

# Experimental study on the effect of selected sterilization methods on mechanical properties of polylactide FFF specimens

Angela Jadwiga Andrzejewska

Department of Mechanics of Materials and Structures, Gdansk University of Technology, Gdansk, Poland

## Abstract

**Purpose** – Biodegradable polymers are widely used in personalized medical devices or scaffolds for tissue engineering. The manufacturing process should be finished with sterilization procedure. However, it is not clear how the different sterilization methods have an impact on the mechanical strength of the three-dimensional (3D)-printed parts, such as bone models or personalized mechanical devices. This paper aims to present the results of mechanical testing of polylactide-based bone models before and after sterilization.

**Design/methodology/approach** – Polylactide specimens prepared in fused filament fabrication technology were sterilized with different sterilization methods: ultraviolet (UV) and ethylene oxide. Mechanical properties were determined by testing tensile strength, Young's modulus and toughness.

**Findings** – The tensile strength of material after sterilization was significantly higher after ethylene oxide sterilization compared to the UV sterilization, but in both sterilization methods, the specimens characterized lower tensile strength and Young's modulus when compared to the control. In comparison of toughness results, there was no statistically significant differences. The findings are particularly significant in the perspective of using individual implants, bone grafts and dental guides.

**Originality/value** – Although fused filament fabrication (FFF) 3D printing devices equipped with UV light sterilization options are available, experimental results of the effect of selected sterilization methods on the mechanical strength of additively manufactured parts have not been described. This paper completes the present state of the art on the problem of sterilization of FFF parts from biodegradable materials.

**Keywords** Mechanical properties, Sterilization, Polylactide, Fused filament fabrication, UV light sterilization, Ethylene oxide sterilization

**Paper type** Research paper

## List of abbreviations

3D	= three-dimensional;
CO <sub>2</sub> laser	= carbon dioxide laser;
EtO	= ethylene oxide;
H <sub>2</sub> O <sub>2</sub>	= hydrogen peroxide;
HDPE	= high density polyethylene;
kGy	= Gray (unit);
MHAp	= mackerel fish hydroxyapatite;
PA	= peracetic acid;
PCL	= polycaprolactone;
PLA	= polylactic acid;
PLCL	= poly-L-lactide-co-ε-caprolactone;
PLGA	= poly(lactide co-glycolide);
TMPTMA	= trimethylpropane trimethacrylate;
TPU	= thermoplastic polyurethane; and
UV	= ultraviolet.

applications, for implantology (Singh *et al.*, 2019; Vasamsetty *et al.*, 2020), bone defect replacements (Andrzejewska, 2019; Bose *et al.*, 2013; Ghorbani *et al.*, 2020) or personalized mechanical devices (Sapoval *et al.*, 2020; Wesemann *et al.*, 2020). The safety of implantable materials should respect a number of standards related to the biocompatibility, proper mechanical properties, but in addition, the microbiological safety aspect seems to be the most important. For this reason, ready-to-use products including personalized medical devices and implantable materials are sterilized.

---

© Angela Jadwiga Andrzejewska. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at <http://creativecommons.org/licenses/by/4.0/legalcode>

*Supplementary materials:* not applicable.

*Author contributions:* It is single-authored paper.

*Funding:* This research received no external funding.

*Conflicts of interest:* The authors declare no conflicts of interest.

Received 20 May 2021

Revised 5 November 2021

1 March 2022

17 May 2022

Accepted 1 August 2022

## 1. Introduction

The expansion of the three-dimensional (3D) printing technology has resulted in a wide range of applications, e.g. in biomedical

---

The current issue and full text archive of this journal is available on Emerald Insight at: <https://www.emerald.com/insight/1355-2546.htm>



Rapid Prototyping Journal  
29/11 (2023) 1–6  
Emerald Publishing Limited [ISSN 1355-2546]  
[DOI 10.1108/RPJ-05-2021-0115]

The mechanical properties of 3D-printed bone models or other personalized medical devices are crucial for its application. The above-mentioned properties may be affected by properties on each stage of manufacturing process like storage of materials, environmental factors during processing and postprocessing sterilization. Also, different methods of sterilization of polymer materials applied in biomedical solutions are used. The different sterilization methods can affect changes in mechanical properties.

