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Synthesis and Characterisation of Polyvinyl pyrrolidone/polyacrylamide (PVP/PAAm) Hydrogels via Hybrid Process: Morphological and Physical Properties, and Antibacterial Activity

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Research Article

Abstract − Hydrogels are three-dimensional networks that constitute either chemical or physical crosslinks. Hydrogels have been used in a variety of applications from biomedical and tissue engineering to wastewater treatment, and robotics. In recent years, many studies have shown that hydrogels are suitable for wound treatment in many respects. While hydrogels keep the wound warm, moist, and closed, the bioactive agents in their composition have an antibacterial activity. Terpenes and terpenoids are natural-based materials which have been reported to have potent antibacterial activity against different pathogens. However, poor solubility, sensitivity to external conditions, and volatility properties of them restrict them use as a wound healing agent. For this purpose, terpenes and terpenoids can be loaded into carrier matris such as hydrogels and they used as a wound dressing. In this study, the preparation of polyvinyl pyrrolidone/polyacrylamide (PVP/PAAm) hydrogels exhibiting antibacterial properties was demonstrated. Bio-derived terpenes and terpenoid (α-bisabolol, d-limonene, and geraniol) were utilized as antibacterial agents, whereas stabilization of PVP/PAAm hydrogels was achieved by using beta-cyclodextrin (β-CD). PVP/PAAm polyblend solutions were polymerized via UV irradiation (photopolymerization). Then freeze-thawing and anneal-swelling were respectively carried out. Once the morphological, and physical properties of the resulting hydrogels were characterized antibacterial efficiency tests were also performed. In the end, it was demonstrated that PVP/PAAm/α-bisabolol and PVP/PAAm/geraniol hydrogels have good antibacterial properties against *Escherichia coli* with 9 mm zone inhibition.

Keywords − *Antibacterial efficiency, freeze-thawing, PVP/PAAm hydrogel, terpene and terpenoids, UV irradiation*

1. Introduction

Hydrogels are crosslinked hydrophilic polymer chains that retain water without dissolving (Okay, 2020; Dafader et al., 2012). Hydrogels with antibacterial properties have been intensively studied due to the advantages of high swelling ratio, biocompatibility properties, and porous morphology, as well. (Luthfianti et al., 2023; Qureshi et al., 2023; Gavini et al., 2016; Chang et al., 2013; Tang et al., 2013). In the last decade, hydrogels with antibacterial property are attracting interest especially in biomedical applications (Yang et al., 2018). Hydrogels can be developed by adjusting the pore morphology, swelling rate, wettability and antibacterial activity using the appropriate combination of monomers, antibacterial agents and other additives (Li et al., 2018). Recent studies are aimed at producing hydrogels containing new bioactive chemicals from natural sources (Ribeiro et al., 2017).

Terpenes (limonene, bisabolol, terpinene) are basic hydrocarbon compounds, whereas terpenoids (oxygen-containing hydrocarbons) are a specialized family of terpenes with reactive groups (Masyita et al., 2022; Per-

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veen and Al-Taweel 2018). Terpenes and terpenoids have been widely investigated and shown to serve significant functions in human health. It has been suggested that terpenes exhibit antibacterial properties against both antibiotic-sensitive and antibiotic-resistant bacteria, usually by enabling cell rupture and inhibiting protein and DNA synthesis (Álvarez-Martínez et al., 2021). Terpenoids (geraniol, linalool, thymol, and menthol) have also been implicated in resistance to disease as part of the secondary metabolites generated by aromatic and therapeutic plants (Burt, 2004). Some difficulties restrict them by being employed in medical applications. Due to the hydrophobic structure of terpenes and terpenoids, it is necessary to dissolve homogeneously in hydrophilic polymer solutions and then form stable emulsions without causing instability problems such as phase separation (Cahyana et al., 2022). Further, terpenes and terpenoids are too volatile, result in considerable loss bioactivity during administration. Therefore, efforts to improve the stability of terpenes and terpenoids in hydrogels can help to protect them.

Pickering emulsion is a novel way for stabilizing emulsions with solid substances instead of surfactants (Mao et al., 2018). Many inorganic materials such as clay, ZnO, SiO_2, and TiO_2, were employed in the experiments; but, in recent years, organic materials such as modified chitosan protein, and cellulose have also been utilized to enhance biocompatibility (Hu et al., 2018). In this regard, carbohydrate-based β-cyclodextrin (β-CD), which is a lattice molecule with a hydrophilic outer surface and a hydrophobic inner cavity, can be used as a Pickering emulsifier (Li et al., 2022). It is dissolved in water and can capture many hydrophobic groups such as terpenes and/or terpenoids in its inner cavity as a guest molecule due to the existence of many hydroxyl groups on its outer surface. This remarkable β-CD structure enables these active molecules (terpenes and terpenoids) to be used in encapsulation, controlled drug delivery and many medical applications by enhancing their bioactivity.

