

World News of Natural Sciences

An International Scientific Journal

WNOFNS 65 (2026) 266-275

EISSN 2543-5426

Electrospun Polylactic Acid Nanofiber Mats Loaded with Andrographolide: Fabrication and Characterization

**Do Ngoc Thuy^{1,*}, Le Ngoc Hung^{1,4}, Nguyen Thi Huong¹,
Le Minh Ha², Mai Van Nam³**

¹ Center for High Technology Research and Development, Vietnam Academy of Science and Technology (VAST), 18-Hoang Quoc Viet, Nghia Do, Hanoi, Vietnam

² Institute of Chemistry, VAST, 18-Hoang Quoc Viet, Nghia Do, Hanoi, Vietnam

³ Hanoi University of Science and Technology, 1 Dai Co Viet Street, Bach Mai, Hanoi, Vietnam

⁴ Viptam Institute of Technology Application, TT3.9, Co Nhue 1, Nghia Do, Hanoi, Vietnam

*E-mail address: dothuy1992831@gmail.com

ABSTRACT

Andrographolide (AG), a bioactive diterpenoid isolated from *Andrographis paniculata*, exhibits significant pharmacological activities but suffers from low aqueous solubility. In this study, polylactic acid (PLA) was used to fabricate biocompatible electrospun nanofiber mats loaded with AG. The AG-loaded PLA nanofibers (AG/PLA-1 and AG/PLA-2) were successfully fabricated via electrospinning and characterized in terms of morphology and fiber diameter distribution using scanning electron microscopy (SEM) and Attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR). SEM analysis revealed smooth and continuous fibers with average diameters of 220 ± 20 nm for AG/PLA-1 and 350 ± 100 nm for AG/PLA-2. ATR-FTIR spectra confirmed the successful incorporation of AG into the PLA matrix without significant chemical interaction, indicating good compatibility between natural compound and polymer. These findings suggest that PLA-based electrospun nanofibers are a promising platform for the delivery of poorly water-soluble compounds such as andrographolide.

Keywords: Electrospinning, PLA, andrographolide, nanofiber, SEM, ATR-FTIR

1. INTRODUCTION

Electrospinning is a versatile nanofabrication method capable of producing continuous fibers with diameters down to a few nanometers. Due to their high surface area-to-volume ratio, tunable porosity, the electrospun nanofibers have attracted growing attention in biomedical engineering, particularly for drug delivery, wound dressings, and regenerative scaffolds (Keirouz et al., 2023). Several polymers have been used for electrospinning with various application aims. They are divided into 3 main groups, including synthetic (polylactic acid PLA, polycaprolactone PCL, poly(lactic-co-glycolic acid) PLGA, polyvinyl alcohol PVA, polyvinylpyrrolidone PVP, polyethylene oxide PEO), natural (gelatin, silk fibroin, chitosan), and semi-synthetic (ethyl cellulose, cellulose acetate) (Acosta et al., 2022). Among these materials, PLA is a semicrystalline, biodegradable polyester widely used for drug delivery, tissue engineering, and biomedical scaffold due to its biocompatibility and mechanical robustness. (Pan et al., 2025; Hemmatian et al., 2021; Ismail et al., 2024). Natural compounds-loaded electrospun-nanofibers not only enhance the solubility, stability, and sustained release of natural agents but also offer a high-surface-area, biocompatible delivery system for bioactive compounds for wound healing, anti-inflammatory treatments, and tissue engineering (Liu et al., 2024). Andrographolide (AG) is a labdane diterpene, the primary active component of *Andrographis paniculata*, known for potent antimicrobial, antitumor, antioxidant, anti-inflammatory, hepatoprotective, and immunostimulatory activities (Zenget al., 2022).

Despite its promising pharmacological activities, the therapeutic AG application is hindered by its poor aqueous solubility, short half-life, and limited permeability. Therefore, the development of the appropriate drug delivery systems are required to enhance its solubility, stability, and bioavailability. Previous studies reported that AG-loaded glyceryl monostearate nanoparticles could effectively enhance lymphatic drug delivery (Oseni et al., 2021). Recently, AG was loaded into PLGA electrospun materials for the application on the antibacterial wound dressing and cervical cancer treatment (Jia et al., 2018, Chen et al., 2019).

This research aimed to fabricate PLA nanofibers loaded with AG via electrospinning, and to characterize their physicochemical properties.

