Physicochemical properties of Electrically Conductive Polypyrrole-Ulvan/Chitosan Composite Films for Applications in Wound Dressings

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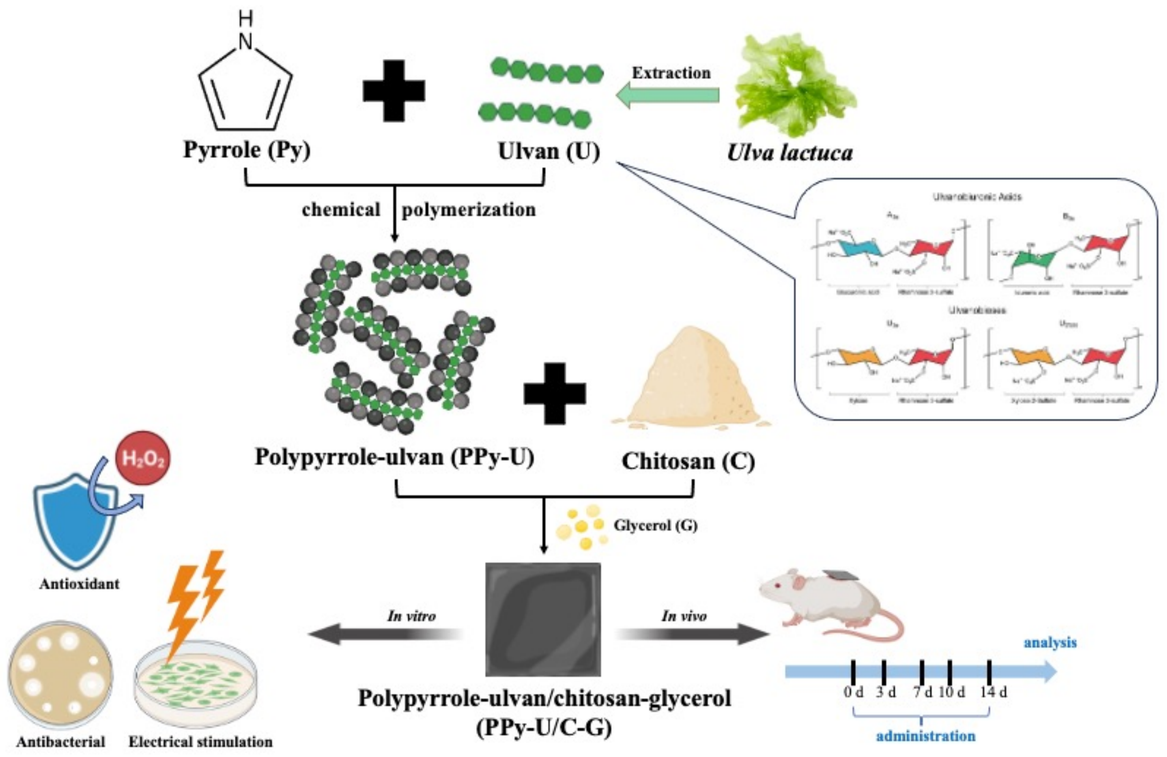
Abstract

Skin injury disrupts the epithelial transmembrane potential, generating endogenous bioelectric currents that guide cell migration and promote healing. To enhance endogenous electrical signaling and reduce infection risk, this study synthesized polypyrrole-ulvan (PPy-U) nanocomposites by polymerizing pyrrole (Py) monomer with ulvan (U), and further crosslinked them with chitosan (C) to fabricate conductive composite films (PPy-U/C). Among them, $PPy_{0.1}$-U/C exhibited the highest electrical conductivity. Fourier-transform infrared (FTIR) spectroscopy confirmed successful crosslinking between PPy and ulvan. The $PPy_{0.1}$-U/C film demonstrated good mechanical strength, especially after glycerol addition. The films exhibited cellular antioxidant activity and significantly enhanced fibroblast (NIH3T3) activity under 4 μA/cm² electrical stimulation. In terms of antibacterial activity, both PPy and $PPy_{0.1}$-U exhibited clear inhibition zones of approximately 18-22 mm. In vivo results showed that the $PPy_{0.1}$-U/C_3-G group achieved the best wound closure at all time points, with an average healing rate of 90.23% on day 14, significantly higher than the control group ($p < 0.05$). Histological analysis revealed that the $PPy_{0.1}$-U_1/C_3-G group had completed re-epithelialization and entered the remodeling phase, indicating superior epithelial regeneration.



