Fabrication of Biohybrid Nanofibers by the Green Electrospinning Technique and Their Antibacterial Activity
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ABSTRACT: The development of bioactive polymer nanofiber sheets based on eco-friendly components is required to meet the needs of various medical applications as well as to preserve the environment. This study aimed to fabricate biohybrid nanofibers based on water-soluble polymers and aqueous extract of myrrh. The myrrh extract was incorporated into poly(vinyl alcohol)/tragacanth gum nanofiber mats (myrrh@PVA/TG) by the green electrospinning technique. Various characteristics of the prepared fibers such as morphology, fiber diameter distribution, crystallinity, and thermal stability were studied. The results confirmed that the morphology of biohybrid nanofibers was uniform without beads and tragacanth gum plays an important role in controlling the average diameter of fibers and the crystallinity. The antibacterial properties of the developed biohybrid nanofibers were investigated against common pathogens of Gram-positive and Gram-negative bacteria by the standard disc diffusion method. A significant antibacterial activity was observed toward bacterial strains after incorporation of aqueous myrrh extract into nanofibers, which increased on increasing the extract ratio. Due to their eco-friendly components and significant antibacterial activity, the prepared biohybrid nanofibers will open new avenues toward incorporating aqueous herbal extracts into degradable polymer fibers for use in many antibacterial applications.

1. INTRODUCTION
Nanomaterials with eco-friendly properties for medical applications are of interest to many researchers all over the world.1–10 Polymer nanofiber sheets are moldable and handleable nanomaterials, with a high surface-to-volume ratio property as well as good mechanical properties.3–5 Therefore, polymer nanofibers are used in various medical applications as a drug carrier,6 in wound dressings,7 in tissue regeneration,8 in vascular grafts,9 and in medical clothing.10 Electrospinning, as one of the most popular and effective techniques, is used in the fabrication of polymer nanofibers from synthetic polymers and biopolymers. It is superior to other techniques in its ability to produce nanofibers in different morphologies with the ability to control the diameter of the nanofibers.8–11

Biopolymers are characterized by biocompatibility, biodegradability, and nontoxicity, which make them the most suitable polymers that can be used in medical fields.12–15 Tragacanth gum (TG) is a polysaccharide with a high molecular weight (8.4 × 10^5 Da) that has been used in several applications due to its biodegradability, nontoxicity, and natural availability.16 The hydrophilicity, degradation behavior, and mechanical strength of TG are indicative of the potential to be used as a skin scaffold for wound-dressing patches.17 However, there is a problem facing researchers in converting some biopolymers such as TG into nanofibers as it is a complex mixture of branched acidic hetero-polysaccharides and is nonspinnable (Scheme S1).18 To overcome this problem, a synthetic polymer with high spinnability such as poly(vinyl alcohol) (PVA) is added to the natural polymer (e.g., TG). PVA is one of the most synthetic polymers that is used to improve the spinnability of biopolymers due to its ability to form a homogeneous solution through interaction with them.19,20 Therefore, fabrication of nanofibers based on a mixture of synthetic polymers and biopolymers expands the scope of their applications. However, the use of nanofibers in biomedical applications such as wound dressings or in medical clothing should exhibit good broad-spectrum antimicrobial behavior, provision of a moist environment, gas permeation, and performance against antibiotic-resistant bacteria to improve their healing processes.21 Since many electrospinnable polymers have low efficacy toward eliminating microbes, the incorporation of bioactive materials into the nanofiber matrix is a suitable method for enhancing their antimicrobial properties. For example, metal nanoparticles (MNPs) have been used as...
effective antimicrobial agents to enhance the antimicrobial property of polymer nanofibers.22–24 However, there are some concerns about the toxicity of MNPs and their effects on living cells.25 Recently, researchers have tended to incorporate herbal extracts,26–28 essential oils,29–32 and bacterial extracts33 into polymer nanofibers as alternatives to MNPs. The herbal extracts are a mixture of different natural compounds that are dissolved in specific solvents. Myrrh is one of the medicinal herbs that was used to treat several diseases in ancient times, especially in Arabic and North African regions.34-35 It belongs to the genus Commiphora and the family Burseraceae and contains water-soluble gum, alcohol-soluble resins, and volatile oil.36 Most of the effective herbal extracts that have been used to improve the antibacterial properties of nanofibers were extracted with organic solvents, in either the powder or liquid form. In general, herbal extracts obtained by organic solvents are more biologically effective than aqueous extracts. However, the use of organic solvents might interfere with the extract in affecting live microbes or their toxic effects on living cells as well as the environment. Thus, the use of water as a solvent to extract bioactive materials from medicinal plants and incorporate inside fabricated nanofibers is required.36 It is worth noting that the number of studies that applied the green electrospinning technique for fabricating bioactive nanofibers is still very limited. In addition, the incorporation of aqueous myrrh extract into the PVA/TG nano fibers is required.36 It is worth noting that the number of studies that applied the green electrospinning technique for fabricating bioactive nanofibers is still very limited. In addition, the incorporation of aqueous myrrh extract into the PVA/TG nano fiber matrix has not been studied to date by the traditional or green electrospinning technique.