2. MATERIALS AND METHODS

2. 1. Materials

The leaves of *Andrographis paniculata* were collected in October 2023 and identified by Dr. Nguyen Sinh Khang, Institute of Ecology and Biological Resources, Vietnam Academy of Science and Technology (VAST). The voucher specimen (AG-L-2023) has been lodged at the Center for High Technology Research and Development (CHTD), VAST, Vietnam. Andrographolide, extracted from *Andrographis paniculata*'s leaves and then purified (purity $\geq 95\%$), was supplied by the CHTD. PLA ($M_w = 88000$) was purchased from Sigma-Aldrich (USA). Acetone and dimethylacetamide (DMAc) were obtained from Sigma-Aldrich (USA). All these chemicals were of analytical grade and used without further purification.

2. 2. Preparation of electrospinning solutions

Two 1:1 acetone /DMAc mixtures (100 ml each) were prepared. Two AG amounts (0.9g and 1.8g) were dissolved in two prepared solvent mixtures (100 ml each) using ultrasonication

for 15–30 minutes at 40 °C. Finally, PLA pellets (12g) were added gradually to each solution of AG-solvents to reach a final concentration of 12% w/v (100 mL of solvent). The final solutions of AG-PLA-solvents were continuously stirred for 2 hours at 40 °C until they appeared clear and viscous. Then, they were sonicated to remove air bubbles. The resulting solutions, incorporating AG at 7.5% and 15% relative to PLA (w/w), were labeled AG/PLA-1, and AG/PLA-2.

2. 3. Electrospinning process

The laboratory-scale electrospinning setup consisted of a 20 kV high-voltage supply, syringe pump (self-made), a syringe pump, and grounded Cu collector. The prepared polymer solution was loaded into a 5 mL plastic syringe fitted with a stainless steel needle (21G). The syringe was mounted on a programmable syringe pump to control the flow rate of the solution during electrospinning. The electrospinning parameters were based on typical electrospinning conditions for PLA-based systems as follows: applied voltage 18 kV, flow rate 0.6 mL/h, tip-to-collector distance: 15 cm, and ambient conditions 23 ± 2 °C and $40 \pm 5\%$ RH. The fibers were deposited onto an aluminum foil-covered Cu collector to form a continuous nanofiber mat. Electrospinning was carried out for approximately 60 minutes to obtain nanofiber films with sufficient thickness for characterization and dissolution studies. After electrospinning, the nanofiber mats were carefully removed from the collector and dried under vacuum at room temperature for 24 hours to remove residual solvent. The dried nanofiber films were stored in a desiccator prior to further characterization and testing.

2. 4. Characterization

2. 4. 1. Morphological analysis (SEM)

The morphology of the electrospun nanofibers was observed using scanning electron microscopy (Hitachi, S-4800). Samples were sputter-coated with a thin layer of gold before imaging. Fiber diameter distributions were calculated from 100 random SEM images using ImageJ analysis software.

2. 4. 2. ATR-FTIR analysis

ATR-FTIR was one of the technologies used to investigate the chemical functional groups of the electrospun samples. The ATR-FTIR measurements were conducted between 4000 cm^{-1} and 400 cm^{-1} on an FTIR Spectrometer (Nicolet Apex, Thermo Scientific) as previously described. All electrospun samples were measured with a spectral resolution of 4 cm^{-1} and 128 scans. Each measurement was replicated three times to affirm the reliability of the data. Assignments of the main bands were confirmed by analyzing the acquired spectra and comparing them with those the pure compound and polymer in the literature.

3. RESULTS AND DISCUSSION

3. 1. Morphology and fiber diameter

Two electrospun nanofiber formulations, AG/PLA-1 and AG/PLA-2, were successfully fabricated using the electrospinning technique, with polylactic acid as the polymer matrix and andrographolide incorporated as the active compound. The morphology of the electrospun

nanofibers was examined using SEM, and the representative images are presented in Figures 1 and 2. For AG/PLA-1, the SEM images reveal a uniform and smooth fiber morphology without bead formation. The fibers exhibit a diameter distribution ranging from 45 to 400 nm, with an average fiber diameter of 220 ± 20 nm, as determined by ImageJ analysis. In contrast, the AG/PLA-2 nanofibers also display a generally smooth morphology, although slight bead formation can be observed.