Polyvinyl pyrrolidone (PVP) is a hydrophilic, non-toxic, biocompatible, and biodegradable synthetic-based polymer. PVP can be easily blended effectively with other polymers and used for synthesis of IPN or semi-IPN hydrogels via crosslinking (Panahi et al., 2021; Evingür et al., 2014; Roy and Saha, 2012; Djefal-Kerrar et al., 2011). Additionally, PVP contains planar and highly polar side groups owing to the link of in the lactam ring (Sheik et al., 2018; Huang et al., 2017). Nevertheless, the usage of neat PVP hydrogels is restricted due to their low liquid absorption ability and low mechanical properties (Roy et al., 2010). To solve this issue, PVP is combined with various polysaccharides or other polymers according to the needs and uses. In general, hydrogels are produced by adding crosslinking into the polymer matrix. PVP hydrogels can be crosslinked via freeze-thawing, γ-irradiation, thermal treatment and also UV crosslinking (Roy and Saha, 2012). Polyacrylamide hydrogels are also synthesized for various applications using free radical polymerization in which happens in hydrophilic monomer solutions. Previously, the fabrication of PVP and PVP/PAAm hydrogels for different uses, particularly in dye removal, tissue scaffolds, drug release systems, and wound dressings, was reported (Lopérgolo et al., 2003). Poly (PVP/acrylamide/glycerol/bentonite clay) hydrogel films were synthesized via gamma radiation (Gad et al., 2021). In another study, aloe vera juice and vitamin C loaded PVP hydrogels have been produced by photopolymerization for biomedical purposes (Kędzierska et al., 2022). Nanocomposite hydrogels based-acrylamide-polyvinyl pyrrolidone containing metal oxide (CuO and ZnO) synthesized by Owonubi et al. (2021). The developed hydrogels with good antibacterial properties were found to be potential in a topical wound dressing.

In the present study, antibacterial PVP/PAAm hydrogels were synthesized by UV crosslinking and freeze-thawing processes. Apart from the previous studies, antibacterial property of the resulting hydrogels were achieved by using bio-derived terpene and terpenoids. In this respect, for the first time in the literature α-bisabolol, d-limonene, and geraniol were used as model antibacterial agents in the preparation of PVP/PAAm hydrogels. Moreoever, β-CD was used for the stabilization during hydrogel preparation and it was also served as a lattice molecule for α-bisabolol, d-limonene, and geraniol. The physical properties and antibacterial efficiency were examined methodically in respect to different active agent. It was demonstrated that the resulting PVP/PAAm based hydrogels would be promising candidates for wound healing applications.

2. Materials and Method

2.1. Materials

Polyvinyl pyrrolidone (PVP) (K-30) and acrylamide (AAm) were kindly donated by Veskim Chemical Company (Istanbul, Turkey). Polyethylene glycol (diacrylate) (PEGDA) (87.8%, Mw~30.000 g/mol) and 2,2-Dimethoxy-2-phenyl acetophenone (DMPA, 99%, Sigma Aldrich Chemie GmbH, Steinheim, Germany) were used as received. β-cyclodextrin cyclodextrin (β-CD) (Cavamax W7 HP Pharma) was donated by Wacker Chemie (Germany). Bisabolol (~ 98%) was purchased from Tatlı Dilimler Naturel Soap and Cosmetic Feedstocks (Antalya, Turkey). d-Limonene (92-98%, Alfasol, Spain) and geraniol (technical grade) were kindly donated by Elso Chemical Industry and Trade Inc. (Istanbul, Turkey). All chemicals were used as received. In all experiments, distilled water was used.

2.2. Synthesis of PVP/PAAm Hydrogels

PVP powders were dissolved in distilled water to obtain 20% (w/v) PVP solutions at room conditions. PEGDA (10%, v/v) and AAm (10%, w/v) were then added to the PVP solution, respectively. Afterwards, photoinitiator (1%, w/v) and β-CD (2% w/v) was mixed with the solution. To obtain a homogenous solution, the mixture was mixed with ultrasonic homogenization for 10 min (50% power). Afterwards, to obtain an emulsion bio-derived antibacterial agent (geraniol, d-limonene or α-bisabolol) was added dropwise, while the ratio of β-CD : the antibacterial agent was set to 1:1. Then the resulting emulsions was cured via UV irradiation (300 W, 20 cm distance) for 30 minutes to achieve crosslinking. In the end, obtained hydrogels were frozen at -20 °C for 18 hours before thawing at 30 °C for two cycles. To obtain anneal-swelled hydrogels, the resulting materials were first dried at 80 °C for 2 hours. Consequently, all hydrogels were immersed in distilled water at 25 °C until they attained a constant weight.

Pure PVP/PAAm hydrogel was also synthesized to utilize as a control sample. With this aim, the above-described synthetic procedure was implemented, without adding an antibacterial agent. All synthesized samples were kept in a desiccator until material characterization. The pure hydrogel was named PPA. Hydrogels prepared by using antibacterial agents were named PPAB, PPAL, and PPAG, where B, L, and G respectively stand for bisabolol, limonene, and geraniol. A schematic illustration of hydrogel preparation is presented in Figure 1. Moreover, the chemical structures of α-bisabolol, d-limonene, and geraniol are given in Figure 2.