Tipnis and Burgess (2018) recognized and developed methods of sterilization of polymeric materials for biomedical applications. Following methods include ethylene oxide, radiation, dry and heat steam, H<sub>2</sub>O<sub>2</sub> and ozone, also peracetic acid (PA), ultraviolet (UV) light, microwave, sound waves and pulsed light.

The study conducted by Haim Zada *et al.* (2019) describes the effect of ethylene oxide sterilization and gamma sterilization on the behavior of poly-L-lactide-co- $\epsilon$ -caprolactone (PLCL) specimens prepared in the multicycle dip-coating process. The main conclusion of the researchers is the recommendation of EtO sterilization instead of gamma radiation for PLCL balloon implants. Chen *et al.* (2019) described the stability of specimens made of high-density polyethylene and Polyamide 6 and exposed to two sterilization methods: novel vaporized hydrogen peroxide and electron beam processes. The specimens were prepared both by additive manufacturing and by injection molding. The research presented by the authors proved that injection molded specimens were more stable than 3D-printed specimens upon sterilization processes.

Ng *et al.* (2019) reported the effect of electron beam irradiation at room temperature on the properties of compression-formed polylactic acid (PLA) in combination with fish bone waste mackerel and trimethylpropane trimethacrylate. The authors noted that when the radiation dose increased, the mechanical properties of the composite improved because of better crosslinking. Meanwhile, in the case of pure PLA, increasing the radiation dose contributed to a decrease in strength.

Artemenko *et al.* (2012) investigated the influence of sterilization methods such as dry heat, autoclave and UV radiation on chemical and biological properties of plasma polymers. General finding of the work was conclusion that there exists no universal sterilization method that assures preservation of the properties of all kinds of plasma polymers.

Davison *et al.* (2018) discussed the results of tests performed on specimens of poly(lactide coglycolide) (PLGA) prepared by compression molding. Specimens were gamma sterilized at 40 kGy and room temperature or low temperature (−80°C) in a nitrogen atmosphere. The results reported that the molecular weight was significantly reduced, as was the glass transition temperature, which indicates a chain rupture. Fourier transform infrared spectroscopy reported minor changes in the chemical structure in methyl and carbonyl groups after irradiation. The glass transition temperature changed significantly between irradiation at −80°C and irradiation at 25°C, but this difference was only 1°C. Consequently, the results indicate that the applied sterilization temperature does not affect PLGA when carried out in a nitrogen atmosphere.

Polymeric tissue engineering scaffolds in Yoganarasimha *et al.* (2019) research were prepared by electrospinning method

from polycaprolactone (PCL) which was sterilized with PA. The main goal of the study was to determine the effect of the selected sterilization method on the cytotoxicity of PCL scaffolds. It has been shown that the rinsing of scaffolds in 80% ethanol for 30 min effectively eliminates toxic PA waste and restores the cytocompatibility.

De Cassan *et al.* (2019) work presents scaffolds manufactured from PCL which were also produced by electrospinning and then sterilized using three methods, i.e. electron beam, gamma radiation and Röntgen radiation. It was shown that the dose of radiation had a significant effect on changes in molecular mass and degree of crystallinity, whereas the type of used radiation had no significant effect on changes in mechanical behavior.

Preem *et al.* (2019) reported study of scaffolds manufactured with the PCL electrospinning method. The generated scaffolds were exposed to UV sterilization, gamma irradiation and chlorine gas. It was observed that gamma sterilization increased the hardness and elasticity of PCL constructs as a result of increased crystallinity of the polymer.

In research Rainer *et al.* (2010) were used structures made with the method of electrospinning from polylactide. Which next, have been subjected to various sterilization processes: soaking in absolute ethanol, drying in oven, autoclave treated, UV irradiation or treated in hydrogen peroxide gas plasma. The study disclosed that UV irradiation and hydrogen peroxide gas plasma are the most effective sterilization techniques, which ensure sterility of the electrospun scaffolds without affecting the chemical and morphological features.

