Opto-Electronics Review 29 (2021) 192-200

PAN POLISH ACADEMY OF SCIENCES

Opto-Electronics Review

journal homepage: http://journals.pan.pl/opelre

The research and analysis of the bactericidal properties of the spacer knitted fabric with the UV-C system

E. Łada-Tondyra[a*], A. Jakubas[a], B. Jabłońska[b], E. Stańczyk-Mazanek[b]

[a]Faculty of Electrical Engineering, Częstochowa University of Technology, 17 Armii Krajowej St., 42-201 Częstochowa, Poland
[b]Faculty of Infrastructure and Environment, Częstochowa University of Technology, 73 Dąbrowskiego St., 42-201 Częstochowa, Poland

Article info

Article history:
Received 27 Aug. 2021
Received in revised form 02 Nov. 2021
Accepted 10 Nov. 2021
Available on-line: 20 Dec. 2021

Keywords:
Fibre optics, sterilization, textronics, ultraviolet radiation, warp-knitted spacer fabric.

Abstract

The research and analysis of the bactericidal properties of the spacer knitted fabric with the UV-C system are presented in this paper. The disintegration factor affecting the bacteria in the knitted fabric is the UV-C radiation in the range of 265–270 nm distributed via woven optical fibres. The way of integrating elements of the system generating the UV-C radiation in the structure of the spacer knitted fabric was designed, as well as various configurations of optical fibres arrangement, fibre density, number of radiation sources, and diode types were tested. The material was contaminated with selected microorganisms indicative of sanitary contamination and important in terms of nosocomial infections. The scope of the research included microbiological (quantitative and qualitative) analyses of selected taxonomic groups of microorganisms (mesophilic bacteria, fungi, actinomycetes) before and after the irradiation process. The analysis of the research results and the applied modification of the knitted fabric turned out to be effective in reducing the amount of potentially pathogenic microorganisms.

1. Introduction

Development of technology in the field of new textronic materials allows for their wider application in everyday use. Textronics is a relatively new field of knowledge that combines such fields of science as: textile, electrical engineering, and computer science and metrology [1]. Textronic products are so-called intelligent fabrics, also known as active, interactive, and adaptive fabrics. Textile products integrate specialized electronic systems with textiles into one functional whole. Intelligent materials can react to external stimuli (e.g., temperature, pressure, etc.) acting as a sensor or as an actuator fulfilling the specific functionality. Textronics is used in many branches of the industry, not only for smart clothing, but also in the automotive, computer, and medical industries [2].

Recent times, especially operating in the shadow of the pandemic, have shown how important it is to protect health. It is important to ensure appropriate sanitary conditions and reduce risk factors not only in hospital conditions, but also at home or other public places and in the work environment. UV-C radiation has been known for many years for its biocidal properties and is used to disinfect rooms and surfaces. UV-C radiation, especially in the wavelength range of 250–280 nm, is particularly effective for the destruction or partial inactivation of various types of microorganisms, including: bacteria, viruses, fungi, and other pathogens. This kind of action is called bactericidal, but it applies to all the taxonomic groups of microorganisms mentioned above (many of them are pathogens). Every living organism has its genetic code written in the deoxyribonucleic acid (DNA). UV-C radiation causes an immediate photochemical reaction during which the genetic record is destroyed and, thus, the process of cell division and other metabolic functions are inhibited. UV-C waves damage the DNA code of cells. As a result, microorganisms lose their ability to reproduce and cease to be a threat to humans [3,4]. Lamps emitting UV-C radiation have been used in medical offices for many years. It is worth mentioning that, according to an announcement

*Corresponding author at: e.lada-tondyra@pcz.pl

https://doi.org/10.24425/opelre.2021.139757
1896-3757/ Association of Polish Electrical Engineers (SEP) and Polish Academic of Sciences (PAS). Published by PAS

by the Central Institute for Labour Protection in Poland [5,6], the SARS-CoV-2 coronavirus, like other viruses and bacteria, is sensitive to ultraviolet radiation, especially at the UV-C wavelength range of 200–280 nm [7–9]. The available studies have also shown the inactivation of drug resistance genes after using the UV-C radiation [10].

The authors, thanks to the combination of current capabilities of developing textronics and known properties of the UV-C radiation, proposed a solution that allows using UV-C in textile materials. It is possible to use the textile technology with an integrated sterilization system using the UV-C radiation which will ensure sterile conditions.

2. Design of the system that generates UV-C radiation

The subject of the study is a design of an innovative system for microbial reduction, the canvas of which is a spacer fabric. The developed distance knit for microbiological reduction is intended for mattress covers used in home, hospital, and hotel conditions. The disintegration factor affecting bacteria in the knitted fabric is UV-C radiation in the wavelength range of 265–280 nm distributed via woven optical fibres. The presented solution is an extension of the concept presented by the authors in Ref. 11. As part of the work on designing the system generating UV-C radiation in a spacer knitted fabric, effectiveness of various configurations of optical fibre distribution was tested, as well as three types of spacer knitwear, two types of PMMA optical fibres, two variants of fibre density, and two methods of connecting diodes to optical fibres.