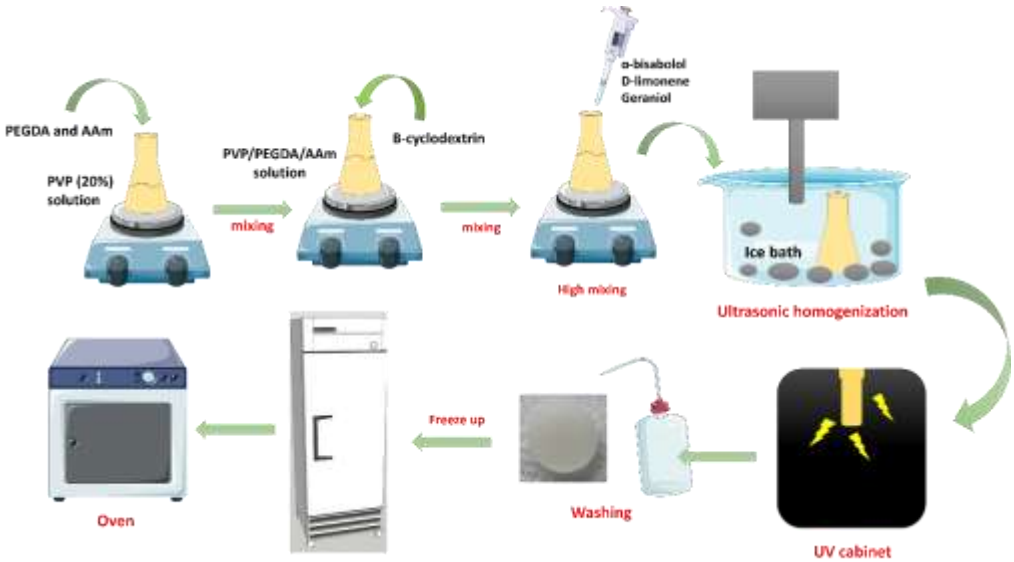

Figure 1. Schematic illustration of hydrogel preparation

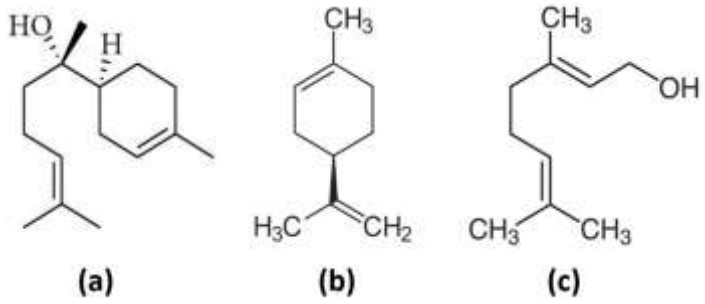

Figure 2. Schematic illustration of antibacterial ingredients (a) α-bisabolol, (b) d-limonene, and (c) geraniol

2.3. Characterisation

2.3.1. Scanning Electron Microscopy (SEM)

To examine the surface morphology of hydrogels, Carl Zeiss/Gemini 300 Field Emission Scanning Electron Microscope (FE-SEM) (ZEISS, Germany) was used. Prior to analysis all hydrogels were gold-coated. Both cross-sectional and surface images were taken at certain magnifications (2 kX and 10 kX).

2.3.2. Fourier Transform Infrared Spectroscopy (FT-IR)

The chemical structures of the hydrogels were verified using Fourier transform infrared (FT-IR) spectroscopy. The data were collected using Nicolet iS50 FT-IR (ThermoFisher Scientific, USA) spectrometer with an ATR adaptor (Smart Orbit Diamond, USA) within the wavelength range between 4000 – 500 cm^{-1}, with 16 scans at 4 cm^{-1} resolution.

2.3.3. Water Contact Angle

Contact angle of hydrogels was determined by using (Biolin Scientific, Gothenburg, Sweden), by capturing 15-20 recordings per second in standard mode for a single drop (3 µL distilled water). Although the drops falling on the sample surface were released initially, stable measurement of the contact angle could only be obtained after the kinetic energy was dissipated (Krainer and Him, 2021). After the water is dropped onto the substrate surface, the device begins imaging the drop at various speeds. The frame rate is recorded for 10 s at 10% (7.6 FPS) (for the µL volumes). The measurements were performed under room conditions of 25 °C and ~ 40% relative humidity. The hydrophilicty of PVP/PAAm based samples influences the contact angle. Therefore, the samples were kept in the desiccator to avoid being harmed by this phenomena. The samples were kept in the desiccator to avoid being harmed by both this condition and the active substances (terpenes). Each sample was captured at three separate locations to get an averaged contact angle value.