Thus, this study aimed to fabricate eco-friendly nanofiber sheets based on biodegradable blend polymers with incorporation of aqueous myrrh extract by the green electrospinning technique. The properties of fabricated nanofibers were studied by different techniques as well as by evaluation of their antibacterial performance against different bacterial strains.

2. RESULTS AND DISCUSSION

2.1. Characterization of Myrrh Extract and Myrrh@PVA/TG Nanofibers. 2.1.1. Analysis of Myrrh Extract by UV/Vis and GC–MS. UV/Vis spectroscopy is a suitable technique to predict the skeleton of molecules and their functional groups in herbal extracts. UV/Vis spectra of watersoluble myrrh extract showed two strong absorption peaks at 201 and 205.5 nm and another two broad peaks at 272 and 360 nm, as shown in Figure 1. The strong peaks at 201 and 205 nm are assigned to the protein. The peak at 272 nm is attributed to the presence of oxygenated compounds and amino compounds.37–40 The found results are in good agreement with previous studies.41,42 Scheme S2 summarizes the main organic compounds present in myrrh extract that were estimated by gas chromatography–mass spectrometry (GC–MS) analysis. It contains seven compounds, all of them containing polar oxygen functional groups.

2.1.2. Morphology of Electrospun Nanofibers. Figure 2 displays the SEM images and fiber diameter distribution of PVA, PVA/TG, and 15%-myrrh@PVA/TG. The morphology of PVA nanofibers appears to be randomly smooth and twisted cylindrical with no beaded structure. After mixing PVA with TG, the morphology of the nanofibers became more random and twisted with the appearance of some knots, as shown in Figure 2b. Moreover, upon the addition of TG, a significant decrease in the average fiber diameters was observed from 406.1 ± 71.3 nm for PVA to 227.03 ± 37.9 nm for PVA/TG.

In contrast, it was found that the incorporation of myrrh extract into PVA/TG nanofibers did not exhibit any significant effect on its morphology, and a slight decrease in the average diameters of fibers was obtained, as shown in Figure 2c. The obtained results agree with previous studies, which reported a decrease in fiber diameters with the addition of TG into PVA.42,43

2.1.3. FTIR Spectra of Electrospun Nanofibers. Figure 3 displays the FTIR spectra of myrrh extract, TG, PVA, PVA/TG, and 15%-myrrh@PVA/TG. In the region between 3000 and 3700 cm⁻¹, broad peaks that were assigned to the hydroxyl group appear for myrrh extract, TG, PVA, PVA/TG, and 15%-myrrh@PVA/TG NFs at 3513, 3600, 3437, 3330, and 3327 cm⁻¹, respectively. For samples PVA/TG and 15%-myrrh@PVA/TG, upon addition of TG, there is a shift in the peak of the hydroxyl group to a lower wavenumber due to the alteration in the chemical environment of the hydroxyl group and the occurrence of an interaction between them and carboxylic groups. In the second region between 2900 and 3000 cm⁻¹, two peaks appeared at 2944 and 2922; 2940 and 2908; and 2940 and 2908 cm⁻¹ for PVA NFs, PVA/TG NFs, and 15%-myrrh@PVA/TG NFs, respectively. These two peaks are attributed to asymmetric and symmetric stretching vibrations of −CH₂− groups. Also, after blending TG with PVA, the peaks in the range of 2000–2500 cm⁻¹ that were assigned to the stretching of carboxylic groups disappeared due to the interaction between TG and PVA. For PVA NFs, only a sharp single peak appeared at 1733 cm⁻¹ due to carbonyl stretching vibrations of ester groups due to their partial hydrolysis. A sharp and weak peak of carbonyl stretching vibrations appeared at 1733 and 1718 cm⁻¹ for both PVA/TG NFs and 15%-myrrh@PVA/TG NFs, which confirmed the presence of both ester and carboxyl groups. In the region between 1500 and 1000 cm⁻¹, only four peaks appeared for PVA NFs at 1374, 1245, 1093, and 1027 cm⁻¹ that are attributed to the vibration of −C−O−C and −C−OH. For PVA/TG NFs, more than four peaks appeared. The new peaks after adding TG to PVA are located between 1400 and 1500 cm⁻¹, which are attributed to −COO− symmetric stretching. However, no new peaks appeared after the addition of the extract to PVA/TG NFs due to the overlap of oxygenated functional groups in the myrrh extract with functional groups of PVA/TG.
2.1.4. XRD Analysis of Electrospun Nanofibers. The XRD technique is a suitable method to confirm the incorporation of TG and its extract in polymer nanofibers by studying its effect on their crystallinity. Figure 4 shows the XRD spectra of PVA NFs, TG, PVA/TG NFs, and 15%-myrrh@PVA/TG NFs. For PVA NFs, XRD spectra showed a strong peak at 19 cm\(^{-1}\), which can be attributed to the reflection plan of the semicrystalline chains of PVA. The XRD spectra of TG showed one broad and poor peaks at 12 and 21.5° due to the highly amorphous structure of TG. Upon addition of TG, it was noticed that there is an obvious decrease in the crystallinity of PVA NFs, which was attributed to the reduction of the intermolecular interference between the polymer chains and the emergence of a new interaction between TG and PVA chains. On the other hand, it was found that the peak width at 19 became slightly narrow and increased in intensity after extract incorporation, indicating that the extract is crystalline in nature and present in the nanofiber matrix.