In view of the work described below, it can be stated that various sterilization methods can be successfully used to sterilize the thermoplastic polymers. Nevertheless, the field of effect of sterilization methods on structural components made by additive manufacturing methods is still not well understood. There are single literature reports demonstrating the proper way of sterilization of porous constructions produced by additive manufacturing methods. Luchini *et al.* (2021) describe results of sterilization with heat-based methods and sanitizing with various chemical solutions of 3D-printed PLA or thermoplastic polyurethane (TPU) parts. This study shows that although personal protective equipment is produced using PLA and the traditional infill-based patterns model may be initially sterile, resterilization is not possible using methods such as isopropanol, bleach and/or H<sub>2</sub>O<sub>2</sub>. In addition, autoclaving is technique typically used to sanitize a variety of materials, but it is not suitable for PLA and TPU 3D-printed parts.

In the manuscript, Pérez Davila *et al.* (2021) analyzed how the most common techniques used to sterilize PLA medical devices are affecting the physicochemical and biocompatible properties of 3D-printed items.

It has been observed that EtO sterilization is the most universal and the most widespread method of low-temperature sterilization in large clinical centers (Boiano and Steege, 2015; Sobaszek *et al.*, 1999). Also it is considered to be the method with high effectiveness and low cost. Although UV methods are used in small rural clinics (Rutala and Weber, 2015), dental practices (Cumbo *et al.*, 2020) or beauty salons (Sowah and Ahiabor, 2014). Moreover, manufacturers of 3D printers offer devices equipped with the possibility of UV sterilization during printing. Therefore, the objective of this study was to investigate the effect of sterilization methods: UV light and

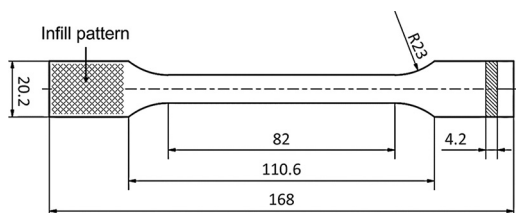
ethylene oxide on the mechanical properties of 3D-printed components produced from biodegradable polylactide. The results of testing the mechanical properties of sterilized parts are important for research and development in regenerative medicine and medical devices, which must be biologically safe for users. The preliminary study of mechanical properties that were conducted should result in the most suitable method for sterilization of 3D-printed parts, to be used in future studies on the effectivity of sterilization methods.

## 2. Methodology

Dog-bone-shaped specimens were used to determine changes in the mechanical behavior of 3D-printed polymeric materials and then sterilized. The geometry and optimal parameters of fused filament fabrication are similar as in further research (Andrzejewska, 2021; Andrzejewska *et al.*, 2019). For this experiment, commercially available 3DXPLA007-EA polylactide (Sigma-Aldrich, Saint Louis, MO, USA) was applied. Specimens were prepared with the method of fused filament fabrication, on a 3D printer Kreator Motion (Krakow, Poland). Printing of elements was based on the planned density of cross-sectional infill equal to 100% and the angular placement of material fibers in relation to the specimen axis, i.e.  $+45^\circ/-45^\circ$ . The specimen shape and geometry based on ISO 527-2:2012 (2012 standard is presented in Figure 1. However, the 3D printing settings of dog-bone-shaped specimen are summarized in Table 1.

Two methods of sterilization were chosen, i.e. UV light sterilization and ethylene oxide sterilization. The process of sterilization based on “Guideline for Disinfection and Sterilization in Healthcare Facilities” of Centers for Disease Control and Prevention. Sterilization with UV radiation was conducted in UV-C sterilizer (Activ, Wroclaw, Poland), using UV radiation of 254 nm wavelength. The time of sterilization of the specimens was 30 min and the process was established at

**Figure 1** Geometry of dog-bone-shaped specimen



**Table 1** 3D printing parameters

No.	Selected parameters	Value
1	Nozzle temperature	200°C
2	Bed temperature	65°C
3	Nozzle diameter	0.4 mm
4	Filament diameter	1.75 mm
5	Layer thickness	0.1 mm
6	Fiber orientation to specimen axis	$+45^\circ/-45^\circ$
7	Outline	2
8	Top/bottom solid layers	6/6

60°C. The UV-sterilized forms were deposited in a desiccator filled with silica gel for 24h. However, the second group of specimens was sterilized with ethylene oxide in Steri-Vac Sterilizer (3M, Saint Paul, MN, USA). The following process parameters were defined: gas concentration: 450 mg/l; temperature: 55°C; relative humidity: 60%; exposure time: 60 min. Subsequently, after exposure to the sterilizing agent, the specimens were subjected to a degasification period lasting 12 h in the sterilizer chamber. The tests of mechanical properties were performed on the INSTRON ElectroPuls E3000 (Norwood, MA, USA) tensile machine with an electromagnetic actuator of  $\pm 3$  kN force. The traverse speed of the testing machine was 1 mm/min. Tests of material's mechanical properties to uniaxial tensile strength before and after sterilization with two methods were realized at room temperature. In each group of tests, five specimens were subjected to mechanical properties measurements (Andrzejewska *et al.*, 2019; ISO 527-2:2012, 2012).