2.3.4. Swelling test

After measuring the dry weight, samples were suitably sliced and placed in a sealed tube containing 2 µL of deionised water. Then hydrogels were removed from the water, wiped away and weighed at regular times. The swelling rate (SR%) of the hydrogels was calculated according to Equation 2.1, where W_1 is the weight of the dry hydrogel and W_2 is the weight of swollen hydrogel.

$$SR\ (\%) = \frac{W1-W2}{W1} x\ 100 \quad (2.1)$$

2.4. Antibacterial Activity

The antibacterial sensitivity of the polymers was tested using standard strains of *Escherichia Coli* ATCC® 25922 and *Staphylococcus Aureus* ATCC® 25923. Trypton Soy Agar (Merck MilliporeTM 105458) was used to culture lyophilized bacterial strains. The seeded culture medium was incubated for 24 hours (37°C) under aerobic conditions. Bacterial suspensions were adjusted to 0.5 McFarland (1 108 CFU/mL) turbidity in isotonic saline solution.

The disk diffusion technique was used to assess antimicrobial effectiveness qualitatively. Bacterial suspensions were seeded on the surface of Mueller Hinton Agar (Merck MilliporeTM 103872) in a volume of 100 µL. Then the hydrogels were placed on the culture medium in contact with the agar surface. The plates were incubated for 24 hours. At the end of the incubation time, the diameters of the inhibitory zones around the material placed for each polymer were qualitatively quantified and analysed (Wayne, 2010).

3. Results and Discussion

3.1. Surface Morphology of the Hydrogels

The surface morphology of the hydrogels is shown in Figure 2. As can be seen from Figure 2A, the pure PPA hydrogel is exhibiting a smooth and homogeneous surface. In addition, SEM images also reveals that the hydrogels prepared by using bisabolol and geraniol (Figure 3B and 3D, respectively) as an antibacterial agent are also exhibiting similar morphology. However, the hydrogel synthesized by using d-limonene demonstrates a porous surface morphology. This result can be explained by limonene, acting as a porogen (Kekevi, 2021; Kramer et al., 2023).

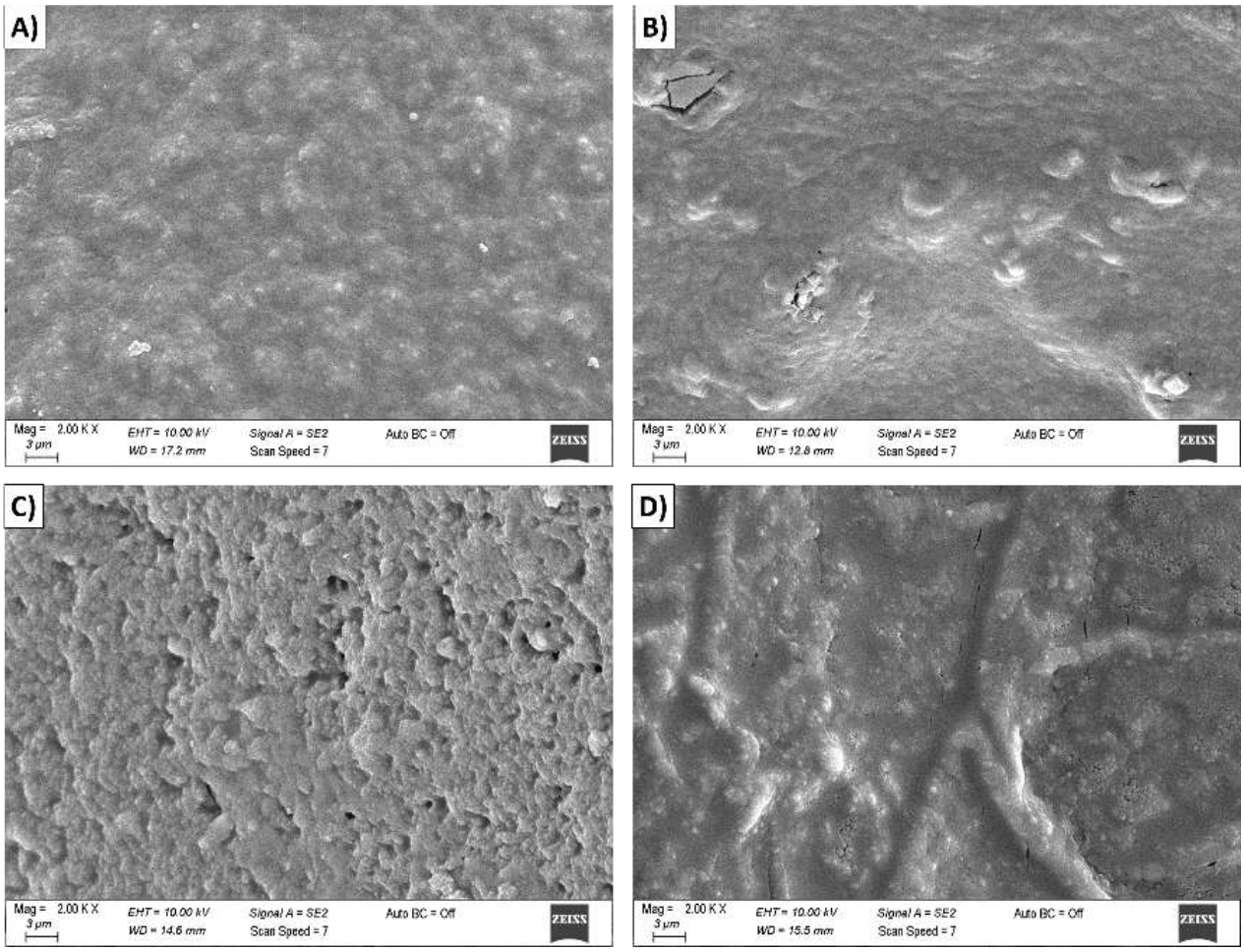

Figure 3. SEM micrographs of the hydrogels (A) PPA, (B) PPAB, (C) PPAL, and (D) PPAG (magnification: 2 kX, scale: 3 µm)