Characterization of PPy-U and PPy-U/C composite film

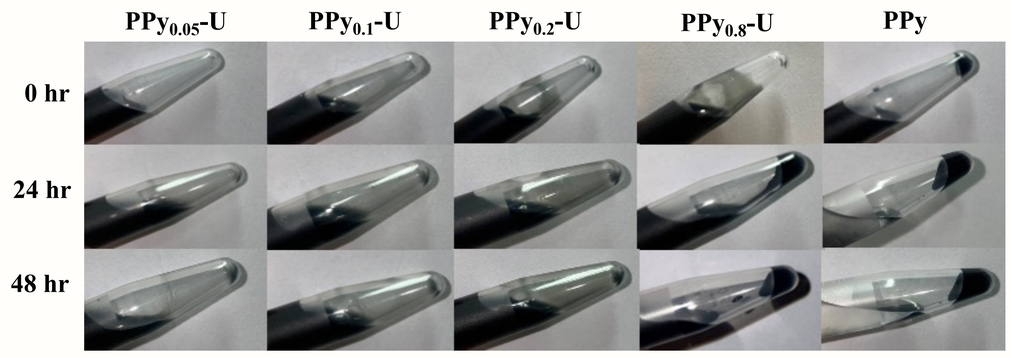


Fig 1. Solubility testing of PPy and PPy-U with tilt site.

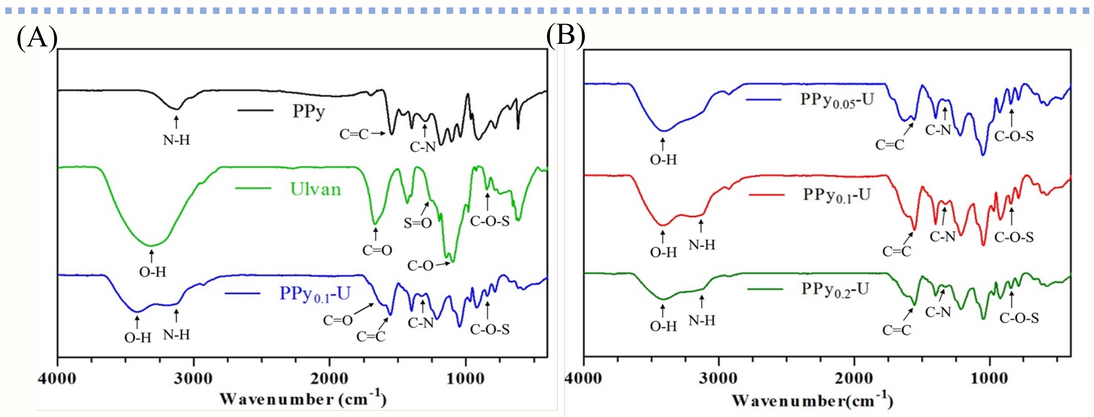


Fig 2. FT-IR spectra of (A) PPy, Ulvan and $PPy_{0.1}$-U. (B) $PPy_{0.05}$-U, $PPy_{0.1}$-U and $PPy_{0.2}$-U.

Table 1. Particle size and zeta potential of PPy-U.

sample	Py:U	Size (nm)	Polydispersity index (PDI)	Zeta potential (mV)
$PPy_{0.05}$-U	0.05 : 1	323.3±10.32	0.23±0.01	-46.33±0.80
$PPy_{0.1}$-U	0.1 : 1	255.1±4.07	0.17±0.01	-39.73±0.41
$PPy_{0.2}$-U	0.2 : 1	237.6±1.58	0.13±0.01	-36.70±0.75
$PPy_{0.8}$-U*	0.8 : 1	591.8±16.07	0.57±0.17	-40.66±0.72

*: precipitation

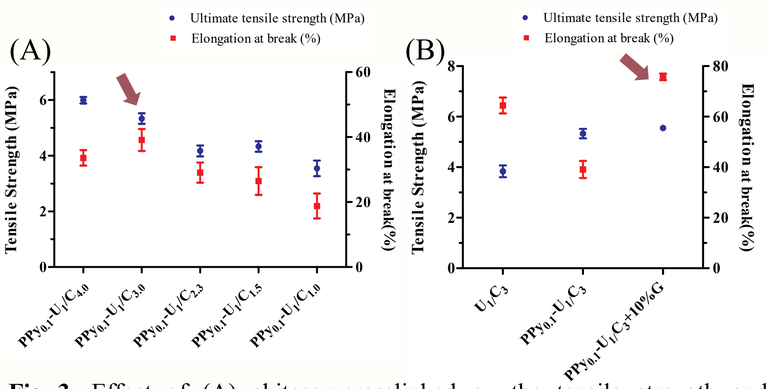


Fig 3. Effect of (A) chitosan-crosslinked on the tensile strength and elongation at break of PPy-U composite films compared with (B) U_1C_3 film.

