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Electrospun nanofibrous scaffolds of ε-polycaprolactone containing graphene oxide and encapsulated with magnetite nanoparticles for wound healing utilizations

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Abstract

Wound healing treatment with a nanofibrous matrix is a serious demand to avoid associated complications, including bacterial infections. Magnetite nanoparticles (MNPs) were encapsulated into electrospun nanofibrous scaffolds of ε-polycaprolactone (PCL) containing graphene oxide (GO) nanosheets. The structural and morphological behaviors of the obtained scaffolds were investigated. The modification of nanofibers via the addition of MNPs generated a slight change of morphology, whereas the fibers’ diameters were around 0.2−0.5, 0.1−0.3, 0.1−0.2, and 0.1−0.3 μm for 0.0NPs-GO@PCL, 0.1NPs-GO@PCL, 0.2NPs-GO@PCL, and 0.3NPs-GO@PCL, respectively. Moreover, the roughness average (Ra) increased from 119 nm to be about 169 nm from the lowest and the highest contributions of MNPs. The Human fibroblasts cell line (HFB4) reached around 98.4 ± 3.1% cell viability for 0.2MNPs-GO@PCL composition. The antibacterial activity of the highest contribution of MNPs reached about 11.4 ± 1.6 mm and 12.3 ± 1.2 mm against S. aureus and E. coli, respectively. The in-vitro cells’ attachment of HFB4 showed that cells were adhered to and proliferated through the nanofibrous scaffolds. Cells also spread and grew significantly as the modification via MNPs. Thus, indicating that designing of new scaffold for wound healing and disinfection utilization could be reached via tailoring of electrospun products encapsulating with biocompatible substances such as graphene oxide and magnetite.

1. Introduction

Skin damage could be caused by different factors including surgery, trauma, burns, and chronic ulcers [1, 2]. This damage is often followed by a self-repairing process, which is vital for survival and organismal balancing. This repairing procedure contains complex and dynamic processes starting from inflammation, reaching tissue growth granulation, and re-epithelialization [3]. Noteworthy, numerous biomaterials have been suggested to scaffold wounds and to support healing operation [4, 5]. These materials are encouraged for this role owing to their biocompatibility, non-toxicity, osteoconductive, chemical stability, great mechanical properties, adequate degradation rate, and high bioactivity [6, 7]. However, it could be stated that increasing degradation rate may minimize mechanical properties, while high bioactivity is accompanied by a high rate of dissolution [8–10]. Therefore, it is essential to design a new material to meet these requirements and to avoid skin regeneration failure [11, 12]. Noteworthy, one of the biggest concerns during the treatment stage is wound infection due to bacterial invasion [13, 14]. Therefore, it is
crucial to adjusting dynamic homeostasis towards inflammation responses to facilitate the healing process [2, 3, 15]. Moreover, bacterial infection may delay healing or even cause the failure of skin reconstruction. The demand materials that may match with the former requirements should be based on a polymeric matrix due to the ability of polymers to adjust the skin morphology. Furthermore, the biodegradable polymer could be a good candidate for drug carrier substances. Biopolymeric ε-poly l-lactide (ε-PLA), is an abundant form in biomedical applications [16–18]. PCL is a semi-crystalline polymer and possesses intrinsic behaviors including biocompatibility, high mechanical strength, and great stability [18–20]. However, it displays a high hydrophobic response, which may hinder its usage for different applications. Herein, reducing its hydrophobicity to control its bioactivity through the biological environment is requested strongly [21–23]. This purpose could be reached via modification of the fabricated polymeric carrier by the addition of hydrophilic substances [24, 25].

Graphene oxide (GO) nanosheets are a two-dimensional (2D) material based on sp² hybridization of carbon bonding [17]. It is excellent reinforcement for elastic polymers due to its unique properties, which include: large-volume surface, high conductivity, excellent mechanical properties, exceptional optical characteristics, and good chemical stability [20]. Besides, the presence of oxygen-containing groups that are connecting to GO surfaces may induce bioactivity towards the ambient environment and thus generating a hydrophilicity trend [26, 27]. This configuration may offer another benefit that correlates to the antibacterial effectiveness. Whereas the antibacterial influence of GO could be adopted on two sources: physical and chemical approaches. The physical effect is attributed to the direct contact between GO edges and bacteria cells, which may deteriorate the latter metabolism, while the chemical one is done via the reduction mechanism. This includes a release of free electrons from the oxyanions that can bond with the protein envelope of a bacterial cell and thus to degenerate their reproduction process [28, 29]. It could be mentioned also that the intensity of release free radicals could be enlarged via light irradiation. Thus, photo-electron generation could be added as an extra property to inhibit bacterial infection [30]. Furthermore, GO displays great biocompatibility and high capacity for drug transportation owing to its high specific surface area and its active surface [31].