3.2. FT-IR Spectroscopy

Comparative FT-IR spectra of the pure and antibacterial agents containing hydrogels are presented in Figure 4. When the FT-IR spectra are examined, the characteristic adsorption bands of PVP, AAm and PEGDA can be seen. In this respect, in Figure 4 the broad band observed at 3385 cm^{-1} in all spectrums corresponds to the asymmetric (-NH_2 stretching) of acrylamide (Gad et al., 2021;). The absorption peak that appeared at 3200 cm^{-1} can be attributed -CH_2 groups of (PVP), (AAm) (Saroj et al., 2013; Gad et al., 2021). The peak at 2946

cm^{-1} demonstrated the presence of asymmetric stretching of $-CH_2$ from PVP. Furthermore, the peak at 1651 cm^{-1} related to the coincide with carbonyl groups of amide groups ($O = CH-NH_2$) of acrylamide and carbonyl groups -C=O of polyvinyl pyrrolidone (PVP) (Djefal-Kerrar et al., 2011). The peak at 2872 cm^{-1} corresponds to symmetric stretching of –CH from polyacrylamide. The C-H bending and CH_2 wagging were seen at 1439 cm^{-1} and 1288 cm^{-1}, respectively (Edikresnha et al., 2017). Moreover, the peak at 568 cm^{-1} was defined as the N-C=O bending, respectively (Rahma et al., 2016). When the active substances (bisabolol, d-limonene, and geraniol) were added, the peak densities of the hydrogels slightly changed and the new peaks were observed at 1032 cm^{-1}, 1024 cm^{-1}, and 1029 cm^{-1} for PPAB, PPAL, PPAG, respectively.

