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Mechanical properties and in vitro evaluation of thermoplastic polyurethane and polylactic acid blend for fabrication of 3d filaments for tracheal tissue engineering

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Abstract

Surgical reconstruction of extensive tracheal lesions is challenging. It requires a mechan-ically stable, biocompatible, and nontoxic material that gradually degrades. One of the possible solutions for overcoming the limitations of tracheal transplantation is a three-dimensional (3D) printed tracheal scaffold made of polymers. Polymer blending is one of the methods used to produce material for a trachea scaffold with tailored characteristics. The purpose of this study is to evaluate the mechanical and in vitro properties of a thermoplastic polyurethane (TPU) and polylactic acid (PLA) blend as a potential material for 3D printed tracheal scaffolds. Both materials were melt-blended using a single screw extruder. The morphologies (as well as the mechanical and thermal characteristics) were determined via scanning electron microscopy (SEM), Fourier Transform Infrared (FTIR) spectroscopy, tensile test, and Differential Scanning calorimetry (DSC). The samples were also evaluated for their water absorption, in vitro biodegradability, and biocompatibility. It is demonstrated that, despite being not miscible, TPU and PLA are biocompatible, and their promising properties are suitable for future applications in tracheal tissue engineering . © 2021 by the authors. Licensee MDPI, Basel, Switzerland. i.

Author keywords

3D filament ; Polylactic acid ; Thermoplastic polyurethane ; Trachea scaffold

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References (84)

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All

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1 Grillo, H.C.

Tracheal replacement: A critical review

(2002) *Annals of Thoracic Surgery*, 73 (6), pp. 1995-2004. Cited 346 times.
doi: 10.1016/S0003-4975(02)03564-6

View at Publisher

2 Kucera, K.A., Doss, A.E., Dunn, S.S., Clemson, L.A., Zwischenberger, J.B.

Tracheal replacements: Part 1

(2007) *ASAIO Journal*, 53 (4), pp. 497-505. Cited 45 times.
doi: 10.1097/MAT.0b013e3180616b5d

View at Publisher

3 *Organ Donation Statistics*. Cited 22 times.
US Health Resources and Services Administration. (accessed on 2 December 2019)
https://www.organdonor.gov/statistics-stories/statistics.html#waiting-list

4 Delaere, P., Van Raemdonck, D.

Tracheal replacement

(2016) *Journal of Thoracic Disease*, 8, pp. S186-S196. Cited 40 times.
http://jtd.amegroups.com/article/download/6714/pdf_1
doi: 10.3978/j.issn.2072-1439.2016.01.85

View at Publisher

5 Chiang, T., Pepper, V., Best, C., Onwuka, E., Breuer, C.K.

Clinical Translation of Tissue Engineered Trachea Grafts (Open Access)

(2016) *Annals of Otology, Rhinology and Laryngology*, 125 (11), pp. 873-885. Cited 37 times.
aor.sagepub.com/
doi: 10.1177/0003489416656646

View at Publisher

6 Elliott, M.J., De Coppi, P., Speggiorin, S., Roebuck, D., Butler, C.R., Samuel, E., Crowley, C., (...), Birchall, M.A.

Stem-cell-based, tissue engineered tracheal replacement in a child: A 2-year follow-up study (Open Access)

(2012) *The Lancet*, 380 (9846), pp. 994-1000. Cited 321 times.
http://www.journals.elsevier.com/the-lancet/
doi: 10.1016/S0140-6736(12)60737-5

View at Publisher

7 Hamilton, N.J., Kanani, M., Roebuck, D.J., Hewitt, R.J., Cetto, R., Culme-Seymour, E.J., Toll, E., (...), Birchall, M.A.

Tissue-Engineered Tracheal Replacement in a Child: A 4-Year Follow-Up Study (Open Access)

(2015) *American Journal of Transplantation*, 15 (10), pp. 2750-2757. Cited 112 times.
http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1600-6143
doi: 10.1111/ajt.13318

View at Publisher

8 Townsend, J.M., Ott, L.M., Salash, J.R., Fung, K.-M., Easley, J.T., Seim, H.B., Johnson, J.K., (...), Detamore, M.S.

Reinforced Electrospun Polycaprolactone Nanofibers for Tracheal Repair in an in Vivo Ovine Model (Open Access)

(2018) *Tissue Engineering - Part A*, 24 (17-18), pp. 1301-1308. Cited 18 times.
http://www.liebertonline.com/tea
doi: 10.1089/ten.tea.2017.0437