Metal oxides such as magnetite (Fe₃O₄) nanoparticles (MNPs) being adopted for a plethora of biomedical applications, including biosensors, tissue engineering, bio-imaging, besides drug delivery utilizations, due to their biocompatibility, absorption efficiency, and high capacity besides good magnetic properties [32, 33]. It could be stated that Ferreira-Ermita et al investigated the biocompatibility behavior and biodegradation rate of MNPs/hydroxyapatite in-vivo through rabbits fascia and muscle tissues and the results showed, after 15, 30, 60, and 90 days of injection, that releasing of Ca: Fe was homogenous with no-toxic effect [34]. The electrospinning technique is considered to be a facile method to produce nanofibrous scaffolds for wound healing and dressing applications due to its ability to control fibers' properties via their preparation conditions [35, 36]. In other words, the high surface regarding volume ratio, high porosity, and great capacity could be adjusted via controlling polymer type and viscosity [37–39]. Furthermore, the high surface/volume ratio enlarge the swelling behavior and thus, these fibers could be encouraged to be used for direct drug delivery system, whereas nanofibers could degrade to transport antibacterial and growth correlating substances to improve the healing process. Moreover, the porous structure of electrospun nanofibers mimics the extracellular matrix (ECM) configuration [19–21]. This porosity ratio ensures wound oxygenation to be maintained, while the moisture should be enhanced to improve the kinetics of healing as well as preventing scab formation.

Combining the former interpretations, PCL nanofibrous scaffolds containing GO nanosheets could be modified using different contributions of MNPs, and thus the Physico-chemical behaviors will be investigated, including morphological features. The response of these scaffolds towards human fibroblast cell lines including cell viability and cell attachment besides the antibacterial behavior, could be analyzed.

2. Materials and techniques

2.1. Chemicals

Polyacrylamide (Mw ~ 65 000 g mol⁻¹, pellets) was purchased from Sigma-Aldrich. The other chemicals included; tetrahydrate ferrous chloride FeCl₂·4H₂O, hexahydrate ferric chloride FeCl₃·6H₂O, ammonium hydroxide (NH₄OH) (30%), chloroform (99%), methanol (98%), and hydrochloric acid (HCl) (30%–34%) were purchased from (LOBA, India). During preparation, double distilled water was used as a solvent and collected from all glass equipment. Besides, inert N₂ gas (purity 99.5%) was used as a solvent from the nitrogen plant.

2.2. Preparation of powdered magnetic nanoparticles (MNPs)

Magnetic nanoparticles (MNPs) were fabricated according to the top-down co-precipitation technique. Two solutions of 0.2 M of FeCl₃·6H₂O and 0.1 M of FeCl₂·4H₂O were prepared in equal 50 ml of distilled water, individually. The N gas was connected to the solution of FeCl₃·6H₂O for 20 min, then the solution of
FeCl$_2$·$4$H$_2$O was added while the stirring is working continuously. The controlled pH of the mixture was adjusted around basic $11 \pm 0.1$ using few drops of ammonium hydroxide. The bubbling of nitrogen gas should be maintained until the experimental is finished to prevent the oxidization of magnetite. After $2$ h of vigorous stirring, the obtained black precipitated filtered and washed thrice with deionized water and absolute ethanol to avoid the residuals ions. The obtained gel was dried at $50$ °C–$60$ °C for $12$ h to produce the black powder of the magnetite.

2.3. Synthesis of GO

The well-known modified Hummers method was described for the synthetic procedure of GO. About $4$ g of commercial graphite was added thoroughly to $96$ ml concentrated $H_2$SO$_4$ with smooth stirring for $45$ min. To this solution, $9.6$ g of KMNO$_4$ was added with continuous stirring for another $115$ min, then the reaction cooled by adding $300$ ml of deionized water with a flow rate of $20$ ml min$^{-1}$ to control the increasing temperature. After ensuring cooled down the temperature, $8$ ml $H_2$O$_2$ was dropped via micropipette (stirring is required). The initial product was filtered and dispersed in $500$ ml of $20$ wt.% $HCl$ under high power sonication ($5$ W/cm$^3$) for $10$ min. The previous process was repeated many times, followed by cleaning on a glass fiber filter with $10$ liters of pure water to attain neutralization and to remove the remaining salts or other residues. The black powdery product was dried in a vacuum oven at $55$ °C for $3$ days and kept under desiccator before use.