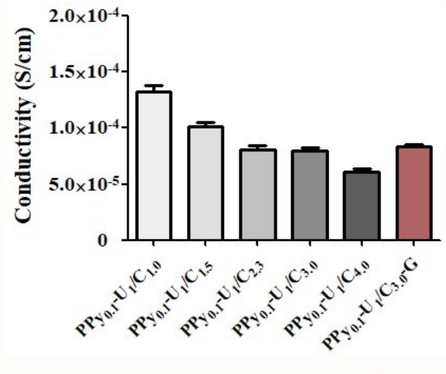


Fig 4. Electrical conductivity of PPy-U/C composite film with different chitosan weight ratio.

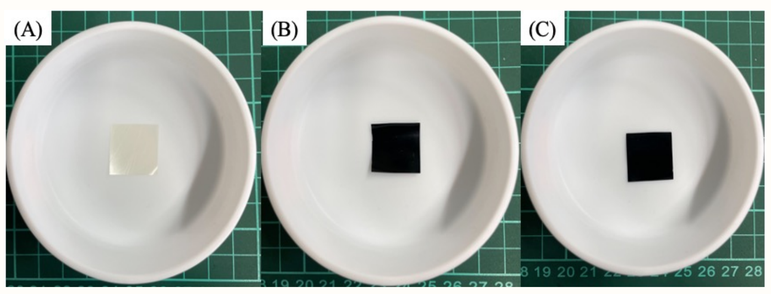


Fig 5. Photographic appearance of (A) U_1/C_3, (B) $PPy_{0.1}$-U_1/C_3, (C) $PPy_{0.1}$-U_1/C_3-G composite films.

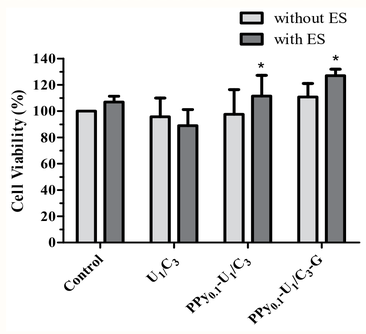


Fig 6. NIH3T3 cell viability on the composite films without or with electric stimulation after 3 days. *$p < 0.05$, compared with without electric stimulation control group.

Antibacterial and Antioxidant Activity

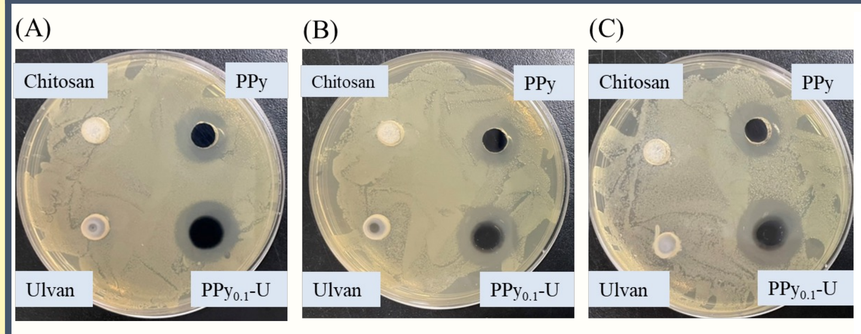


Fig 7. The inhibition zone test of Chitosan, Ulvan, PPy and $PPy_{0.1}$-U on (A) *P. aeruginosa,* (B) *S. aureus* and (C) *E. coli*.

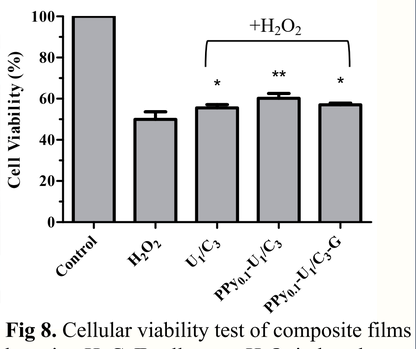


Fig 8. Cellular viability test of composite films by using HaCaT cells upon H_2O_2 induced oxidative stress. Control is medium.*$p < 0.05$, **$p < 0.01$, compared with H_2O_2 group.