View at Publisher

9 Jing, X., Mi, H.-Y., Salick, M.R., Cordie, T., Crone, W.C., Peng, X.-F., Turng, L.-S.

Morphology, mechanical properties, and shape memory effects of poly(lactic acid)/ thermoplastic polyurethane blend scaffolds prepared by thermally induced phase separation

(2014) *Journal of Cellular Plastics*, 50 (4), pp. 361-379. Cited 38 times.
doi: 10.1177/0021955X14525959

View at Publisher

10 Xia, D., Jin, D., Wang, Q., Gao, M., Zhang, J., Zhang, H., Bai, J., (...), Fu, W.
Tissue-engineered trachea from a 3D-printed scaffold enhances whole-segment tracheal repair in a goat model

(2019) *Journal of Tissue Engineering and Regenerative Medicine*, 13 (4), pp. 694-703. Cited 17 times.
http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1932-7005
doi: 10.1002/term.2828

View at Publisher

11 Gao, M., Zhang, H., Dong, W., Bai, J., Gao, B., Xia, D., Feng, B., (...), Zheng, J.
Tissue-engineered trachea from a 3D-printed scaffold enhances whole-segment tracheal repair (Open Access)

(2017) *Scientific Reports*, 7 (1), art. no. 5246. Cited 62 times.
www.nature.com/srep/index.html
doi: 10.1038/s41598-017-05518-3

View at Publisher

12 O'Brien, F.J.
Biomaterials & scaffolds for tissue engineering (Open Access)

(2011) *Materials Today*, 14 (3), pp. 88-95. Cited 1925 times.
http://www.journals.elsevier.com/materials-today/
doi: 10.1016/S1369-7021(11)70058-X

View at Publisher

13 Sung, H.-J., Meredith, C., Johnson, C., Galis, Z.S.
The effect of scaffold degradation rate on three-dimensional cell growth and angiogenesis

(2004) *Biomaterials*, 25 (26), pp. 5735-5742. Cited 595 times.
doi: 10.1016/j.biomaterials.2004.01.066

View at Publisher

14 (2015) *Standard Terminology for Additive Manufacturing–General Principles–Terminology*, 1, pp. 1-9.
ISO/ASTM 52900. ASTM International: West Conshohocken, PA, USA, (accessed on 5 September 2021)
http://compass.astm.org/EDIT/html_annot.cgi?ISOASTM52900+15

15 Tofail, S.A.M., Koumoulos, E.P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., Charitidis, C.
Additive manufacturing: scientific and technological challenges, market uptake and opportunities (Open Access)

(2018) *Materials Today*, 21 (1), pp. 22-37. Cited 583 times.
http://www.journals.elsevier.com/materials-today/
doi: 10.1016/j.mattod.2017.07.001

View at Publisher

16 Bourell, D., Kruth, J.P., Leu, M., Levy, G., Rosen, D., Beese, A.M., Clare, A.

Materials for additive manufacturing

(2017) *CIRP Annals - Manufacturing Technology*, 66 (2), pp. 659-681. Cited 369 times.
http://www.elsevier.com/wps/find/journaldescription.cws_home/709764/description#description
doi: 10.1016/j.cirp.2017.05.009

View at Publisher

17 Jung, S.Y., Lee, S.J., Kim, H.Y., Park, H.S., Wang, Z., Kim, H.J., Yoo, J.J., (...), Kim, H.S.

3D printed polyurethane prosthesis for partial tracheal reconstruction: A pilot animal study

(2016) *Biofabrication*, 8 (4), art. no. 045015. Cited 36 times.
http://iopscience.iop.org/article/10.1088/1758-5090/8/4/045015/pdf
doi: 10.1088/1758-5090/8/4/045015

View at Publisher

18 Gao, B., Jing, H., Gao, M., Wang, S., Fu, W., Zhang, X., He, X., (...), Zheng, J.

Long-segmental tracheal reconstruction in rabbits with pedicled Tissue-engineered trachea based on a 3D-printed scaffold

(2019) *Acta Biomaterialia*, 97, pp. 177-186. Cited 16 times.
http://www.journals.elsevier.com/acta-biomaterialia
doi: 10.1016/j.actbio.2019.07.043

View at Publisher

19 Kim, I.G., Park, S.A., Lee, S.-H., Choi, J.S., Cho, H., Lee, S.J., Kwon, Y.-W., (...), Kwon, S.K.

Transplantation of a 3D-printed tracheal graft combined with iPS cell-derived MSCs and chondrocytes (Open Access)