2.4. Nanofibrous scaffolds fabrication

Exactly, $5$ g of PCL was dissolved in $50$ ml of a co-solvent of $8:2$ (v/v) chloroform: methanol to exhibit a clear and viscous solution. $55$ mg of yielded powder of GO was introduced into PCL to be produced as nanofibers. Then different concentrations of MNPs were added individually to be $0.0$, $0.1$, $0.2$, and $0.3$ g of MNPs fine powder was added individually for bottles containing (PCL + GO). These bottles then were mixed sonicator of high power ultrasonic probe for $15$ min. Then, the MNPs-GO@PCL nanocomposite structures were injected into a syringe pump for electrical pressing using a custom electrical processing setup. The established factors were: $15$ kV, feed rate $1.2$ mm h$^{-1}$, the estimated distance between Taylor cone and collector $15$ cm, cleaning time $30$ s, and the ejaculated needle diameter was $21$ μ. The representative cartoon diagram of the fabricated MNPs-GO@PCL nanofibrous process is shown in figure 1.

2.5. Characterization

The x-ray diffraction analysis (XRD) was tested with an x-ray diffractometer (analytical-x’ pertpro, Cu k$_{α,1}$ radiation, $λ = 1.5404$ Å, $45$ kV, $40$ mA, Netherlands). $5° \leq \theta \leq 70°$ is the range of measurement, step size of $0.02°$, and an irradiation time of $0.5$ s per step. The crystallite size was measured using Scherrer’s principle for the electrospun polymeric phase as follow $[40, 41]$:

$$D = \frac{kλ}{β_{hal} \cos θ}$$

Figure 1. Flow chart of synthesizing MNPs-GO@PCL nanofibrous matrix.
The main function moieties were measured by the FT-IR spectra (JASCO FT/IR 6800). The spectral resolution of 2 cm$^{-1}$ within 475–4000 cm$^{-1}$ at room temperature. The surface morphology was identified by field emission scanning electron microscope (FE-SEM, QUANTA-FEG250, Netherlands) under operating voltage 20–30 kV. Gwyddion software (version 2.45) used to examine the surface roughness [42], after subjected to FE-SEM.

2.6. In vitro cytotoxicity test
To assess the cell biocompatibility, at 37 °C and 5% CO$_2$, human fibroblasts cell line HFB4 was grown in Dulbecco’s modified Eagle medium (DMEM, Gibco) to examine the viability of cells sown on nanofibers. Cells seeded at a density of $5 \times 10^3$ cells/cm$^2$ and grown on fibers in 12-well plates. After three days of incubation, the medium was removed and MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) was introduced into each well, after which its cell viability was analyzed by an optical method. Cell viability was defined as the percentage of viable cells per to the total number of cells [18, 43]:

$$\text{Viability (\%)} = \frac{\text{Mean optical density of test samples}}{\text{Mean optical density of the control}} \times 100 \quad (2)$$

2.7. Cells growth on the matrix
For more clarification, FE-SEM is used to monitor the interaction between human HFB4 osteoblast cells seeded on nanofibers. Each sample was cut into two parts 1.0 to 1.0 cm in size, which was then exposed to a UV irradiation for 25 min to ensure sterilization. Approximately 2 ml cells ($5 \times 10^5$ cells) were added to each well. For two days, the plate was covered and incubated at 37 °C. After that, nanofibers were treated with phosphate-buffered saline solution (PBS). For the cells’ attachment to the surface of the nanofibers, the scaffolds were immersed in a 2.5% concentrated glutaraldehyde solution for 50 min. They were then dehydrated in the open air for 30 min. In the end, they were sprayed with gold for 1 min to be examined by FE-SEM imaging.

2.8. Evaluation of antibacterial activity
Both gram-negative (Staphylococcus aureus = S. aureus) and gram-negative (Escherichia coli = E. coli) were tested for the sake of determining an antibacterial activity. The initial recommended concentration is 50 mg/ml for each test composition. After predetermined 3 days of incubation, the zone of inhibition was determined.