Animal model

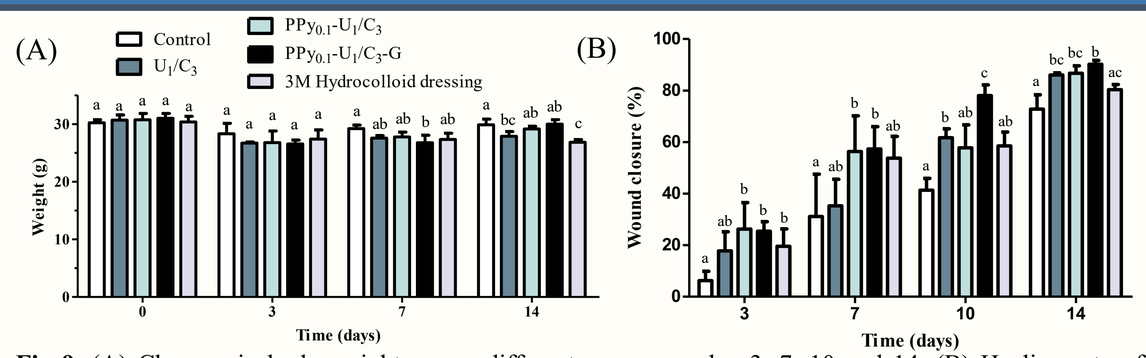


Fig 9. (A) Changes in body weight across different groups on day 3, 7, 10 and 14. (B) Healing rate of the defects on day 3, 7, 10 and 14.

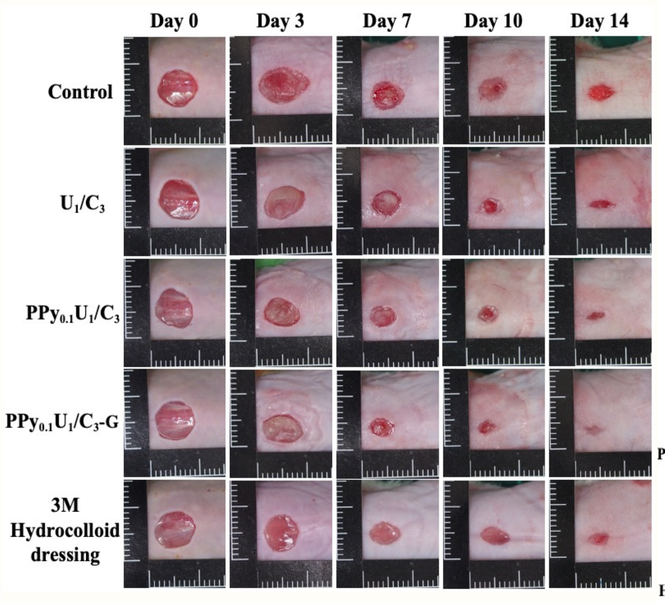


Fig 10. Full thickness skin defects and their healing trajectories in ICR mice.

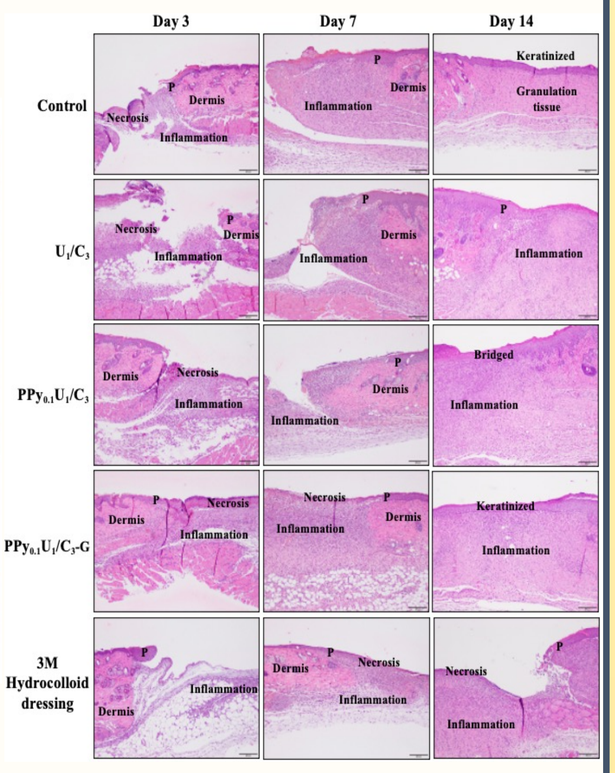


Fig 11. H&E staining of wounds on day 3, 7 and 14.

Conclusion

This study successfully developed bioactive and conductive polypyrrole-ulvan/chitosan composite films (PPy-U/C). Among them, $PPy_{0.1}$-U/C_3 exhibited optimal conductivity and mechanical properties, which were further improved by glycerol addition. The films demonstrated cellular antioxidant activity and promoted fibroblast activity under mild electrical stimulation. Both PPy and $PPy_{0.1}$-U exhibited significant antibacterial activity (18-22 mm inhibition zones). In vivo studies demonstrated that $PPy_{0.1}$-U_1/C_3-G films effectively accelerated wound healing, achieving a 90.23% closure rate by day 14, with complete re-epithelialization and tissue remodeling observed. Overall, the $PPy_{0.1}$-U_1/C_3-G films show strong potential as conductive dressings for wound healing and infection prevention.