(2020) *Scientific Reports*, 10 (1), art. no. 4326. Cited 24 times.
www.nature.com/srep/index.html
doi: 10.1038/s41598-020-61405-4

View at Publisher

20 She, Y., Fan, Z., Wang, L., Li, Y., Sun, W., Tang, H., Zhang, L., (...), Chen, C.

3D Printed Biomimetic PCL Scaffold as Framework Interspersed With Collagen for Long Segment Tracheal Replacement (Open Access)

(2021) *Frontiers in Cell and Developmental Biology*, 9, art. no. 629796. Cited 7 times.
https://www.frontiersin.org/journals/cell-and-developmental-biology#
doi: 10.3389/fcell.2021.629796

View at Publisher

21 Xie, F., Zhang, T., Bryant, P., Kurusingal, V., Colwell, J.M., Laycock, B.
Degradation and stabilization of polyurethane elastomers (Open Access)

(2019) *Progress in Polymer Science*, 90, pp. 211-268. Cited 117 times.
http://www.sciencedirect.com/science/journal/00796700
doi: 10.1016/j.progpolymsci.2018.12.003

View at Publisher

22 Williamson, M.R., Black, R., Kielty, C.
PCL-PU composite vascular scaffold production for vascular tissue engineering: Attachment, proliferation and bioactivity of human vascular endothelial cells

(2006) *Biomaterials*, 27 (19), pp. 3608-3616. Cited 208 times.
doi: 10.1016/j.biomaterials.2006.02.025

View at Publisher

23 Bergmeister, H., Seyidova, N., Schreiber, C., Strobl, M., Grasl, C., Walter, I., Messner, B., (...), Schima, H.
Biodegradable, thermoplastic polyurethane grafts for small diameter vascular replacements

(2015) *Acta Biomaterialia*, 11 (1), pp. 104-113. Cited 80 times.
http://www.journals.elsevier.com/acta-biomaterialia
doi: 10.1016/j.actbio.2014.09.003

View at Publisher

24 Yu, E., Zhang, J., Thomson, J.A., Turng, L.-S.
Fabrication and characterization of electrospun thermoplastic polyurethane/fibroin small-diameter vascular grafts for vascular tissue engineering (Open Access)

(2016) *International Polymer Processing*, 31 (5), pp. 638-646. Cited 17 times.
http://www.hanser-elibrary.com/doi/pdf/10.3139/217.3247
doi: 10.3139/217.3247

View at Publisher

25 Du, Y.J., Brash, J.L., McClung, G., Berry, L.R., Klement, P., Chan, A.K.C.
Protein adsorption on polyurethane catheters modified with a novel antithrombin-heparin covalent complex (Open Access)

(2007) *Journal of Biomedical Materials Research - Part A*, 80 (1), pp. 216-225. Cited 71 times.
doi: 10.1002/jbm.a.30977

View at Publisher

26 Kim, L., Hermel-Davidock, T., Weimer, M.W., Burkolz, J.K.
(2017) *Catheter Tubing with Tailored Modulus Response*
U.S. Patent 10596302B2, 17 April

27 Shie, M.-Y., Chang, W.-C., Wei, L.-J., Huang, Y.-H., Chen, C.-H., Shih, C.-T., Chen, Y.-W., (...), Shen, Y.-F.

3D printing of cytocompatible water-based light-cured polyurethane with hyaluronic acid for cartilage tissue engineering applications (Open Access)

(2017) *Materials*, 10 (2), art. no. 136. Cited 62 times.
http://www.mdpi.com/1996-1944/10/2/136/pdf
doi: 10.3390/ma10020136

View at Publisher

28 Ge, Z., Li, C., Heng, B.C., Cao, G., Yang, Z.

Functional biomaterials for cartilage regeneration

(2012) *Journal of Biomedical Materials Research - Part A*, 100 A (9), pp. 2526-2536. Cited 88 times.
doi: 10.1002/jbm.a.34147

View at Publisher

29 Södergård, A., Stolt, M.

Properties of lactic acid based polymers and their correlation with composition

(2002) *Progress in Polymer Science (Oxford)*, 27 (6), pp. 1123-1163. Cited 1101 times.
doi: 10.1016/S0079-6700(02)00012-6

View at Publisher

30 Casalini, T., Rossi, F., Castrovinci, A., Perale, G.

A Perspective on Polylactic Acid-Based Polymers Use for Nanoparticles Synthesis and Applications (Open Access)