The fiber diameter ranges from 150 to 550 nm, with a larger average diameter of 350 ± 100 nm. The average fiber diameters of the electrospun nanofibers AG/PLA-1 and AG/PLA-2 were slightly lower than that reported for pure PLA electrospun nanofibers (447 ± 12 nm) (Bahramian et al., 2025), which may be attributed to the incorporation of Andrographolide affecting the solution properties during electrospinning. All electrospun samples displayed smooth, bead-free morphologies.

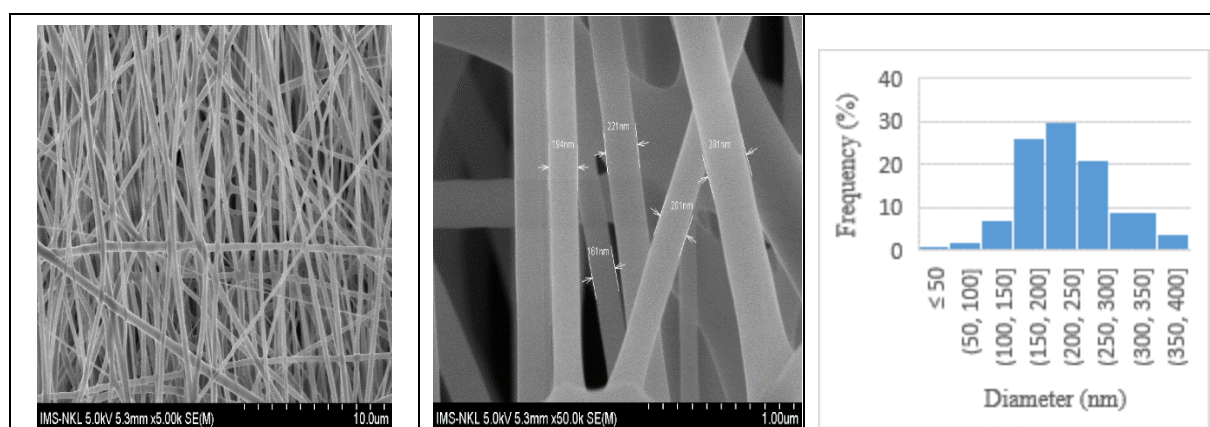


Figure 1. SEM micrographs of AG/PLA-1 electrospun nanofibers (SE, 5kV): (a) Low magnification $\times 5,000$, (b) High magnification $\times 50,000$, and (c) Fiber diameter distribution (45–400 nm) with a mean fiber diameter of 220 ± 20 nm (ImageJ analysis).

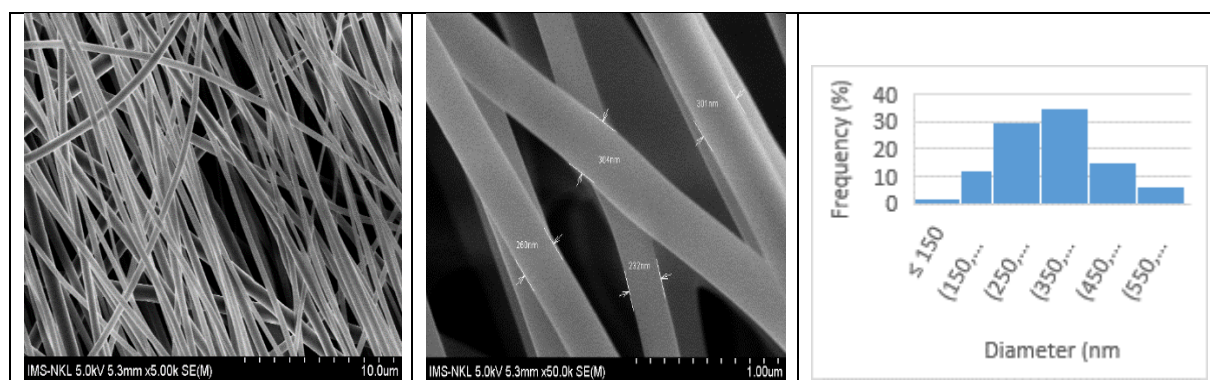


Figure 2. SEM micrographs of AG/PLA-2 electrospun nanofibers (SE, 5kV): (a) Low magnification $\times 5,000$, (b) High magnification $\times 50,000$, and (c) Fiber diameter distribution (150–550 nm) with a mean fiber diameter of 350 ± 100 nm (ImageJ analysis)

The quantitative results of fiber diameter distribution and morphological characteristics are summarized in Table 1. The mean fiber diameters increased with AG content, reflecting higher viscosity and conductivity of AG-loaded solutions.