3. Results and discussion

3.1. Crystallographic pattern study
The phase formation of the nanofibrous scaffolds was investigated using XRD as obvious in figure 2. It could be seen that magnetite has been crystallized in a cubic symmetry upon ICDD card no. 01-088-0315 [44, 45]. The peaks around $2\theta = 35.51^\circ, 43.152^\circ, 57.1^\circ$, and 62.72$^\circ$ could be assigned to the Miller indices of (311), (400), (220), and (111), respectively.
511), and (440). On the other hand, the high-intensity peaks that were observed around 2θ = 21.452° and 2θ = 23.814° could be attributed to PCL configuration. PCL tends to possess semi-crystalline behavior.

### 3.2. FT-IR spectral analyses

Figure 3 shows the FTIR spectral assignments of the obtained nanofibrous MNPs-GO@PCL. Significant characteristic bands for the magnetite at 451.8 and 584.3 cm$^{-1}$ originated from the vibrational mode of Fe–O bonds belonging to iron oxide [46]. The broad peaks at 2864.3 to 2940.9 cm$^{-1}$ owing to O–H vibrations of water which are absorbed through porous structure [47, 48]. The peak at 1633 cm$^{-1}$ was a characteristic peak of the bending mode of H–O–H, which may refer to the high content of hydroxyl groups on the MNPs surface [49, 50]. The characteristic bands of MNPs are tabulated in table 1.

### 3.3. Microstrucral and morphological features

The fabricated nanofibrous scaffold of PCL encapsulated with the highest contribution of MNPs has been invetigated by TEM as shown in figure 4. As obvious, the nanofibers were formed as long tubes with diameter in range of 30 nm. These tubes were decorated with MNPs that were shown as spherical shapes with diameters around 20–35 nm. This finding is similar to previous reportig where Mansour et al studied the microstructural behavior of MNPs encapsulated into PVA/cellulose acetate nanofiber. The TEM micrographs showed the nanofiber had been decorated with MNPs which had formed as spherical shapes of 30–90 nm [19].

The morphology of the as-synthesized MNPs-GO@PCL nanofibers surface is shown in figures 5(a)–(e). It could be detected that nanofibrous scaffolds of 0.0MNPs-GO@PCL were formed in a non-oriented network with narrow range distributed diameters in range of 0.2–0.5 μm. The GO nanosheets are observed to be sandwiched

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**Table 1.** Characteristic peaks of MNPs-GO@PCL nanofibers different content of MNPs.

|     | 0.0MNPs-GO@PCL | 0.1MNPs-GO@PCL | 0.2MNPs-GO@PCL | 0.3MNPs-GO@PCL | Assignment                                           | References |
|-----|----------------|----------------|----------------|----------------|-----------------------------------------------------|------------|
| 451.8 | 456.1          | 454.4          | 455.2          |                | Fe–O stretching bond                                | [46, 51]   |
| 584.3 | 583.3          | 583.1          | 582.3          |                |                                                     |            |
| 1164.8 | 1163.5         | 1163.1         | 1162.4         |                | C–O–C stretching vibrations                         | [52]       |
| 1243.3 | 1239.4         | 1236.3         | 1240.1         |                | C–O and C–C stretching                             | [53, 54]   |
| 1297.7 | 1298.3         | 1300.2         | 1299.3         |                | stretching of CH$_{2}$ and OH group                 |            |
| 1365.2 | 1367.5         | 1361.8         | 1365.8         |                |                                                     |            |
| 1471.3 | 1473.3         | 1472.1         | 1470.2         |                | C=O                                                 | [55]       |
| 1723.5 | 1723.6         | 1723.5         | 1724.3         |                | stretching mode of C–H                              | [56, 57]   |
| 2864.3 | 2865           | 2864.2         | 2863.3         |                |                                                     |            |
| 2940.9 | 2940.8         | 2940.1         | 2940.4         |                |                                                     |            |
between fibers with dimensions exceed 23 μm. The lowest contribution of MNPs as 0.1MNPs-GO@PCL is displayed in figure 5(c). It was configured in a randomly distributed network with diameters starting from 0.1 to 0.3 μm. GO nanosheets tend to be connected strongly with nanofibers, which may generate high resistance towards applied stress compared with the former composition. The scaffold of 0.2MNPs-GO@PCL was shown as networked nanofibers with diameters around 0.1–0.2 μm. The nanofibers tend to be spread starting from the GO nanosheets like filopodia distribution, enhancing the adhesion between constituents of a scaffold. GO nanosheets are spread in an area exceeding 20 μm. The composition with the highest contribution of MNPs is shown with diameters 0.1–0.3 μm. GO nanosheets are not only spread on the surface of the scaffold, but they also are sandwiched through fibers. Moreover, nanofibers seem to be branched from GO. The nanosheets of GO tend to be formed in a semi-circular shape with diameters around 15 μm. It could be stated that MNPs were not detected as separated particles through the former micrographs, which indicates that MNP were encapsulated successfully into PCL nanofibers. This encapsulation matches well with the results from the TEM micrograph. Furthermore, the high porosity that might be observed through the nanofibrous scaffolds is considered the main factor to facilitate the transformation of nutrients and vascularization when these scaffolds are used in biomedical applications. It is noticed that the presence of GO may block the porous surface, which introduces a negative impact on the growth of the cells. On the other hand, the reduction of porosity contribution could enhance the resistance of nanofibers to deteriorate under applied stress. Therefore, balancing between the porosity ratio and the content of GO is key for the manipulation of both cell growth and mechanical properties. Consequently, the compositional variation could offer an essential tool to control the obtained behaviors.