The first stage of constructing the system was selecting the appropriate type of optical fibre and the type of spacer fabric. The modern conventional optical fibre is a dielectric transmission medium whose task is to transmit optical signals [12]. The material from which the optical fibre is made does not conduct electricity, but it can conduct optical radiation (photon beam). Lighting fibres can be made in principle of any material that is optically transparent in a certain wavelength range. They are generally divided according to the material from which they are made: plastic [plastic optical fibre (POF) which is most often made of polymethyl methacrylate (PMMA)] and glass [glass optical fibre (GOF)] [12]. The material from which the optical fibre is made determines its parameters. The analysis of the POF and GOF attenuation curves shows that they have similar average attenuation in the visible range, but also transmit UV and IR radiation. POF optical fibres poorly attenuate shorter wavelengths, i.e., blue and green radiation and transmit well the UV radiation (Fig. 1). In contrast, GOF optical fibres transmit well red and IR radiation. Due to the appropriate physical and mechanical properties (adequate strength, no brittleness, resistance to damage), POF (PMMA) optical fibres were used for the tests.

The suitability of PMMA fibres for the UV-C range was experimentally verified using a HAAS 2020 spectroradiometer on the test bench shown in Fig. 2. A 50-cm long fibre was tested. The PMMA fibre showed a 280-nm attenuation of 0.023 dB/cm. The experiments were carried out at a temperature of 25 °C and a humidity of 65%. The measurement results are shown in Figs. 3(a) and 3(b).

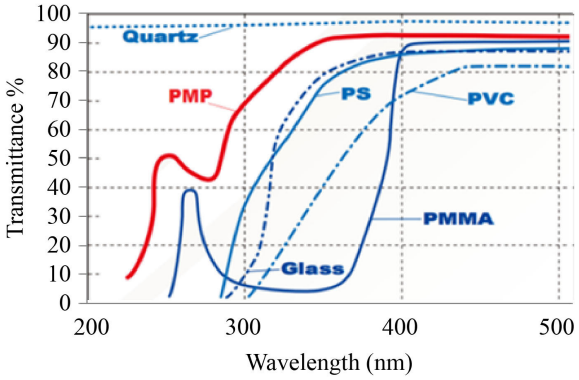

Fig. 1. Optical transmittance of the selected materials [13].

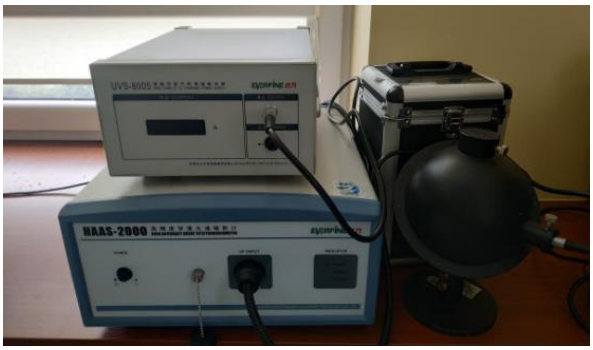

Fig. 2. Measurement station: HAAS-2000 spectroradiometer, UVs-8005 power supply, Ulbricht sphere.

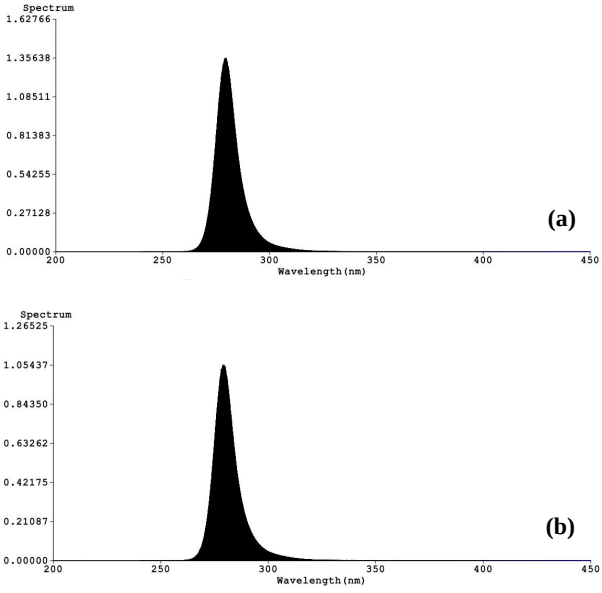

Fig. 3. Spectrum test report: for 2.5 mW, 280 nm diode (a), for the end of a 50-cm section of a PMMA optical fibre connected to the same diode (b).