## 3. Results and discussion

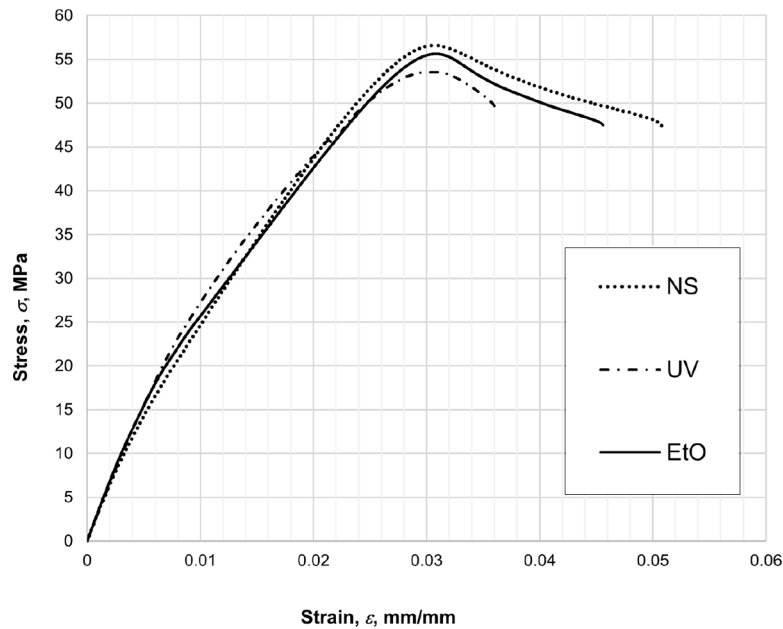
Three parameters were used in the analysis of the influence of the selected sterilization method on changes in mechanical behavior of the biodegradable material. The tensile mechanical behavior of the sterilized polylactide parts was determined: ultimate tensile strength ( $\sigma_m$ ), Young's modulus ( $E$ ) and toughness, i.e. the amount of absorbed energy needed to break the specimen ( $Q$ ) (Jyoti *et al.*, 2022; Mohammadi *et al.*, 2017; Yang *et al.*, 2019). The toughness is parameter expressed by equation (1):

$$Q = \int_t \sigma d\varepsilon \quad (1)$$

Figure 2 presented representative cases of stress–strain curves of nonsterilized control specimens and specimens exposed to two different methods of sterilization. On the grounds of the presented charts, it can be observed that specimens before sterilization were characterized by the greatest value of tensile strength and the greatest elongation. However, the specimens after sterilization, in relation to the selected method, were characterized by reduced strength and elongation in comparison with nonsterilized specimens. Higher values of strength and elongation were reported for specimens after ethylene oxide sterilization. Temperature-induced sterilization contributes to scission of the polymer chain, which results in reduced tensile strength and elongation (Otaguro *et al.*, 2010; Papadimitriou *et al.*, 2021).

In the process of determining the statistical significance of differences, the recorded and calculated values of mechanical parameters were collected and then the results were analyzed. Table 2 summarizes the mean value, standard deviation and median of the determined strength parameters. The coefficient of variation of results received for the three selected parameters was determined for each group of tested specimens. Besides, the statistical significance of differences in results between individual groups of specimens was compared. Estimates of statistical significance of the differences were performed using GraphPad Prism. Comparison of specimens before and after sterilization by two methods was performed by one-way ANOVA test and post hoc Fisher's least significant difference

**Figure 2** The representative stress–strain curves of the specimens before (NS) and after UV light or EtO sterilization