The roughness behavior of the nanofibrous surface is illustrated in figures 6(a)–(d). As shown in table 2, a remarkable increase of roughness average (Ra) from 119 nm to 152 nm after the addition of MNPs from 0.0MNPs-GO@PCL to 0.1MNPs-GO@PCL, and thus elevated to 169 nm at the highest contribution of MNPs. Both the root mean square roughness and the optimal height of the roughness (Rq) were shown to follow the trend of Ra. However, the maximum roughness valley depth (Rv) started with 484 nm, and plunged slightly to 483 nm, then improved to 492 nm and decreased again to 486 nm upon the variation of MNPs contribution respectively [58]. On the other hand, the maximum roughness peak height [59] begun with 486 nm and jumped to 613, 626, and 756 upon the addition of MNPs, respectively. This noticeable variation of trends between (Rv, Rp) and (Ra, Rq) could be assigned to the differentiation of parameters’ definition. In other words, Rq takes into consideration both heights and notches, while Rv refers to the depth of notches, and Rp denotes the heights only. Therefore, Rq is an approximate average for both Rv and Rp. Both notches and heights represent roughness of the surface, which may induce adhesion towards the host tissue. The high values of heights (Rq values) compared with their anlague for notches (Rp values) indicated that the predominant mechanism for intecation with the surrounding environments is a physical one. In other words, hights seem to act as a hook to be interlocked with the neighboring molecules. This trend could be an effective approach to exhibit a high tendency of physical
adhesion towards proteins and macromolecules. Thus, enlarging roughness properties can show an effective technique to enhance biocompatibility between the scaffold and the biological tissues. The total integration between the host environment and the implant material highly demands to avoid scaffold deterioration [22–24]. Therefore, the development of surface roughness may introduce a facile strategy to induce complete cohesion, and thus, scaffolds could act to enhance the healing process.

3.4. Cell viability

The cytotoxicity of material towards the host environment is a key factor to estimate its feasibility for the implantation process. The statistical analysis was performed by Medcalc software version 15.0 (Medcalc 15.0, Mariakerke and Belgium). Continuous variables were expressed as mean ± standard deviation (SD). One sample t-test has been done and P value was obtained. Cell proliferation was examined against the human fibroblast cell line (HFB4) in vitro. As depicted in figure 7, the minimum cell viability ratio was not down than 96.1 ± 4.9%, while the highest ratio was around 98.4 ± 3.1%, which was achieved at 0.2MNPs-GO@PCL nanofibrous scaffolds with P < 0.0001. This relatively high ratio of cell viability indicates the high biocompatibility of these scaffolds, which may encourage their utilization for wound healing and disinfection applications.

Figure 5. (a)–(e) FESEM micrographs MNPs-GO@PCL nanofiber scaffolds at different contributions of MNPs: (a) 0.0MNPs-GO@PCL, (b) 0.1MNPs-GO@PCL, (c) 0.2MNPs-GO@PCL and (d) 0.3MNPs-GO@PCL, (e) diameters distribution of nanofibers scaffolds.
3.5. Antibacterial activity

The biggest obstacles that may delay the healing of the wound is a bacterial infection. Therefore, manipulation of a new scaffold should be encapsulated with an antibacterial agent to inhibit bacterial growth, whereas a healing procedure is going. The antibacterial activity was examined against both *E. coli* and *S. aureus* as described in figure 8. The antibacterial activity was significantly improved by adding MNPs, and the zone of inhibition was improved from 5.6 ± 1.1 mm and 4.3 ± 0.8 mm to be 12.3 ± 1.2 mm and 11.4 ± 1.6 mm against both *E. coli* and *S. aureus*, respectively. It could be mentioned that oxyanion groups that are connected on the surface of GO nanosheets tend to be diffused through the biological medium. These ions seem to be active towards the wall proteins of bacteria, which may facilitate their degeneration. It could be added that the encapsulation of MNPs through PCL nanofibers may induce the formation of more oxyanions. This behavior is hypothesized because higher contributions of MNPs induce higher surface roughness, which is often accompanied by higher biodegradation affinity, and thus higher ions are suggested to be released. Therefore, the growing behavior of antibacterial is accompanied by the encapsulation of MNPs in PCL nanofibers with the presence of GO nanosheets through the network.