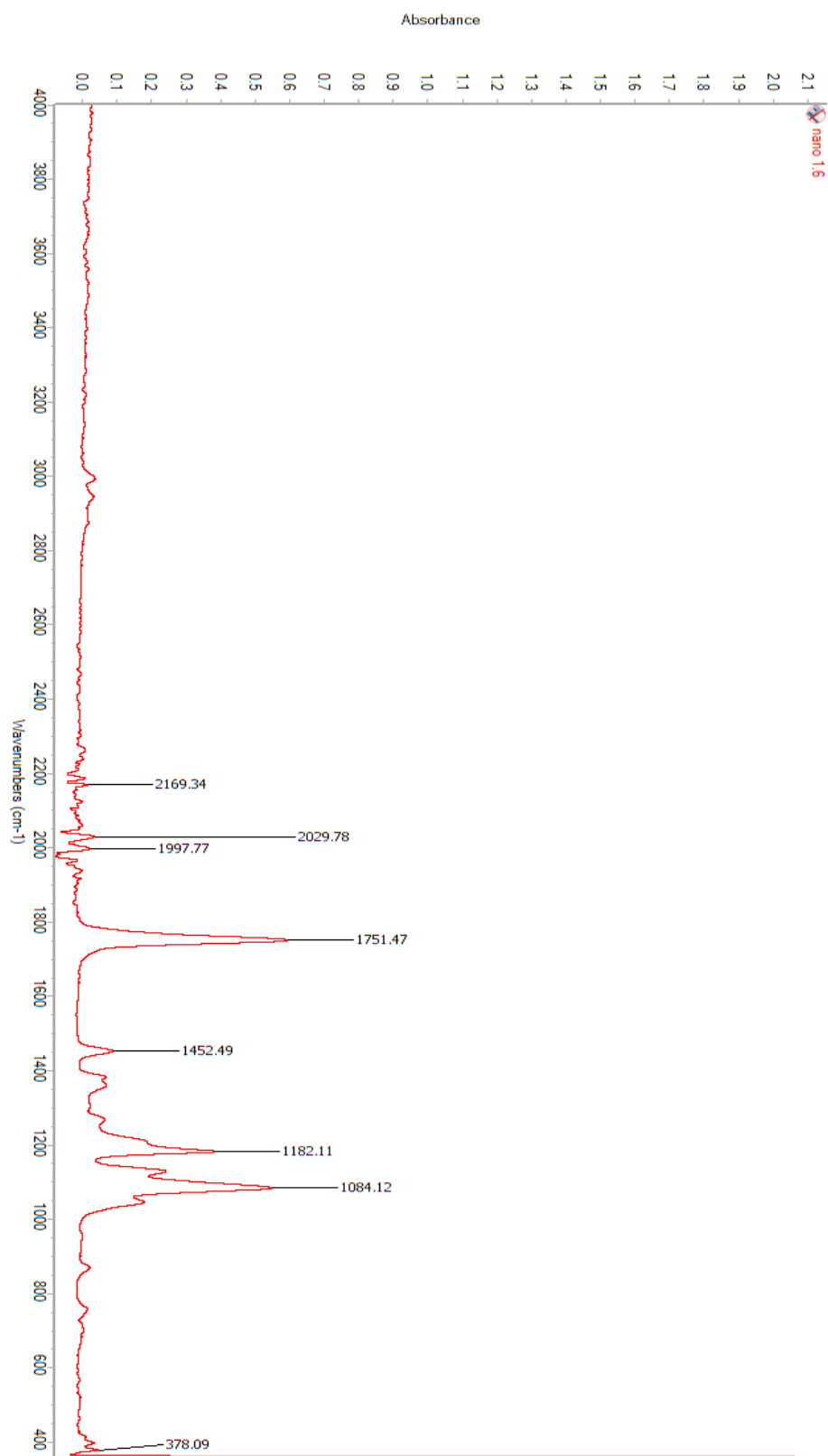
Table 1. Average fiber diameters and morphological characteristics of electrospun nanofibers.

