change is notable in terms of thickness; while the average thickness for Pe is 0.13 mm, it increases to 0.16 mm for Pe-HA.

Film transparency is generally affected by additives in films, processing conditions, thickness, and compatibility between components. Transparency values of 16.06 for Pe and 30.53 for Pe-HA were reached (Table 3). According to these results, the transparency value increased as expected with the addition of HA. The increase in the weight per unit area for Pe-HA is also a reason for the increase in transparency in the film.

It was observed that Pe and Pe-HA did not disperse in the salt solution (Table 3). On the other hand, it is reported in the literature that the Kaltostat dressing completely disintegrates. One of the most studied topics is increasing the mechanical strength of wound dressings. For example, the mechanical properties of alginate-based dressing hydrogels increased with the addition of chitosan for infected chronic wounds and diabetic foot ulcers, as observed by Kurhade et.al (Kurhade et al., 2013) According to the results obtained, the synthesized hydrogel dressings (Pe and Pe-HA) had visual and mechanical properties under test conditions. Figure 9 provides visual information about the transparency of the films, and it was observed that the film's integrity was not damaged. This feature will provide a great advantage when removing the prepared hydrogels from the wound.

## Conclusion

This study indicates the substantial potential for wound dressing applications of pectin-based hydrogel films supplemented with hyaluronic acid. The data suggest that these hydrogel films can be used effectively during wound therapy. The study's findings show that Pe-HA hydrogels have great flexibility, enough water absorption capacity, and a significant advantage in maintaining the moisture balance surrounding wounds. Furthermore, the water vapor permeability of these films is comparable to that of healthy skin. These outcomes propose that Pe-HA hydrogel films hold promise for applications in wound treatment, skincare, and related fields. To conclude, hyaluronic acid-enriched pectin hydrogel films may offer a promising option in the field of wound treatment.

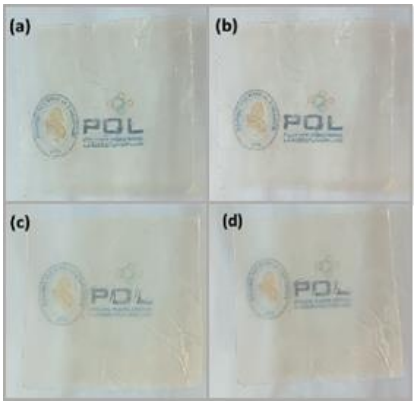


Figure 9. Photographs showing the dispersion properties of the prepared hydrogels: (a) Pe dry, (b) Pe wet, (c) Pe-HA dry, (d) Pe-HA wet.

## Conflict of Interest

The authors declare that they have no conflicts of interest with respect to the research, authorship, and publication of this paper.

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