(2019) *Frontiers in Bioengineering and Biotechnology*, 7, art. no. 259. Cited 84 times.
http://journal.frontiersin.org/journal/bioengineering-and-biotechnology#archive
doi: 10.3389/fbioe.2019.00259

View at Publisher

31 Liu, S., Yu, J., Li, H., Wang, K., Wu, G., Wang, B., Liu, M., (...), Zhang, M.

Controllable drug release behavior of polylactic acid (PLA) surgical suture coating with ciprofloxacin (CPFX)-polycaprolactone (PCL)/ polyglycolide (PGA) (Open Access)

(2020) *Polymers*, 12 (2), art. no. 288. Cited 19 times.
https://res.mdpi.com/d_attachment/polymers/polymers-12-00288/article_deploy/polymers-12-00288-v2.pdf
doi: 10.3390/polym12020288

View at Publisher

32 Tappa, K., Jammalamadaka, U., Weisman, J.A., Ballard, D.H., Wolford, D.D., Pascual-Garrido, C., Wolford, L.M., (...), Mills, D.K.

3D printing custom bioactive and absorbable surgical screws, pins, and bone plates for localized drug delivery (Open Access)

(2019) *Journal of Functional Biomaterials*, 10 (2), art. no. 17. Cited 24 times.
http://www.mdpi.com/journal/jfb
doi: 10.3390/jfb10020017

View at Publisher

33 Sikhosana, S.T., Gumede, T.P., Malebo, N.J., Ogundeji, A.O.

Poly(Lactic acid) and its composites as functional materials for 3-d scaffolds in biomedical applications: A mini-review of recent trends (Open Access)

(2021) *Express Polymer Letters*, 15 (6), pp. 568-580. Cited 3 times.
http://www.expresspolymlett.com/letolt.php?file=EPL-0011050&mi=c
doi: 10.3144/expresspolymlett.2021.48

View at Publisher

34 Saini, P., Arora, M., Kumar, M.N.V.R.

Poly(lactic acid) blends in biomedical applications

(2016) *Advanced Drug Delivery Reviews*, 107, pp. 47-59. Cited 221 times.
www.elsevier.com/locate/drugdeliv
doi: 10.1016/j.addr.2016.06.014

View at Publisher

35 Hamad, K., Kaseem, M., Ayyoob, M., Joo, J., Deri, F.

Polylactic acid blends: The future of green, light and tough

(2018) *Progress in Polymer Science*, 85, pp. 83-127. Cited 218 times.
http://www.sciencedirect.com/science/journal/00796700
doi: 10.1016/j.progpolymsci.2018.07.001

View at Publisher

36 Lin, T.A., Lou, C.-W., Lin, J.-H.

The effects of thermoplastic polyurethane on the structure and mechanical properties of modified polypropylene blends (Open Access)

(2017) *Applied Sciences (Switzerland)*, 7 (12), art. no. 1254. Cited 11 times.
http://www.mdpi.com/2076-3417/7/12/1254/pdf
doi: 10.3390/app7121254

View at Publisher

37 Grimmer, J.F., Gunnlaugsson, C.B., Alsberg, E., Murphy, H.S., Kong, H.J., Mooney, D.J., Weatherly, R.A.

Tracheal reconstruction using tissue-engineered cartilage (Open Access)

(2004) *Archives of Otolaryngology - Head and Neck Surgery*, 130 (10), pp. 1191-1196. Cited 58 times.
doi: 10.1001/archotol.130.10.1191

View at Publisher

38 Komura, M., Komura, H., Kanamori, Y., Tanaka, Y., Suzuki, K., Sugiyama, M., Nakahara, S., (...), Iwanaka, T.

An animal model study for tissue-engineered trachea fabricated from a biodegradable scaffold using chondrocytes to augment repair of tracheal stenosis

(2008) *Journal of Pediatric Surgery*, 43 (12), pp. 2141-2146. Cited 73 times.
doi: 10.1016/j.jpedsurg.2008.08.038

View at Publisher

39 Kang, N., Liu, X., Guan, Y., Wang, J., Gong, F., Yang, X., Yan, L., (...), Xiao, R.

Effects of co-culturing BMSCs and auricular chondrocytes on the elastic modulus and hypertrophy of tissue engineered cartilage

(2012) *Biomaterials*, 33 (18), pp. 4535-4544. Cited 45 times.
doi: 10.1016/j.biomaterials.2012.03.019

View at Publisher

40 Romanova, O.A., Tenchurin, T.H., Demina, T.S., Sytina, E.V., Shepelev, A.D., Rudyak, S.G., Klein, O.I., (...), Panteleyev, A.A.