Sample	Fiber diameter distribution	Mean fiber diameter	Morphology
AG/PLA-1	45-400 nm	220 ±20 nm	Smooth, bead-free
AG/PLA-2	150-550 nm	350 ±100 nm	Smooth, slight bead

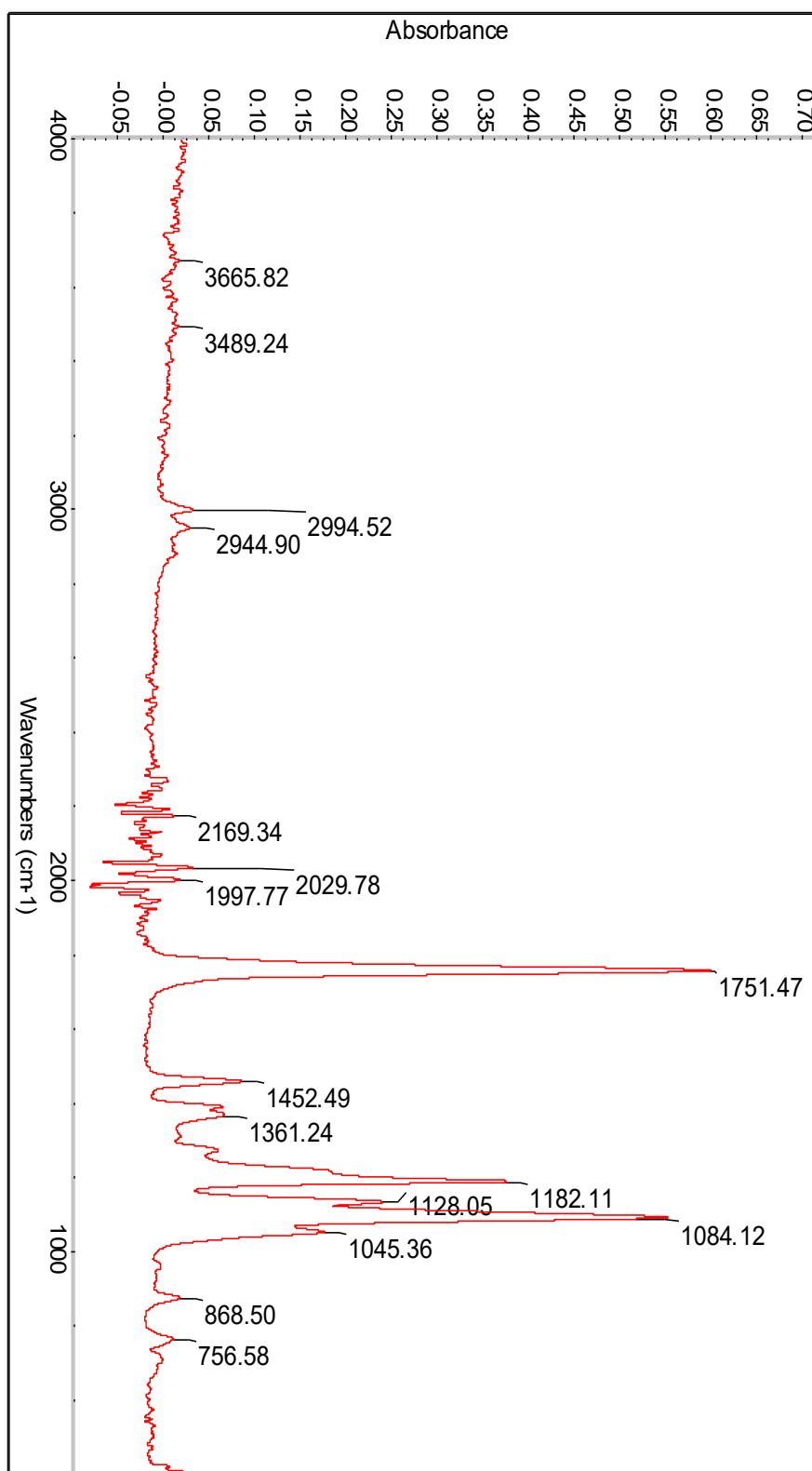
3. 2. ATR-FTIR analysis

The FTIR spectra of the electrospun nanofiber formulations AG/PLA-1 and AG/PLA-2 presented in Figure 3 and Table 2 were analyzed, compared with those of pure AG and PLA. The results show that both materials exhibit two characteristic peaks at 1182 cm^{-1} and 1751 cm^{-1} , corresponding to the stretching vibration of the C-O-C group and C=O carbonyl group, and a peak at 1452 cm^{-1} attributed to the -CH bending vibration. In addition, the peak at 2944 cm^{-1} corresponds to the symmetric stretching vibration of CH_3 , while the peak at 2994 cm^{-1} corresponds to the asymmetric CH_3 stretching vibration of the polymer component PLA (Farahani et al., 2021; Zahidova et al., 2023). In addition, the presence of AG in the electrospun fibers was evidenced by the characteristic band observed at $\sim 1084 \text{ cm}^{-1}$, assigned to the C-O stretching vibration of andrographolide, which is consistent with the spectral features of pure AG. The absorption bands at 760 cm^{-1} , 878 cm^{-1} , and 1015 cm^{-1} were attributed to different vibrational modes of AG, corresponding to the C-C-C ring vibration of the R2 moiety, the C-C stretching adjacent to the R1 ring, and the C-C backbone vibrations, respectively. Furthermore, in AG, the absorption band at approximately 1135 cm^{-1} is attributed to the C-O stretching vibration of the R3 ring structure, while the broad band centered around 3400 cm^{-1} corresponds to the O-H stretching vibration, likely arising from hydroxyl groups adjacent to the R1 ring.

The infrared spectroscopy results confirm the presence of both AG and PLA in the electrospun nanofiber materials AG/PLA-1 and AG/PLA-2 (Singh et al., 2006; Singh et al., 2007). These results indicate that both PLA and andrographolide are successfully incorporated into the electrospun nanofiber matrices. Compared with the spectra of the individual components, the characteristic peaks of both AG and PLA were retained in the spectra of AG/PLA-1 and AG/PLA-2, indicating that the electrospinning process did not alter the chemical structure of either component. However, slight shifts and broadening of some bands were observed in the nanofiber spectra, which