**Table 2** Calculated values of tensile strength parameters

PLA part	Ultimate tensile strength, $\sigma_M$ (MPa)		Young's modulus, $E$ (MPa)		Toughness, $Q$ (MJ/m <sup>3</sup> )	
	Mean $\pm$ STD	Median	Mean $\pm$ STD	Median	Mean $\pm$ STD	Median
Nonsterilized	57.92 $\pm$ 0.66	58.22	3585.45 $\pm$ 123.32	3598.36	1.007 $\pm$ 0.004	1.021
UV light-sterilized	53.38 $\pm$ 0.16	53.37	3116.28 $\pm$ 195.01	3045.35	1.080 $\pm$ 0.060	1.049
EtO-sterilized	55.54 $\pm$ 0.47	55.55	3121.81 $\pm$ 216.14	3121.92	1.059 $\pm$ 0.090	1.040

test. The analysis was carried out at the significance level of  $p < 0.05$  (Norani *et al.*, 2021; Zhu *et al.*, 2021).

In case of the analysis of the coefficient of variation of results in each group of specimens, the coefficient value was lower than 10% regardless of the analyzed parameter. Statistical comparison of differences in specific parameters between groups of nonsterilized and UV or ethylene oxide sterilized specimens showed statistically significant differences in tensile strength ( $p$ -value  $< 0.0001$ ). Furthermore, statistically significant differences in Young's modulus were shown in comparison of specimens before and after sterilization by both methods ( $p$ -value = 0.0017). However, there were no statistically significant differences in changes in Young's modulus between the specimens that were sterilized ( $p$ -value = 0.9626). When comparing toughness results, no statistically significant differences were found between samples before and after sterilization with both methods.

Figure 3 shows a comparison of several groups of specimens in relation to parameters reached in a tensile test and calculated on the basis of experimental data.

Although statistically significant differences in tensile strength values have been shown between nonsterilized and sterilized specimens with different methods, the reduction in strength values does not exceed 2 MPa for EtO sterilization and, respectively, 4 MPa for UV sterilization. The results obtained after EtO sterilization are very similar to the results obtained by other researchers in publication (Zhao *et al.*, 2019),

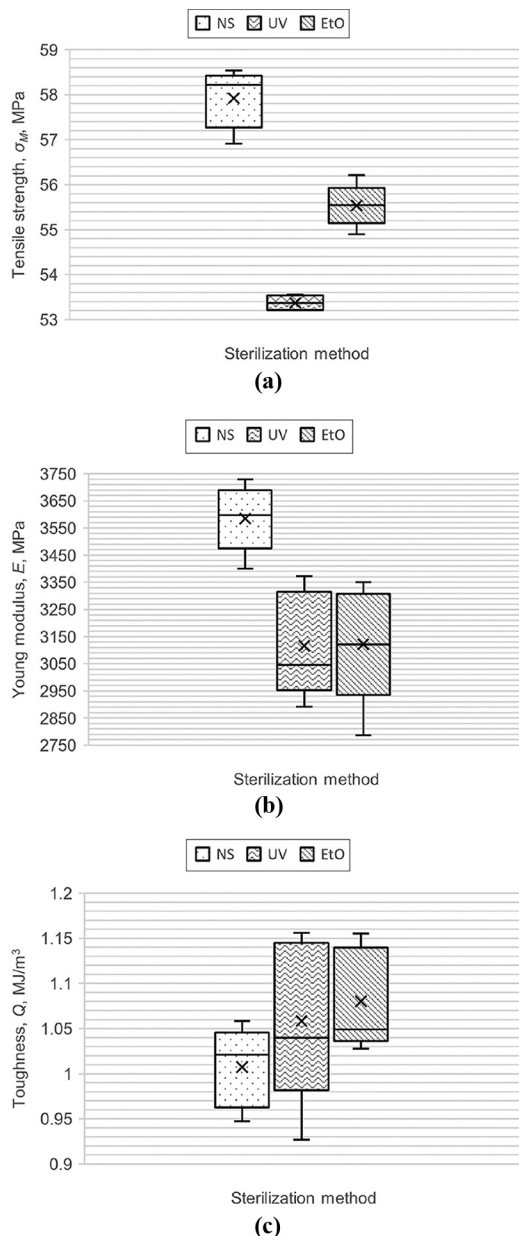
whereas the expected strength value of the material may be varied and may depend on the method of specimens preparation, grade of material, content of two forms of the monomeric acid (D- or L-lactic acid), etc. The stress and strain values in printed specimens will be affected by the printing temperature and then the sterilization temperature. The effect of heating strongly influences the changes of polymeric bonds in the entire specimen. As noted in Grasso *et al.* (2018), stress redistribution is crucial in tests on specimens previously treated with temperatures close to the glass transition temperature of PLA and then cooled.