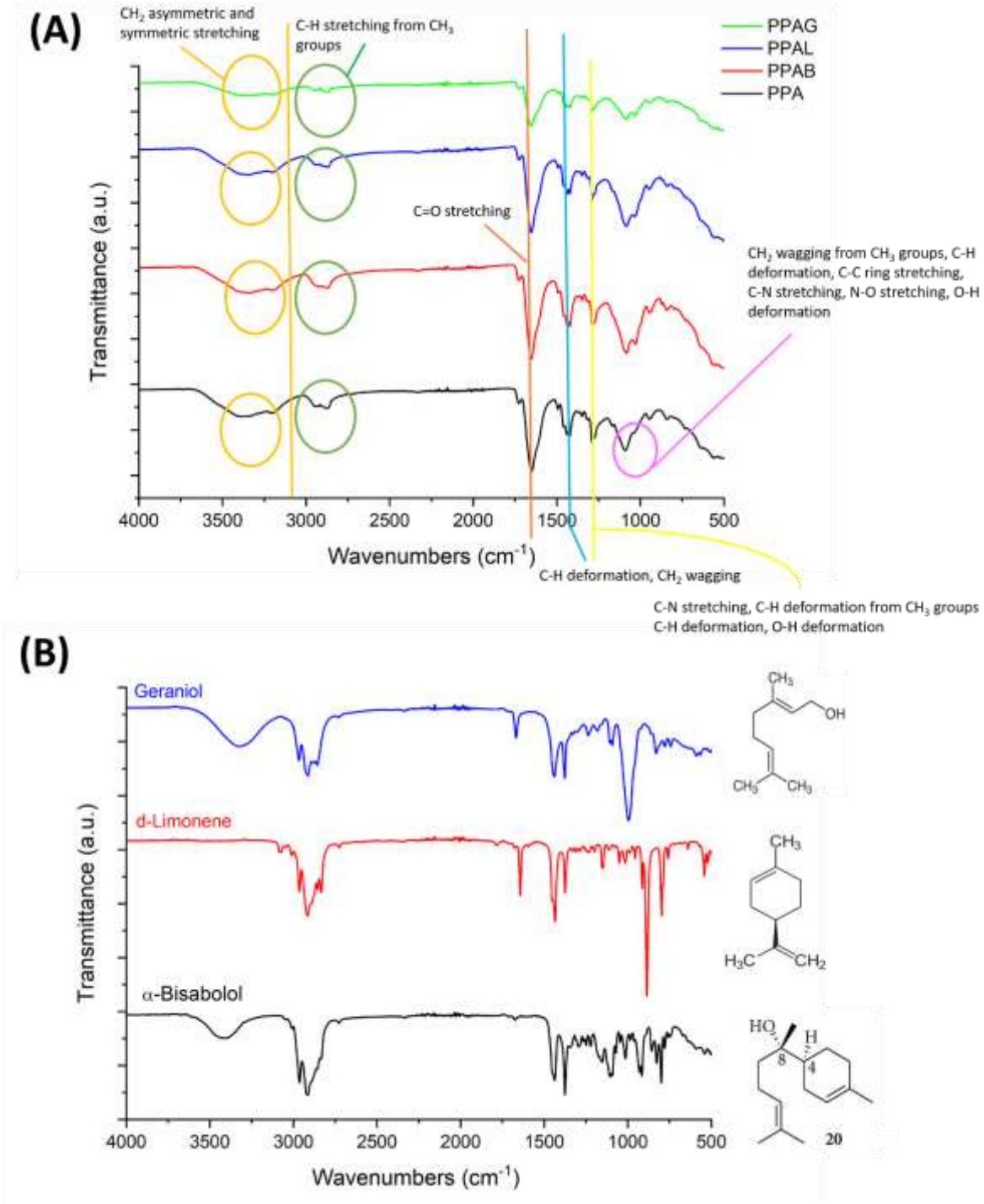

Figure 4. Comparative FT-IR spectra of (A) hydrogels, (B) α-bisabolol, d-limonene, and geraniol

The stretching band of C=C bonds at 1644 cm^{-1} belongs to the spectra of d-limonene (Kekevi, 2021). Typical strong bands that show for both the monomer and polymer at 3085-2833 cm^{-1} are due to methylene bond vibration (C-H), whereas bands in the 1435-1350 cm^{-1} range are ascribed to alkyl group C-H bond deformation ($-CH_3$) (Derdar et al., 2019).

The α-bisabolol spectrum contains regions with distinct peaks, such as the broadband at 3400 cm^{-1}, which is connected to -OH stretching, the peaks between 3052 and 2828 cm^{-1}, which is associated with axial deformation of C-H bonds, and the peaks between 1438 and 1375 cm^{-1}, which is related to angular deformation of C-H bonds) (Souza et al., 2016; Silva et al., 2009).

The band between 1378-1020 cm^{-1} shows absorption of $-CH_2$ twisting and wagging vibration for the geraniol spectrum. As a result, the methylene groups generate a sequence of bands in this region, which is typical of lengthy chains (Worzakowska and Ścigalski, 2013).

3.3. Contact Angle Analysis

The hydrophilic nature of hydrogels was examined with the determination of contact angles and contact angles' are presented in Figure 5.

The chemical and geometrical structure of a hydrogel surface influences its wettability. Furthermore, uncured areas of the hydrogels' surface may exist, and the curing intensity can be affected by the contact angle values (Kamoun et al., 2018). Hydrophilic materials can significantly improve healing by maintaining the wound wet while absorbing water. Therefore, it is desirable to select wound dressing materials with low wettability. Solid surfaces with contact angles less than 90° are referred hydrophilic, whereas those with contact angles more than 90° are regarded hydrophobic. Young's equation is crucial for the contact angle limitation of 90° of hydrophilicity and hydrophobicity (Xiao et al., 2000). Nevertheless, a new limit of hydrophilicity and hydrophobicity has been proposed by Berg et al. (1994) to be 65° by taking into account the exact chemical and structural state of a water droplet. According to Vogler (1998) hydrophobic surfaces allow hydrophobic forces and are less water wettable than the Berg limit of 65, while hydrophilic surfaces do not enable hydrophobic forces. PVP and PAAm are water-soluble polymers and their contact angles' are respectively 44° and 24° (Doğan et al., 2019; Bhavsar and Tripathi, 2018; Wu and Shanks 2004). Herein, the contact angle of hydrogels was also found to be lower than 65°, indicating the hydrophilic nature of the surfaces. However, recorded contact angles' of hydrogels reveals the increased hydrophobic property, due to the addition of bio-derived terpene/terpenoid-based antibacterial agents (Fasihi et al., 2023; Altaf et al., 2021). In this respect, the contact angle of PPA is measured as 39.9° ± 1.8, while the contact angles' of PPAB, PPAL and PPAG are found to be 55.6 ± 2.7, 63.9 ± 3, and 50.3 ± 2.5, respectively. Since the polarity of d-limonene has the lowest and geraniol has the highest polarity, the order of the change of contact angles' is not surprising. As can be seen from the Figure 4A, an excess of binding between geraniol and the PVP/PAAm matrix indicates that there are no free active agents left on the material surface, which can be attributed to a decrement of the contact angle, because the active agents are oil-based materials. Further, the presence of cyclo groups in the chemical structure of α-bisabolol and d-limonene is paralleled by the fact that the contact angles of PPL and PPB samples are greater than PPG.