may be attributed to intermolecular interactions between AG and PLA, particularly hydrogen bonding between the OH groups of AG and the C-O groups of PLA. Such interactions could promote homogeneous dispersion of the drug within the polymer matrix and improve drug-polymer compatibility. Overall, the FTIR results confirm the successful incorporation of AG into the PLA nanofiber structure and suggest favorable molecular interactions between the natural compound AG and polymer PLA, which may contribute to the stabilization of the drug in the electrospun nanofiber system.



(A)



(B)

Figure 3. ATR-FTIR spectra: (A) AG/PLA-1 and (B) AG/PLA-2 electrospun nanofibers

Table 2. ATR-FTIR vibrations of two AG/PLA electrospun nanofibers compared to pure AG and PLA

No	IR functional groups	ATR-FTIR vibrations (cm ⁻¹)			
		AG	PLA	AG/PLA-1	AG/PLA-2
1	C–C–C ring R2	715		small	760,33
2	C–C adjacent to ring R1	877		870,12	878,50
3	C–C back bone	1031		1.017,52	1015,36
4	C–O streching	1085		1.084,12	1.084,12
5	C-O-C stretching		1.188	1.182,11	1.182,11
6	C–O ring R3, adjacent to ring R3	1158		1.135,16	1.128,05
7	C–C ring R1 and R2, adjacent to ring R1	1367		1.364,35	1.361,24
8	C-H single bond bending		1.455	1.452,49	1.462,40
9	Ester C=O stretching or C=O stretching	1728	1.750	1.751,47	1.751,47
10	Symmetric CH ₃		2.941	small	2.944,90
11	Asymmetric CH ₃ group		2.993	small	2.994,52
12	O–H adjacent to ring R1	3402		small	3.400,52

4. CONCLUSION

In this study, PLA-based electrospun nanofiber mats loaded with AG were successfully fabricated using a simple electrospinning technique. The obtained nanofibers exhibited uniform morphology with nanoscale diameters, where AG incorporation influenced fiber diameter and morphology depending on AG loading. ATR-FTIR results verified the successful incorporation of AG into the PLA matrix without altering the chemical structure of either component.

The preservation of characteristic functional groups, together with slight peak shifts, suggests favorable intermolecular interactions which contribute to good compound–polymer compatibility and homogeneous dispersion of AG within the nanofiber matrix. This approach is expected to enhance AG dispersion and potentially improve dissolution behavior and bioavailability. The findings highlight the potential of PLA-based electrospun nanofibers for future applications in drug delivery and biomedical fields.