Non-woven bilayered biodegradable chitosan-gelatin-polylactide scaffold for bioengineering of tracheal epithelium (Open Access)

(2019) *Cell Proliferation*, 52 (3), art. no. e12598. Cited 15 times.
http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1365-2184
doi: 10.1111/cpr.12598

View at Publisher

41 Omori, K., Tada, Y., Suzuki, T., Nomoto, Y., Matsuzuka, T., Kobayashi, K., Nakamura, T., (...), Asato, R.

Clinical application of in situ tissue engineering using a scaffolding technique for reconstruction of the larynx and trachea

(2008) *Annals of Otology, Rhinology and Laryngology*, 117 (9), pp. 673-678. Cited 117 times.
http://www.annals.com/toc/auto_article_process.php?year=2008&page=673&id=15273&sn=0
doi: 10.1177/000348940811700908

View at Publisher

42 Hamaji, M., Kojima, F., Koyasu, S., Tsuruyama, T., Komatsu, T., Ikuno, T., Date, H., (...), Nakamura, T.

Development of a composite and vascularized tracheal scaffold in the omentum for in situ tissue engineering: A canine model (Open Access)

(2014) *Interactive Cardiovascular and Thoracic Surgery*, 19 (3), pp. 357-362. Cited 11 times.
doi: 10.1093/icvts/ivu177

View at Publisher

43 Best, C.A., Pepper, V.K., Ohst, D., Bodnyk, K., Heuer, E., Onwuka, E.A., King, N., (...), Chiang, T.

Designing a tissue-engineered tracheal scaffold for preclinical evaluation (Open Access)

(2018) *International Journal of Pediatric Otorhinolaryngology*, 104, pp. 155-160. Cited 28 times.
www.elsevier.com/locate/ijporl
doi: 10.1016/j.ijporl.2017.10.036

View at Publisher

44 Haliloglu, T., Onar, V., Yildirim, G., Sapci, T., Savci, N., Kahvecioglu, O., Karavus, A.

Tracheal reconstruction with porous high-density polyethylene tracheal prosthesis

(2000) *Annals of Otology, Rhinology and Laryngology*, 109 (10 I), pp. 981-987. Cited 17 times.
aor.sagepub.com/
doi: 10.1177/000348940010901013

View at Publisher

45 Lin, C.-H., Su, J.-M., Hsu, S.-H.

Evaluation of type II collagen scaffolds reinforced by poly(ε-caprolactone) as tissue-engineered trachea

(2008) *Tissue Engineering - Part C: Methods*, 14 (1), pp. 69-77. Cited 53 times.
http://www.liebertonline.com/tec
doi: 10.1089/tec.2007.0336

View at Publisher

46 Rehmani, S.S., Al-Ayoubi, A.M., Ayub, A., Barsky, M., Lewis, E., Flores, R., Lebovics, R., (...), Bhora, F.Y.

Three-Dimensional-Printed Bioengineered Tracheal Grafts: Preclinical Results and Potential for Human Use

(2017) *Annals of Thoracic Surgery*, 104 (3), pp. 998-1004. Cited 25 times.
www.elsevier.com/locate/athoracsur
doi: 10.1016/j.athoracsur.2017.03.051

View at Publisher

47 Yin, H., Wang, J., Gu, Z., Feng, W., Gao, M., Wu, Y., Zheng, H., (...), Mo, X.

Evaluation of the potential of kartogenin encapsulated poly(L-lactic acid-co-caprolactone)/collagen nanofibers for tracheal cartilage regeneration

(2017) *Journal of Biomaterials Applications*, 32 (3), pp. 331-341. Cited 20 times.
http://jba.sagepub.com/
doi: 10.1177/0885328217717077

View at Publisher

48 Chang, C.S., Yang, C.Y., Hsiao, H.Y., Chen, L., Chu, I.M., Cheng, M.H., Tsao, C.-K.

Cultivation of auricular chondrocytes in poly(ethylene glycol)/poly(ε-caprolactone) hydrogel for tracheal cartilage tissue engineering in a rabbit model (Open Access)

(2018) *European Cells and Materials*, 35, pp. 350-364. Cited 10 times.
http://www.ecmjournal.org/papers/vol035pdf/vol035a24.pdf
doi: 10.22203/eCM.v035a24