The important parameter found in tests presented in this research is toughness, which determines the specimen's susceptibility to fracture. In the documents of other scientists, no information was found regarding the determination of toughness parameter, specifically its changes because of the sterilization of biodegradable 3D-printed material.

## 5. Conclusions

The results of the research presented in this paper compared the influence of the method of sterilization on mechanical properties of biodegradable material:

- The obtained results provided, in general, a lower strength of the sterilized specimens;
- The reduction in strength value from 2 to 4 MPa should not be considered as a disincentive to sterilize 3D-printed elements; and

**Figure 3** Comparison of mechanical properties

**Notes:** (a) Tensile strength; (b) Young's modulus; (c) toughness

- The geometry of the specimens was measured before and after sterilization. Changes in geometrical dimensions (cross-sectional area) did not exceed 10%. Value of the cross-sectional area after sterilization was taken for strength calculations. Because of the effect of temperature (close to glass transition temperature), a change in the ordering of polymer chains and crystalline transformations may have occurred, but further studies are necessary to confirm above.

Based on mechanical properties both EtO and UV light sterilization are suitable for sterilizing bone models or personalized medical devices. EtO sterilization results in

lower strength loss and is declared in literature as more microbiologically effective than UV. The effectiveness of sterilization 3D-printed parts will be evaluated in future research.

## References

- Andrzejewska, A. (2019), "Biomechanical properties of 3D-printed bone models", *Biosystems*, Vol. 176, doi: [10.1016/j.biosystems.2019.01.001](https://doi.org/10.1016/j.biosystems.2019.01.001).
- Andrzejewska, A. (2021), "Three-dimensional printing of bone models", *Advances in Intelligent Systems and Computing*, Vol. 1223, doi: [10.1007/978-3-030-52180-6\\_1](https://doi.org/10.1007/978-3-030-52180-6_1).
- Andrzejewska, A., Pejkowski, Ł. and Topoliński, T. (2019), "Tensile and fatigue behavior of additive manufactured polylactide", *3D Printing and Additive Manufacturing*, Vol. 6 No. 5, pp. 272-280.
- Artemenko, A., Kylián, O., Choukourov, A., Gordeev, I., Petr, M., Vandrovová, M., Polonskyi, O., Bačáková, L., Slavinska, D. and Biederman, H. (2012), "Effect of sterilization procedures on properties of plasma polymers relevant to biomedical applications", *Thin Solid Films*, Vol. 520 No. 24, pp. 7115-7124.
- Boiano, J.M. and Steege, A.L. (2015), "Ethylene oxide and hydrogen peroxide gas plasma sterilization: precautionary practices in U.S. hospitals", *Zentralsterilisation (Wiesbaden)*, Vol. 23 No. 4, pp. 262-268.
- Bose, S., Vahabzadeh, S. and Bandyopadhyay, A. (2013), "Bone tissue engineering using 3D printing", *Materials Today*, Elsevier Ltd., Vol. 16 No. 12, pp. 496-504.
- Chen, Y., Neff, M., McEvoy, B., Cao, Z., Pezzoli, R., Murphy, A., Gately, N., Hopkins Jnr, M., Rowan, N.J. and Devine, D.M. (2019), "3D printed polymers are less stable than injection moulded counterparts when exposed to terminal sterilization processes using novel vaporized hydrogen peroxide and electron beam processes", *Polymer*, Vol. 183, p. 121870.
- Cumbo, E., Gallina, G., Messina, P. and Scardina, G.A. (2020), "Alternative methods of sterilization in dental practices against COVID-19", *International Journal of Environmental Research and Public Health*, Vol. 17 No. 16, pp. 1-14.
- Davison, L., Themistou, E., Buchanan, F. and Cunningham, E. (2018), "Low temperature gamma sterilization of a bioresorbable polymer, PLGA", *Radiation Physics and Chemistry*, Elsevier Ltd, Vol. 143, pp. 27-32.
- de Cassan, D., Hoheisel, A.L., Glasmacher, B. and Menzel, H. (2019), "Impact of sterilization by electron beam, gamma radiation and X-rays on electrospun poly-( $\epsilon$ -caprolactone) fiber mats", *Journal of Materials Science: Materials in Medicine*, Springer US, Vol. 30 No. 4, pp. 1-11.
- Ghorbani, F., Li, D., Ni, S., Zhou, Y. and Yu, B. (2020), "3D printing of acellular scaffolds for bone defect regeneration: a review", *Materials Today Communications*, Vol. 22, p. 100979.
- Grasso, M., Azzouz, L., Ruiz-Hincapie, P., Zarrelli, M. and Ren, G. (2018), "Effect of temperature on the mechanical properties of 3D-printed PLA tensile specimens", *Rapid Prototyping Journal*, Vol. 24 No. 8, pp. 1337-1346.
- Haim Zada, M., Kumar, A., Elmalak, O., Mechrez, G. and Domb, A.J. (2019), "Effect of ethylene oxide and gamma