2.1.5. Thermal Behavior of Electrospun Nanofibers. The effect of TG and myrrh extract on the thermal stability of PVA NFs was studied using TGA analysis. Figure 5 displays the weight loss and derivative of the TGA thermogram vs temperature for PVA NFs, PVA/TG NFs, and myrrh@PVA/TG NFs with extract ratios of 5, 10, and 15%. The thermal degradation of PVA NFs was carried out in three steps. The first step occurred in the range 202–408 °C, with a maximum peak of 320 °C and a loss of more than 64% of the PVA weight. This step was attributed to the loss of the hydroxyl groups and the remaining acetate groups in the partially hydrolyzed PVA. The second step happened in the range 408–431 °C with a maximum peak at 420 °C, while the third step took place in the range 431–511 °C with a maximum peak at 450 °C. These two steps are due to the breakdown of the PVA carbon structure. After adding TG, the mixture showed a similar stability to that of pure PVA nanofibers with a slight shift in the maximum peak of the first degradation step from 320 to 310 °C, indicating the homogeneity between the PVA and TG. On the other hand, it was found that the thermal stability of PVA/TG NFs decreased after adding myrrh extract. TGA analysis of PVA NFs and incorporated NFs with TG and myrrh extract (5, 10, and 15% of the polymer volume) confirmed the presence of both the TG and extract in the nanofiber matrix.
The differential scanning calorimetry (DSC) thermograms of pure PVA NFs, powder TG, PVA/TG NFs, and myrrh@PVA/TG NFs are displayed in Figure 6. PVA NFs have three exothermic peaks at 40.5, 190, and 320 °C, which are assigned to the glass transition ($T_g$), melting point ($T_m$), and decomposition point ($T_d$), respectively. In contrast, TG has two exothermic peaks, a wide one that starts at 40 and ends at 210 °C and a narrow peak at 250 °C. The broad peak is attributed to the hydrophilic nature of functional groups contained in the TG, while the second one refers to the $T_m$ of the TG. In the PVA/TG NFs, the $T_g$ was single and shifted from 40.5 to 42 °C due to the strong intermolecular interaction between the components. In contrast, the melting point was constant for both PVA NFs and PVA/TG NFs with little change at the beginning and end of the peak. After adding the extract, the $T_g$ decreased slightly, which could be attributed to the competitive interaction between myrrh extract components and the TG with the PVA.