3.6. Cells attachment *in-vitro*

The *in vitro* response of the human fibroblast cell line (HFB4) to the surface of nanofibers is an important property in evaluating the effectiveness of the framework for wound healing applications. Therefore, the as-synthesized nanofibers scaffolds were cultivated through biological media, while the HFB4 cell line was seeded.
on the nanofibers for 3 days. As obvious in figures 9(a)–(d), the composition of no contribution of MNPs, it could be stated that cells possess the tendency to grow and spread through nanofibers, while cells have adhered strongly towards the fiber. The higher content of MNPs, as 0.1MNPs-GO@PCL nanofibrous, encourages more cells to be proliferated, whereas the spread area of these cells seems to be higher than the former one. Increasing of MNP’s contribution to be 0.2MNPs-GO@PCL, the cells are connected, while their filopodia tend to follow the curving of nanofibers spreading. The highest contribution of MNPs as 0.3MNPs-GO@PCL in figure 9(d) shows that cells not only grow on the surface of the nanofibers but also seeded deep through the pores of the scaffold. This could improve their adhesion through the nanofibrous and facilitate cross-linking between scaffold and host environment. It could detect that increasing of MNPs may offer a reservoir of ions that are essential to induce the forming of new tissue. Therefore, releasing ions through the media, while the contribution of MNPs is increased displays a significant effect on the growth of cells [60, 61]. In addition to this, the great surface roughness that was generated with the additional MNPs induced adhesion behavior which is highly required for cells to be attached on the scaffold [25, 62]. Besides, the high ratio of porosity introduces a good facility to transport oxygen and nutrients, whereas vascularization could be formed through them.

Figure 7. Cell viability ratio of MNPs-GO@PCL nanofiber scaffolds at different contributions of MNPs after cultivation with HFB4 cell line *in vitro* for 3 days 95% CI 91.3 to 94.5 and highly significant with (*P* < 0.0001).

Figure 8. Antibacterial activity of MNPs-GO@PCL nanofiber scaffolds at different contributions of MNPs after cultivation with both *E. coli* and *S. aureus* for 3 days.
4. Conclusion

Different contributions of magnetite nanoparticles were encapsulated through nanofibrous scaffolds of polycaprolactone containing graphene oxide that were synthesized using the electrospinning technique. The morphological variation of the nanofibrous scaffolds showed a slight change in both fibers’ diameters and distribution. The narrow size distribution of 0.2–0.5 \( \mu m \) was detected with no contribution of MNPs, while diameters achieved about 0.1–0.3, 0.1–0.2, and 0.1–0.3 \( \mu m \) for 0.1NPs-GO@PCL, 0.2NPs-GO@PCL, and 0.3NPs-GO@PCL, respectively. The surface roughness was considerably varied upon the encapsulation of MNPs, whereas the roughness average (Ra) increased from 119 to be about 169 nm, and the maximum roughness peak height increased from 486 to 756 nm from no contribution of MNPs to the highest one. The cell viability elucidated that the nanofibers were biocompatible towards the HFB4 cell line. The antibacterial activity was also investigated and showed that the inhibition zone achieved around 11.4 \( \pm \) 1.6 mm and 12.3 \( \pm \) 1.2 against \textit{S. aureus} and \textit{E. coli} respectively in the case of the highest contribution of MNPs (0.3NPs-GO@PCL). The cell’s attachment test illustrated that the HFB4 cell line was proliferated and grew intensively through nanofibrous and the growth was enhanced significantly with the addition of MNPs. Therefore, it could be stated that the development of biomaterials for wound healing utilizations could be encouraging via tailoring of nanofibrous scaffolds containing different additions of substances such as graphene oxide and magnetite nanoparticles.

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Figure 9. HFB4 cells attachments towards MNPs-GO@PCL nanofibrous scaffolds at different contributions of MNPs after cultivation for 3 days in–vitro.
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