View at Publisher

49 Safshekan, F., Tafazzoli-Shadpour, M., Abdouss, M., Shadmehr, M.B.

Mechanical characterization and constitutive modeling of human trachea: Age and gender dependency (Open Access)

(2016) *Materials*, 9 (6), art. no. 456. Cited 43 times.
http://www.mdpi.com/1996-1944/9/6/456/pdf
doi: 10.3390/ma9060456

View at Publisher

50 Dong, Z., Li, Y., Zou, Q.

Degradation and biocompatibility of porous nano-hydroxyapatite/polyurethane composite scaffold for bone tissue engineering

(2009) *Applied Surface Science*, 255 (12), pp. 6087-6091. Cited 150 times.
http://www.journals.elsevier.com/applied-surface-science/
doi: 10.1016/j.apsusc.2009.01.083

View at Publisher

51 Mi, H.-Y., Salick, M.R., Jing, X., Jacques, B.R., Crone, W.C., Peng, X.-F., Turng, L.-S.

Characterization of thermoplastic polyurethane/polylactic acid (TPU/PLA) tissue engineering scaffolds fabricated by microcellular injection molding (Open Access)

(2013) *Materials Science and Engineering C*, 33 (8), pp. 4767-4776. Cited 189 times.
doi: 10.1016/j.msec.2013.07.037

View at Publisher

52 Tang, Q., Gao, K.

Structure analysis of polyether-based thermoplastic polyurethane elastomers by FTIR, ^{1}H NMR and ^{13}C NMR

(2017) *International Journal of Polymer Analysis and Characterization*, 22 (7), pp. 569-574. Cited 21 times.
http://www.tandf.co.uk/journals/titles/1023666x.html
doi: 10.1080/1023666X.2017.1312754

View at Publisher

53 Pan, R., Yang, L., Zheng, L., Hao, L., Li, Y.

Microscopic morphology, thermodynamic and mechanical properties of thermoplastic polyurethane fabricated by selective laser sintering (Open Access)

(2020) *Materials Research Express*, 7 (5), art. no. 055301. Cited 4 times.
https://iopscience.iop.org/article/10.1088/2053-1591/ab8b87/pdf
doi: 10.1088/2053-1591/ab8b87

View at Publisher

54 Guo, Z., Yang, C., Zhou, Z., Chen, S., Li, F.

Characterization of biodegradable poly(lactic acid) porous scaffolds prepared using selective enzymatic degradation for tissue engineering (Open Access)

(2017) *RSC Advances*, 7 (54), pp. 34063-34070. Cited 29 times.
http://pubs.rsc.org/en/journals/journalissues
doi: 10.1039/c7ra03574h

View at Publisher

55 Yang, X.-Z., Wang, Y.-C., Tang, L.-Y., Xia, H., Wang, J.

Synthesis and characterization of amphophilic block copolymer of polyphosphoester and poly(L-lactic acid)

(2008) *Journal of Polymer Science, Part A: Polymer Chemistry*, 46 (19), pp. 6425-6434. Cited 52 times.
doi: 10.1002/pola.22951

View at Publisher

56 Oliaei, E., Kaffashi, B., Davoodi, S.

Investigation of structure and mechanical properties of toughened poly(l -lactide)/thermoplastic poly(ester urethane) blends

(2016) *Journal of Applied Polymer Science*, 133 (15), art. no. 43104. Cited 36 times.
http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1097-4628
doi: 10.1002/app.43104

View at Publisher

57 Jašo, V., Cvetinov, M., Rakič, S.S.S., Petrovič, Z.S.

Bio-plastics and elastomers from polylactic acid/thermoplastic polyurethane blends

(2014) *Journal of Applied Polymer Science*, 131 (22), art. no. 41104. Cited 49 times.
http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1097-4628
doi: 10.1002/app.41104

View at Publisher

58 Focarete, M.L., Scandola, M., Dobrzynski, P., Kowalczuk, M.

Miscibility and mechanical properties of blends of (L)-lactide copolymers with atactic poly(3-hydroxybutyrate)

(2002) *Macromolecules*, 35 (22), pp. 8472-8477. Cited 113 times.
doi: 10.1021/ma020940z

View at Publisher

59 Zhang, K., Ran, X., Wang, X., Han, C., Han, L., Wen, X., Zhuang, Y., (...), Dong, L.

Improvement in toughness and crystallization of poly(L -lactic acid) by melt blending with poly(epichlorohydrin-co-ethylene oxide)