2.2. *In Vitro* Antibacterial Assessment of Electrospun Nanofibers. The percentage of the crude extract was designated as 5% based on the antibacterial activity of the pure extract using water. The extract of myrrh was encapsulated with PVA/TG in different concentrations, PVA/TG, 5%-myrrh@PVA/TG, 10%-myrrh@PVA/TG, and 15%-myrrh@PVA/TG. The antibacterial efficiency of these concentrations was studied against pathogenic bacteria—*Staphylococcus aureus* drug-resistant, *Escherichia fergusonii*, *Proteus mirabilis*, and *Aeromonas enteropelogenes*, as shown in Figure 7—which cause infections of the skin, catheter, and urinary tract. The obtained results showed that 15%-myrrh@PVA/TG NFs displayed a remarkable antibacterial activity against *E. fergusonii*, *P. mirabilis*, and *S. aureus* with mean 15.33, 14.67, and 13.33 mm of inhibition zones, respectively (Figure 8). Moreover, the encapsulated 15%-myrrh@PVA/TG displayed moderate activity against *A. enteropelogenes* with an inhibition zone of 7.74 mm using PVA/TG as the negative control, which showed no activity. Generally, there is variation in the antibacterial activity of myrrh@PVA/TG samples on changing the concentration of myrrh. For example, 10%-
myrrh@PVA/TG showed less activity compared to 15%-myrrh@PVA/TG with a slight decrease in the inhibition zone diameters. The observed inhibition zone diameters of 10%-myrrh@PVA/TG against *E. fergusonii* and *P. mirabilis* were 13.67 and 11.67 mm, respectively. However, 10%-myrrh@PVA/TG showed the lowest activity against *A. enteropelogenes* and *S. aureus* drug-resistant, with diameters of inhibition zones of 6.88 and 8.67 mm, respectively. Additionally, the low concentrations of myrrh extract in 5%-myrrh@PVA/TG showed a remarkable activity against the tested pathogenic bacteria *P. mirabilis* and *E. fergusonii* with inhibition zones of 11 and 10 mm, respectively. However, their activity against drug-resistant *S. aureus* was 7.67 mm of inhibition zones and 5.03 mm against *A. enteropelogenes*.

Antibacterial activities of PVA encapsulated with plant extracts were achieved in different studies. Moreover, myrrh plant is commercially available as a component for multidrug pharmaceutical preparations. For example, Mirazid contains the purified myrrh oleo-resin extract and is used as an anthelmintic soft gel capsule. Myrrh is also used as an antiseptic and anti-inflammatory drug for the mouth and throat due to its antimicrobial activity. Yang et al. studied the antibacterial activity of *Coptis chinensis* extract encapsulated in PVA with different concentrations (5, 10, and 15%) against both *S. aureus* and *Staphylococcus epidermidis*. In this study, the lowest concentration (5%) showed an antibacterial activity with 10 mm zone of inhibition against both *S. aureus* and *S. epidermidis*. In another study, the antibacterial activity of *Lawsonia inermis* leaf extract embedded in PVA showed its efficiency at the ratio of 2.793% against both *S. aureus* and *E. coli*, with inhibition zones of 9 and 2 mm, respectively. In a different study, the antibacterial activities of PVA/*Rhodomyrtus tomentosa* extract with nanofibers at different concentrations of 0.25, 0.5, 1.5, and 2.5% were investigated against various Gram-positive and Gram-negative bacteria. Only concentrations of 1.5 and 2.5% exhibited effective results against *E. coli* with inhibition zones of 8 and 9.33 mm, respectively.

This study exposed the remarkable antibacterial activity of myrrh@PVA/TG against bacteria implicated in different infections in humans compared with different reported studies. Skin infections such as wound infections are common, and there has been an increase in infections in different countries, which are primarily caused by colonization of bacteria, especially the Gram-positive bacterium *S. aureus*. Moreover,
Gram-negative bacteria such as Proteus sp., Aeromonas sp., and Escherichia sp. are also responsible for wound infections.\textsuperscript{31,52}

The comparison of the antibacterial performance of the prepared biopolymer nanofibers based on myrrh@PVA/TG with some previously reported extract@nanofibers is summarized in Table 1. The antibacterial activity of myrrh@PVA/TG against Gram-negative bacteria was higher than that of the nanofibers in previous studies. Furthermore, the prepared biopolymer nanofibers are distinguished by being environmentally friendly, as an environmentally friendly solvent (water) was used, whether in the extraction process of myrrh or in the electrosprinning process of blend polymer nanofibers.