- ( $\gamma$ ) sterilization on the properties of a PLCL polymer material in balloon implants”, *ACS Omega*, Vol. 4 No. 25, pp. 21319-21326.
- ISO 527-2:2012 (2012), “Plastics – determination of tensile properties – part 2: test conditions for moulding and extrusion plastics”.
- Jyoti, A., Shaikkea, D., Cambridge, U.K. and Angeles, L. (2022), “Mechanical metamaterials: toughness and design criteria”, No. February, pp. 1-6.
- Luchini, K., Sloan, S.N.B., Mauro, R., Sargsyan, A., Newman, A., Persaud, P., Hawkins, D., Wolff, D., Staudinger, J. and Creamer, A.B. (2021), “Sterilization and sanitizing of 3D-printed personal protective equipment using polypropylene and a single wall design”, *3D Printing in Medicine*, Vol. 7 No. 1, pp. 1-10.
- Mohammadi, P., Toivonen, M.S., Ikkala, O., Wagermaier, W. and Linder, M.B. (2017), “Aligning cellulose nanofibril dispersions for tougher fibers”, *Scientific Reports*, Springer US, Vol. 7 No. 1, pp. 1-11.
- Ng, H.M., Bee, S.T., Sin, L.T., Ratnam, C.T. and Rahmat, A.R. (2019), “Effect of electron beam irradiation sterilization on biomedical polylactic acid composite filled with scomberomorus guttatus-derived hydroxyapatite”, *Composites Part B: Engineering*, Elsevier Ltd., Vol. 176 No. October 2018, p. 107273.
- Norani, M.N.M., Abdollah, M.B., Abdullah, M., Amiruddin, H., Ramli, F.R. and Tamaldin, N. (2021), “3D printing parameters of acrylonitrile butadiene styrene polymer for friction and wear analysis using response surface methodology”, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, Vol. 235 No. 2, pp. 468-477.
- Otaguro, H., de Lima, L., Parra, D.F., Lugão, A.B., Chinelatto, M.A. and Canevarolo, S.V. (2010), “High-energy radiation forming chain scission and branching in polypropylene”, *Radiation Physics and Chemistry*, Vol. 79 No. 3, pp. 318-324.
- Papadimitriou, C., Melidis, L., Kotoulas, L., Makris, N. and Katakalos, K. (2021), “Thermomechanical characterization of CFRPs under elevated temperatures for strengthening existing structures”, *Fibers*, Vol. 9 No. 12, doi: [10.3390/fib9120080](https://doi.org/10.3390/fib9120080).
- Pérez Davila, S., González Rodríguez, L., Chiussi, S., Serra, J. and González, P. (2021), “How to sterilize polylactic acid based medical devices?”, *Polymers*, Vol. 13 No. 13, pp. 1-18.
- Preem, L., Vaarmets, E., Meos, A., Jögi, I., Putrinš, M., Tenson, T. and Kogermann, K. (2019), “Effects and efficacy of different sterilization and disinfection methods on electrospun drug delivery systems”, *International Journal of Pharmaceutics*, Vol. 567 No. August, doi: [10.1016/j.ijpharm.2019.118450](https://doi.org/10.1016/j.ijpharm.2019.118450).
- Rainer, A., Centola, M., Spadaccio, C., Gherardi, G., Genovese, J.A., Licoccia, S. and Trombetta, M. (2010), “Comparative study of different techniques for the sterilization of poly-L-lactide electrospun microfibers: effectiveness vs material degradation”, *The International Journal of Artificial Organs*, Vol. 33 No. 2, pp. 76-85.
- Rutala, W.A. and Weber, D.J. (2015), “Disinfection, sterilization, and control of hospital waste”, *Mandell, Douglas, and Bennett’s Principles And Practice Of Infectious Diseases*, No. January, pp. 3294-3309.