(2011) *Polymer Engineering and Science*, 51 (12), pp. 2370-2380. Cited 47 times.
doi: 10.1002/pen.22009

View at Publisher

60 Imre, B., Bedo, D., Domján, A., Schön, P., Vancso, G.J., Pukánszky, B.

Structure, properties and interfacial interactions in poly(lactic acid)/polyurethane blends prepared by reactive processing (Open Access)

(2013) *European Polymer Journal*, 49 (10), pp. 3104-3113. Cited 47 times.
doi: 10.1016/j.eurpolymj.2013.07.007

View at Publisher

61 Mahmud, M.S., Buys, Y.F., Anuar, H., Sopyan, I.
Miscibility, morphology and mechanical properties of compatibilized polylactic acid/thermoplastic polyurethane blends
(2018) *Materials Today, Proceedings of the RAMM 2018*, 17, pp. 778-786. Penang Malaysia, 27–29 November Elsevier Ltd.: Amsterdam, The Netherlands, 2019

62 Wang, J., Zhang, Y., Sun, W., Chu, S., Chen, T., Sun, A., Guo, J., (...), Xu, G.

Morphology Evolutions and Mechanical Properties of In Situ Fibrillar Polylactic Acid/Thermoplastic Polyurethane Blends Fabricated by Fused Deposition Modeling

(2019) *Macromolecular Materials and Engineering*, 304 (7), art. no. 1900107. Cited 12 times.
http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1439-2054
doi: 10.1002/mame.201900107

View at Publisher

63 Roberts, C.R., Rains, J.K., Paré, P.D., Walker, D.C., Wiggs, B., Bert, J.L.

Ultrastructure and tensile properties of human tracheal cartilage

(1997) *Journal of Biomechanics*, 31 (1), pp. 81-86. Cited 80 times.
www.elsevier.com/locate/jbiomech
doi: 10.1016/S0021-9290(97)00112-7

View at Publisher

64 Safshekan, F., Tafazzoli-Shadpour, M., Abdouss, M., Shadmehr, M.B., Ghorbani, F.

Investigation of the mechanical properties of the human tracheal cartilage

(2017) *Tanaffos*, 16 (2), pp. 107-114. Cited 7 times.
http://www.tanaffosjournal.ir/files_site/paperlist/r_804_171227113829.pdf

65 Wang, Y., Liu, S., Ding, K., Zhang, Y., Ding, X., Mi, J.

Quaternary tannic acid with improved leachability and biocompatibility for antibacterial medical thermoplastic polyurethane catheters

(2021) *Journal of Materials Chemistry B*, 9 (23), pp. 4746-4762. Cited 2 times.
http://pubs.rsc.org/en/journals/journal/tb
doi: 10.1039/d1tb00227a

View at Publisher

66 Domínguez-Robles, J., Mancinelli, C., Mancuso, E., García-Romero, I., Gilmore, B.F., Casettari, L., Larrañeta, E., (...), Lamprou, D.A.

3D printing of drug-loaded thermoplastic polyurethane meshes: A potential material for soft tissue reinforcement in vaginal surgery (Open Access)

(2020) *Pharmaceutics*, 12 (1), art. no. 63. Cited 41 times.
https://www.mdpi.com/1999-4923/12/1/63/pdf
doi: 10.3390/pharmaceutics12010063

View at Publisher

67 Lis-Bartos, A., Smieszek, A., Frańczyk, K., Marycz, K.

Fabrication, characterization, and cytotoxicity of thermoplastic polyurethane/poly(lactic acid) material using human adipose derived mesenchymal stromal stem cells (hASCs) (Open Access)

(2018) *Polymers*, 10 (10), art. no. 1073. Cited 10 times.
https://www.mdpi.com/2073-4360/10/10/1073/pdf
doi: 10.3390/polym10101073

View at Publisher

68 Thomas, S., Shanks, R., Chandrasekharakurup, S.

Design and Applications of Nanostructured Polymer Blends and Nanocomposite Systems

(2015) *Design and Applications of Nanostructured Polymer Blends and Nanocomposite Systems*, pp. 1-426. Cited 15 times.
http://www.sciencedirect.com/science/book/9780323394086
ISBN: 978-032339454-3; 978-032339408-6
doi: 10.1016/C2013-0-13999-2

View at Publisher

69 Feng, F., Ye, L.

Morphologies and mechanical properties of polylactide/thermoplastic polyurethane elastomer blends