### 3. CONCLUSIONS

In this study, different ratios of aqueous myrrh extract were incorporated into eco-friendly PVA/TG nanofibers by the green electrosprinning technique. The morphology of biopolymer nanofibers was uniform without beads, and the average diameters of nanofibers decreased by the incorporation of myrrh extract as well as by adding tragacanth gum and were 406, 227, and 220 nm for PVA, PVA/TG, and myrrh@PVA/TG, respectively. FTIR spectra confirmed the interaction between the extract with PVA/TG via the oxygenated functional groups. The crystallinity and thermal stability of PVA NFs were higher than those of blend PVA/TG and myrrh@PVA/TG, respectively. Myrrh@PVA/TG NFs were peeled off from the collector distance (TCD) of 15 cm, with a flow rate of 0.5 mL/h, at 23% relative humidity and 21 °C. The obtained fibers were collected on a stainless-steel collector covered by a film of polyethylene. Finally, the nanofibers were peeled off from the collector by applying a voltage of 16 kV, at a tip-to-collector distance (TCD) of 15 cm, with a flow rate of 0.5 mL/h, at 23% relative humidity and 21 °C. The obtained fibers were collected on a stainless-steel collector covered by a film of polyethylene.

### 4. EXPERIMENTAL SECTION

#### 4.1. Materials

Tragacanth gum is flake-like, and it was purchased from the local market in Riyadh, Saudi Arabia. Poly(vinyl alcohol) (PVA, $M_w = 72$ k g mol$^{-1}$, 85% hydrolyzed) was obtained from Fluka, Switzerland. The plant material was collected to be used in this experiment, including dried exudates stuck to the bark of a myrrh tree growing in the Directorate of Bait al-QahHodeida, Yemen.

#### 4.2. Fabrication of Myrrh@PVA/TG Nanofibers

##### 4.2.1. Extraction of Aqueous Myrrh

Myrrh was extracted from gum-resin of guggul according to the method described by Al-Sabri et al.\textsuperscript{44} as follows. First, gum-resin of guggul was washed with tap water and sterilized water in successive steps and was then dried at room temperature. Myrrh solution (10% w/v) in water was prepared and stored at 4 °C until use.

##### 4.2.2. Preparation of the PVA, TG, and Myrrh@PVA/TG Solutions

A solution of PVA (10% w/v) was obtained by dissolving PVA (2 g) in distilled water (20 mL) and stirring for 6 h at 60 °C. The TG solution (1% w/v) was prepared by dissolving TG flakes (0.2 g) in distilled water (20 mL) by adding a few drops of acetic acid with continuous stirring and heating at 60 °C for 12 h. The PVA/TG solution was prepared by mixing both PVA and TG solutions in a weight ratio of 5:1. For preparing the myrrh@PVA/TG solution, 1.2, 2.4, and 3.6 mL of myrrh extract were added to the PVA/TG solution separately with stirring for 4 h at 40 °C to form a homogeneous solution with a light-brown color. Myrrh@PVA/TG solutions were coded as 0%-myrrh@PVA/TG, 5%-myrrh@PVA/TG, 10%-myrrh@PVA/TG, and 15%-myrrh@PVA/TG according to the ratio of myrrh extract with respect to PVA/TG (w/v) as 0.0, 5.0, 10.0, and 15.0% v/v, respectively.

#### 4.2.3. Fabrication of PVA/TG and Myrrh@PVA/TG Nanofibers

After preparing a series of myrrh@PVA/TG solutions, they were transferred to a 20 mL syringe linked to a stainless-steel needle (diameter = 0.09 cm) and then electrospun by an electrosprinning machine (Chungra EMT Co. Ltd., Seoul, Korea; model CPS-60K02VT). The electrosprinning process was carried out by applying a voltage of 16 kV, at a tip-to-collector distance (TCD) of 15 cm, with a flow rate of 0.5 mL/h, at 23% relative humidity and 21 °C. The obtained fibers were collected on a stainless-steel collector covered by a film of polyethylene.

### Table 1. Antibacterial Performance of Various Plant Extract@polymer Nanofibers against Both Gram-Positive and Gram-Negative Bacteria