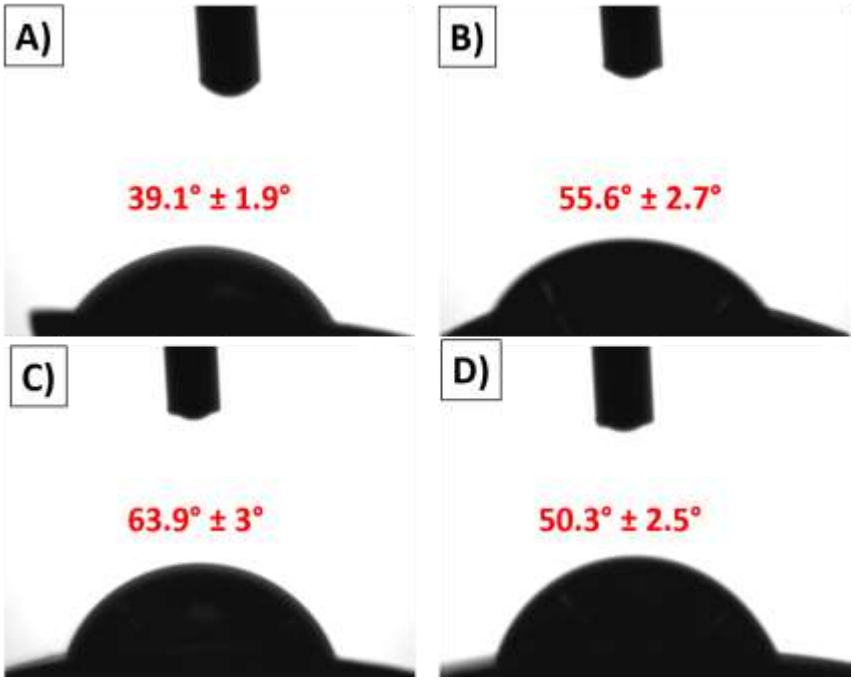

Figure 5. Contact angles of the hydrogels (a) PPA, (b) PPAB, (c) PPAL (d) PPAG

3.4. Swelling Test

The profile of swelling capacity vs time of a hydrogel sample is obtained to evaluate the swelling rate by performing free-absorbency capacity tests at sequential time intervals (Figure 6). It was recorded hydrogels reach equilibrium after 6 hours of the swelling test. In the end, swelling ratios of hydrogels were found to be 355 %, 500 %, 447 %, and 230 %, respectively for PPA, PPAB, PPAL, and PPAG. However, considering the contact angles, the hydrogel containing limonene was expected to have the lowest degree of swelling. This result can be attributed to the porous morphology of PPAL hydrogel (Figure 3C). On the other hand, as it is well-known an increase in crosslink leads to a decrease in the swelling ratio. It is known that the contribution of limonene units in free radical polymerization reactions is restricted due to steric hindrance (Kekevi, 2021). A similar situation can be also possible for α-bisabolol due to its chemical structure. Geraniol, on the other hand, might contribute to crosslinking reaction and increased the crosslinking density of the resulting hydrogel. In the FT-IR spectrum of PPA hydrogels, the intensities of the peaks with CH_2=CH_2 double binding are decrease compared to PPAB, PPAL, PPAG (Figure 4).

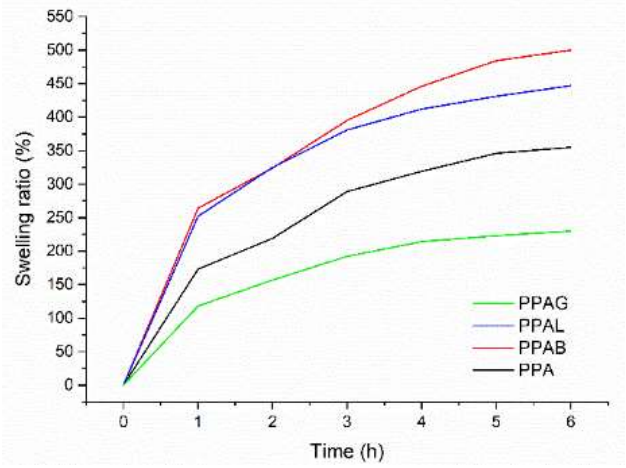

Figure 6. Swelling test of hydrogels in distilled water

3.5. Antibacterial Activity

All hydrogels were tested for antibacterial activity against standard strains of *Escherichia coli* ATCC® 25922, and *Staphylococcus aureus* ATCC® 25923 using a zone inhibition test (Figure 7). Antibacterial efficiency is essential throughout the treatment process because wounds exposed to physical problems are more sensitive to pathogens, resulting in a slowdown in the healing period. *S. aureus* and *P. aeruginosa* are the most common microorganisms that lead to infection in skin wounds (Agra et al., 2013; Ersoy et al., 2020).