(2011) *Journal of Applied Polymer Science*, 119 (5), pp. 2778-2783. Cited 146 times.
doi: 10.1002/app.32863

View at Publisher

70 Rains, J.K., Bert, J.L., Roberts, C.R., Pare, P.D.

Mechanical properties of human tracheal cartilage

(1992) *Journal of Applied Physiology*, 72 (1), pp. 219-225. Cited 101 times.
doi: 10.1152/jappl.1992.72.1.219

View at Publisher

71 Bonakdar, S., Emami, S.H., Shokrgozar, M.A., Farhadi, A., Ahmadi, S.A.H., Amanzadeh, A.

Preparation and characterization of polyvinyl alcohol hydrogels crosslinked by biodegradable polyurethane for tissue engineering of cartilage

(2010) *Materials Science and Engineering C*, 30 (4), pp. 636-643. Cited 100 times.
doi: 10.1016/j.msec.2010.02.017

View at Publisher

72 Gogolewski, S., Gorna, K., Zaczynska, E., Czarny, A.

Structure-property relations and cytotoxicity of isosorbide-based biodegradable polyurethane scaffolds for tissue repair and regeneration

(2008) *Journal of Biomedical Materials Research - Part A*, 85 (2), pp. 456-465. Cited 43 times.
doi: 10.1002/jbm.a.31481

View at Publisher

73 Revati, R., Majid, M.S.A., Ridzuan, M.J.M., Basaruddin, K.S., Rahman Y., M.N., Cheng, E.M., Gibson, A.G.

In vitro degradation of a 3D porous Pennisetum purpureum/PLA biocomposite scaffold

(2017) *Journal of the Mechanical Behavior of Biomedical Materials*, 74, pp. 383-391. Cited 22 times.
http://www.elsevier.com/wps/find/journaldescription.cws_home/711005/description#description
doi: 10.1016/j.jmbbm.2017.06.035

View at Publisher

74 Chen, Q., Bruyneel, A., Clarke, K., Carr, C., Czernuszka, J.
Collagen-Based Scaffolds for Potential Application of Heart Valve Tissue Engineering
(2012) *J. Tissue Sci. Eng*, 11, pp. 1-5. Cited 21 times.
[CrossRef]

75 Tian, H., Tang, Z., Zhuang, X., Chen, X., Jing, X.

Biodegradable synthetic polymers: Preparation, functionalization and biomedical application

(2012) *Progress in Polymer Science (Oxford)*, 37 (2), pp. 237-280. Cited 873 times.
http://www.sciencedirect.com/science/journal/00796700
doi: 10.1016/j.progpolymsci.2011.06.004

View at Publisher

76 Brzeska, J., Heimowska, A., Sikorska, W., Jasińska-Walc, L., Kowalczuk, M., Rutkowska, M.

Chemical and Enzymatic Hydrolysis of Polyurethane/Polylactide Blends (Open Access)

(2015) *International Journal of Polymer Science*, 2015, art. no. 795985. Cited 13 times.
http://www.hindawi.com/journals/ijps/
doi: 10.1155/2015/795985

View at Publisher

77 Araque-Monrós, M.C., Vidaurre, A., Gil-Santos, L., Gironés Bernabé, S., Monleón-Pradas, M., Más-Estellés, J.

Study of the degradation of a new PLA braided biomaterial in buffer phosphate saline, basic and acid media, intended for the regeneration of tendons and ligaments (Open Access)

(2013) *Polymer Degradation and Stability*, 98 (9), pp. 1563-1570. Cited 35 times.
doi: 10.1016/j.polymdegradstab.2013.06.031

View at Publisher

78 Yoo, E.S., Im, S.S.

Effect of crystalline and amorphous structures on biodegradability of poly(tetramethylene succinate)

(1999) *Journal of Environmental Polymer Degradation*, 7 (1), pp. 19-26. Cited 22 times.

View at Publisher

79 Mondal, S., Martin, D.

Hydrolytic degradation of segmented polyurethane copolymers for biomedical applications

(2012) *Polymer Degradation and Stability*, 97 (8), pp. 1553-1561. Cited 83 times.
doi: 10.1016/j.polymdegradstab.2012.04.008

View at Publisher

80 Elsawy, M.A., Kim, K.-H., Park, J.-W., Deep, A.

Hydrolytic degradation of polylactic acid (PLA) and its composites

(2017) *Renewable and Sustainable Energy Reviews*, 79, pp. 1346-1352. Cited 303 times.
doi: 10.1016/j.rser.2017.05.143

View at Publisher

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