- Sapoval, M., Gaultier, A.L., Del Giudice, C., Pellerin, O., Kassis-Chikhani, N., Lemarteleur, V., Fouquet, V., Tapie, L., Morenton, P., Tavitian, B. and Attal, J.P. (2020), “3D-printed face protective shield in interventional radiology: evaluation of an immediate solution in the era of COVID-19 pandemic”, *Diagnostic and Interventional Imaging*, Vol. 101 No. 6, pp. 3-5.
- Singh, S., Prakash, C. and Ramakrishna, S. (2019), “3D printing of polyether-ether-ketone for biomedical applications”, *European Polymer Journal*, Elsevier, Vol. 114 No. May, pp. 234-248.
- Sobaszek, A., Hache, J.C., Frimat, P., Akakpo, V., Victoire, G. and Furon, D. (1999), “Working conditions and health effects of ethylene oxide exposure at hospital sterilization sites”, *Journal of Occupational and Environmental Medicine*, United States, Vol. 41 No. 6, pp. 492-499.
- Sowah, R.A. and Ahiabor, C. (2014), “Effectiveness of UV sterilisation chambers in barbering shops and salons”, *Journal of Natural Sciences Research*, Vol. 4 No. 20, pp. 67-74.
- Tipnis, N.P. and Burgess, D.J. (2018), “Sterilization of implantable polymer-based medical devices: a review”, *International Journal of Pharmaceutics*, Elsevier B.V., Vol. 544 No. 2, pp. 455-460.
- Vasamsetty, P., Pss, T., Kukkala, D., Singamshetty, M. and Gajula, S. (2020), “3D printing in dentistry – exploring the new horizons”, *Materials Today: Proceedings*, Vol. 26, doi: [10.1016/j.matpr.2020.01.049](https://doi.org/10.1016/j.matpr.2020.01.049).
- Wesemann, C., Pieralli, S., Fretwurst, T., Nold, J., Nelson, K., Schmelzeisen, R., Hellwig, E. and Spies, B.C. (2020), “3-D printed protective equipment during COVID-19 pandemic”, *Materials*, Vol. 13 No. 8, p. 1997.
- Yang, H., Wang, B. and Ma, L. (2019), “Mechanical properties of 3D double-U auxetic structures”, *International Journal of Solids and Structures*, Vols 180/181, pp. 13-29.
- Yoganarasimha, S., Best, A. and Madurantakam, P.A. (2019), “Peracetic acid sterilization induces divergent biological response in polymeric tissue engineering scaffolds”, *Applied Sciences (Switzerland)*, Vol. 9 No. 18, pp. 1-12.
- Zhao, Y., Zhu, B., Wang, Y., Liu, C. and Shen, C. (2019), “Effect of different sterilization methods on the properties of commercial biodegradable polyesters for single-use, disposable medical devices”, *Materials Science and Engineering: C*, Elsevier, Vol. 105 No. March, p. 110041.
- Zhu, S., Ruiz de Azua, I.V., Feijen, S., van der Goot, A.J., Schutyser, M. and Stieger, M. (2021), “How macroscopic structure of 3D printed protein bars filled with chocolate influences instrumental and sensory texture”, *LWT*, Elsevier Ltd., Vol. 151 No. May, p. 112155.

### Corresponding author

Angela Jadwiga Andrzejewska can be contacted at: [angela.andrzejewska@pg.edu.pl](mailto:angela.andrzejewska@pg.edu.pl)

For instructions on how to order reprints of this article, please visit our website:

[www.emeraldgroupublishing.com/licensing/reprints.htm](http://www.emeraldgroupublishing.com/licensing/reprints.htm)

Or contact us for further details: [permissions@emeraldinsight.com](mailto:permissions@emeraldinsight.com)