Acknowledgments

The project was supported by the Vietnam Academy of Science and Technology grant ĐL0000.06/22-23

References

- [1] Keirouz A, Wang Z, Reddy VS, et al. The history of electrospinning: Past, present, and future developments. *Adv Mater Technol* 2023; 8(11): 2201723
- [2] Acosta M, Santiago MD, Irvin JA. Electrospun Conducting Polymers: Approaches and Applications. *Materials (Basel)*. 2022, 15(24): 8820. doi: 10.3390/ma15248820
- [3] Pan X, Jiang Q, Zhong Y, Cui P, Hao W, Yang W. Biomedical applications of poly(lactic acid) electrospun nanofibers: A review. *Int J Biol Macromol*. 2025, 322(Pt 4): 146977. doi: 10.1016/j.ijbiomac.2025.146977
- [4] Hemmatian T, Seo KH, Yanilmaz M, Kim J. The Bacterial Control of Poly (Lactic Acid) Nanofibers Loaded with Plant-Derived Monoterpenoids via Emulsion Electrospinning. *Polymers (Basel)* 2021, 13(19): 3405. doi: 10.3390/polym13193405
- [5] Ismaili, D., Parin, F.N., Sıcak, Y. et al. Electrospun lavender essential oil-loaded polylactic acid nanofibrous mats for antioxidant applications. *Polym. Bull.* 81, 13975–13992 (2024). <https://doi.org/10.1007/s00289-024-05370-2>
- [6] Liu Q, Luo S, Peng J, Chang R. Electrospun Nanofibers from Plant Natural Products: A New Approach Toward Efficient Wound Healing. *Int J Nanomedicine* 19: 13973-13990. doi: 10.2147/IJN.S501970
- [7] Zeng B, Wei A, Zhou Q, Yuan M, Lei K, Liu Y, Song J, Guo L, Ye Q. Andrographolide: A review of its pharmacology, pharmacokinetics, toxicity and clinical trials and pharmaceutical researches. *Phytother Res.* 2022; 36(1): 336-364. doi: 10.1002/ptr.7324
- [8] Oseni BA, Azubuike CP, Okubanjo OO, Igwilo CI, Panyam J. Encapsulation of Andrographolide in poly(lactide-co-glycolide) Nanoparticles: Formulation Optimization and in vitro Efficacy Studies. *Front Bioeng Biotechnol.* 2021; 9: 639409. doi: 10.3389/fbioe.2021.639409
- [9] Jia Y, Zhang H, Yang S, Xi Z, Tang T, Yin R, Zhang W. Electrospun PLGA membrane incorporated with andrographolide-loaded mesoporous silica nanoparticles for sustained antibacterial wound dressing. *Nanomedicine (Lond)*. 2018; 13(22): 2881-2899. doi: 10.2217/nnm-2018-0099
- [10] Chen YP, Liu YW, Lee D, Qiu JT, Lee TY, Liu SJ. Biodegradable andrographolide-eluting nanofibrous membranes for the treatment of cervical cancer. *Int J Nanomedicine* 2019; 14: 421-429. doi: 10.2147/IJN.S186714
- [11] Bahramian, B., Abedi-Firoozjah, R., Salari, A., Mahmoudzadeh, M., Mazloomi, S.M., Rezaie, M., Ehsani, A., Tavassoli, M., & Jafari, S.M. (2025). Polylactic acid-based biodegradable electrospun nanofibers: A sustainable approach for food packaging. *Future Foods* 12, 100802. <https://doi.org/10.1016/j.fufo.2025.100802>
- [12] Farahani A, Zarei-Hanzaki A, Abedi HR, Tayebi L, Mostafavi E. Polylactic Acid Piezo-Biopolymers: Chemistry, Structural Evolution, Fabrication Methods, and Tissue Engineering Applications. *J Funct Biomater*. 2021; 12(4): 71. doi: 10.3390/jfb12040071

- [13] Zahidova F, Yildiz S, Özdemir A, Gülfen M, Yemiş GP. Modification of poly(L-lactic acid)-based films and evaluation of physical and antibacterial properties by using multivariate data analysis. *Int J Biol Macromol.* 2023; 241: 124583. doi: 10.1016/j.ijbiomac.2023.124583
- [14] Singh, P.K., Hasan, T., Prasad, O., Sinha, L., Raj, K., & Misra, N. (2006). FT-IR spectra and vibrational spectroscopy of Andrographolide. *Spectroscopy*, 20, 275-283
- [15] Singh, P.K., Hasan, T., Prasad, O., Sinha, L., Jain, S., Raj, K., Sundaraganesan, N., & Misra, N. (2007). Vibrational analysis of deoxy-andrographolide using MM/QM methods. *Spectroscopy*, 21, 279-292