Naturally produced molecules such as phytochemicals and essential oils can be used as antimicrobial agents (EOs) (Moo et al., 2019). Bioactive compounds with a molecular weight of 500 g/mol may be useful as antibacterial supporters (Mahizan et al., 2019; Barbieri et al., 2017; Langeveld et al., 2014). The efficiency of an antimicrobial agent with a low molecular weight natural product, like terpene derivatives, can be evaluated according to its abbility of reducing fungal and bacterial biofilm formation. Terpenes contained in essential oils have mostly antibacterial activity. and demonstrates effective skin permeation like a therapeutic agent (Guimarães et al., 2019). Topical treatments of terpenes are beneficial in improving both the microbicide and wound healing rate due to their higher bioavailability in the diseased wound site (Lasoń et al., 2020). Many terpenes have a less antibacterial action than terpenoids due to the functional groups (-OH group) of phenolic terpenoids. Hydroxyl groups, such as those existing in thymol, eugenol, terpineol, and carvacrol, are chemically active and create hydrogen bonds with specific enzyme active sites, deactivates them leading de cell membrane disintegration or disruption (Guimarães et al., 2019; Ouattara et al., 1997; Chauhan and Kang, 2014). In this respect, prior researches confirmed the increased resilience of *Gram-positive* bacteria and claimed that the better resistance of *Gram-positive* cells may be due to their cell walls possessing a thick layer of peptidoglycan. This possibly enables antimicrobial agents challenging to penetrate and therefore giving stiffness to cells. In this study, hydrogels did not show any antimicrobial activity against *S. aureus*, as well (Magiatis et al., 2002; Lopez-Romero et al., 2015). PPB and PPG hydrogels showed antibacterial activity with a zone diameter of 9 mm, while PPD sample did not show any activity. It has been found that materials with hydrophilic groups can maintain their antimicrobial activity and provide biocompatibility. Therefore, it can be concluded that the contact angle findings and the activity results exhibit correlation. Moreover, many studies have shown that surface hydrophilicity is closely related to antimicrobial properties. The bacterial growth is seen to decrease when surface hydrophobicity increases. Surprisingly, microbial adherence to materials' surfaces was observed to rise rapidly towards the Berg limit for *Acinetobacter* (Fletcher et al., 1985). In the similar studies, *E.coli*, *Pseudomonas* and soil bacteria growth were determined to have a sigmoidal attachment pattern that was not seen on material surfaces with variable water contact angle, with more cells adhering to hydrophobic surfaces and fewer adhered to hydrophilic surfaces (Van Loosdrecht et al., 1990; Vogel et al., 1998). It is supposed that the bacterial growth may be greater and does not show any activity because the contact angle value of PPD sample (63.9°) is close to the Berg limit (65°).

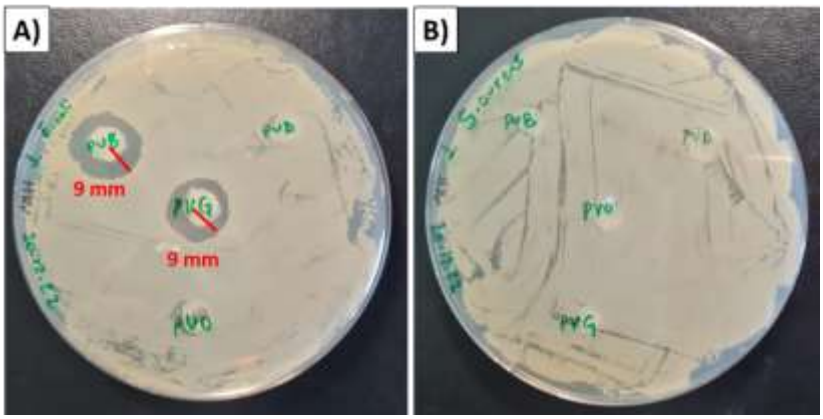

Figure 7. Antibacterial activity of the hydrogels against *E. coli*, (A) and (B) *S. aureus*

4. Conclusion

Antibacterial polyvinyl pyrrolidone PVP/PAAm - based hydrogels with terpen and terpenoids were synthesized by 3-in-1 type process. In this context, PVP/PAAm hydrogels containing α-bisabolol, d-limonene, and geraniol were prepared using a three-step process that included photopolymerization, freeze-thawing procedures, and anneal-swelling processes, respectively. In the existence of d-limonene in polyblend matrix caused d-limonene to act as a porogen in the material. The wettability increases with the addition of bio-derived terpen/terpenoid polyblend solutions and resulting hydrogels were all recorded to have contact angle lower than 65° (Berg limit). Moreover, PPL hydrogel exhibited the highest contact angle value due to the apolar structure of d-limonene. PPL is at this hydrophobicity limit has been associated with the sample's ability to display any antibacterial activity. According to FT-IR spectra and swelling tests, it was found the interaction between geraniol - polyblend matrix is greater than the between interaction α-bisabolol - matrix and the d-limonene - matrix. Antibacterial activity tests showed that hydrogels prepared with α-bisabolol and geraniol both exhibit good antibacterial activity with 9 mm against *E. coli* bacteria. The good matrix - active agent interaction in the PPG hydrogel also confirms this activity. Overall, these findings offer light on the significance of wettability in antibacterial efficiency and functional mechanisms for wound heraling applications.

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Author Contributions

Fatma Nur Parin: The author has all contributions to this article.

Conflicts of Interest

The author declare no conflict of interest.

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