| Nanofiber composition | Extract material | Polymer/extract solvent | Target bacteria | Bacteria type | Inhibition zone (mm)  | Refs |
|----------------------|------------------|--------------------------|-----------------|---------------|-----------------------|------|
| PAN                  | moringa leaf     | DMF                      | S. aureus       | Gram +        | 12.0                  | 53   |
| PCL–PVP              | chamomile        | CHCl$_2$–DMF             | E. coli         | Gram –        | 15.0                  |      |
| chitosan–PEO         | green tea        | CH$_3$COOH               | E. coli         | Gram –        | 7.6                   | 54   |
| Chitosan–pullulan     | aloe vera        | H$_2$O                   | E. coli         | Gram –        | 4.0                   | 55   |
| PVA                  | rhodomyrtus tomentosa | H$_2$O/MeOH       | E. coli         | Gram –        | 2.5                   | 56   |
| PVA–PEO              | lawsonia inermis | H$_2$O/EtOH              | E. coli         | Gram –        | 6.0                   | 57   |
| PLA–cellulose        | propolis         | CHCl$_3$                | P. aeruginosa   | Gram –        | 6.67                  |      |
| PVA/TG               | myrrha           | H$_2$O                   | S. aureus       | Gram +        | 10.0                  | 58   |
|                      |                  |                          | S. aureus       | Gram +        | 2.5                   |      |
|                      |                  |                          | E. coli         | Gram –        | 12.0                  |      |
|                      |                  |                          | E. coli         | Gram –        | 0.0                   |      |
|                      |                  |                          | S. aureus       | Gram +        | 14.5                  |      |
|                      |                  |                          | F. fergusonii   | Gram –        | 15.33 (this work)     |      |
|                      |                  |                          | P. mirabilis    | Gram –        | 14.67                 |      |
|                      |                  |                          | A. enteropeloge | Gram –        | 7.74                  |      |
|                      |                  |                          | S. aureus       | Gram +        | 13.33                 |      |
collector and dried in a vacuum oven at 40 °C for 12 h before characterization and evaluating their biological activity (Scheme 1).

4.3. Characterizations. The UV/vis test of myrrh extract in a quartz cuvette was performed using a Bruker spectrophotometer at 200−700 nm with distilled water as the reference. The morphology and composition of the fabricated PVA, PVA/TG, and myrrh@PVA/TG nanofibers and the effect of the myrrh extract on the surface and diameters of the nanofibers were investigated by field emission scanning electron microscopy (FESEM). The average of the fiber diameter distribution was calculated using ImageJ software. Fourier transform infrared (FTIR) spectroscopy was performed to define the functional groups and the type of interaction among PVA, TG, and myrrh extract. The thermal behaviors of PVA, TG, PVA/TG, and myrrh@PVA/TG were studied by thermogravimetric analysis (TGA, TA instrument) and differential scanning calorimetry (DSC). The crystallinity of the prepared nanofibers was investigated by X-ray diffraction (XRD, X-Pert APD, Philips) using Cu Kα radiation with a wavelength of 0.154 nm.

4.4. Identification of the Chemical Compounds in Myrrh Extract. The identification of myrrh extract was done as follows: aqueous myrrh extract was dried, and then, the solid extract was dissolved in ethanol. Constituents of myrrh in ethanol were identified by coupled GC/mass spectrometry (GC/MS). The GC/MS analyses were performed on a fused silica capillary column (30 m 0.25 mm i.d., film thickness 0.25 m, DB5) equipped with an on-column injector and directly coupled to a magnetic sector mass spectrometer (Perkin Elmer, Clarus 500). Electron impact (70 eV, source temperature 250 °C) was used to achieve ionization. The oven temperature was kept at 30 °C for 5 min before being increased by 5 °C/min to 250 °C. Helium served as the carrier gas. Tentative identifications were made by comparing spectra to mass spectral databases (NIST, 2005) and confirmed by peak enhancement on GC with authentic chemical samples.

4.5. Preparation of Tested Bacteria. E. fergusonii (MG818962.1), P. mirabilis (MG818966.1), A. enteropelogenes (MG818965.1), and drug-resistant S. aureus were obtained from King Khaled University Hospital, King Saud University. Tested bacteria were cultured onto Mueller Hinton agar and incubated at 37 °C for 24 h.

4.5.1. In Vitro Antibacterial Assessment. Antibacterial activities of PVA, PVA/TG, and myrrh@PVA/TG nanofibers were determined by the standard disc diffusion method. First, fabricated nanofibers were arranged in discs, with dimensions of 5 mm diameter and weight ~10 ± 00 mg, by a sterile disc puncher tool. Then, a suspension of bacteria (~1.5 × 10⁸ CFU/mL) was prepared to correspond to the 0.5 McFarland standard. Next, the suspension was cultured by a sterile swab on Mueller Hinton agar culture media. After 15 min, fabricated nanofiber discs were placed and arranged on the cultured media by sterile forceps. Finally, the cultured media with involved discs were incubated for 24 h. The antibacterial efficiency of the fabricated nanofibers was evaluated by measuring the diameters of inhibition zones around discs.

ASSOCIATED CONTENT

* Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.1c07141.

Additional details of the schematic structure of TG and chemical structure of the main organic compounds in myrrh extract (PDF)

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Notes

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