This material is characterized by a high maximum operating temperature (80 °C) and high tensile strength (75 MPa, and 100 MPa for compression), high transparency (92%), easy processing, and resistance to inorganic substances. The propagation of light in an optical fibre is based on the phenomenon of a total internal reflection where the optical fibre ability to collect the useful light energy is determined by numerical aperture (NA) which depends on the fibre acceptance angle. The optical fibre

consists of a core and a surrounding layer which is the cladding. In a traditional (end emitting) optical fibre, after exceeding the limit value of the optical fibre acceptance angle, the cladding prevents the light from leaking out. However, the authors wanted the light to propagate along the optical fibre entire length to ensure the antibacterial effect of the radiation not only at the end of the optical fibre, but also along its full length. Therefore, the side emitting optical fibres were used, the cladding of which partially transmits the light. Due to the way they are constructed, with a cladding that is intentionally less effective, light gradually escapes along the whole length of the fibre creating an even fairly glow (Fig. 4).

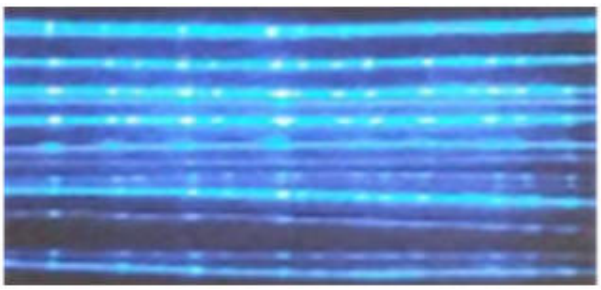

Fig. 4. Side emitting optical fibres.

For the purposes of the research, optical fibres with a diameter of 0.75 mm and a diameter of 0.5 mm side emitting with micro-windows were tested. These optical fibres are woven into the structure of the spacer knitted fabric.

The spacer knitted fabric consists of two outer layers connected to each other by an inner layer of spacer monofilaments. Spacer fabrics can be used in different product groups such as mobile textiles (car seat covers, dashboard cover), industrial textiles (composites), medical textiles (anti-decubitus blankets), and sports textiles [14]. The structure of the knitted fabric is open and makes it permeable to air. Such a special 3D structure allows for placing sensors or other electronic devices or, as in the proposed system, optical fibres (Fig. 5).

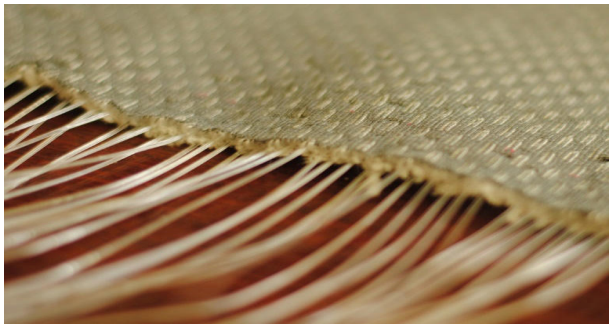

Fig. 5. Spacer fabric with interwoven optical fibres.

Three types of a spacer-knitted fabric were considered, differing in the monofilament layer thickness (3 mm, 4 mm, 5 mm) and the wave density. There were no significant differences in terms of the possibility of integration with the optical fibre mesh system, each of the proposed types of spacer fabric (Fig. 6) can be used in the system construction. However, due to the loss of elasticity of the knitted fabric when a thicker optical fibre is woven, a 0.5-mm thick fibre was selected for further research.

Fig. 6. Spacer fabric with interwoven optical fibres.

The research next stage was to model the location of optical fibres in the knitted fabric structure. Two variants of fibre densification were assumed. The 1:1 and 1:2 variants assume the location of the optical fibres in parallel in the structure of the spacer knitted fabric with the following density: 1:1 one optical fibre for one knitted column, 1:2 one optical fibre for every second knitted column (Figs. 7 and 8).

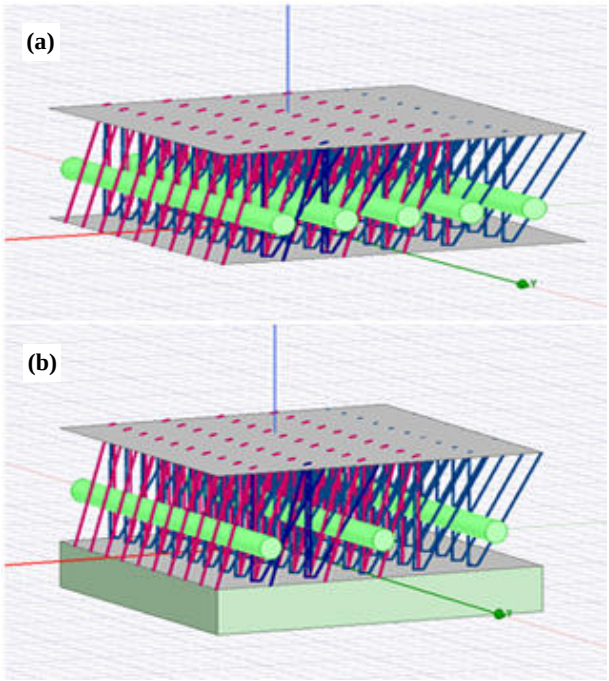

Fig. 7. Model of a distance-knitted fabric with optical fibres in the monofilament structure: variant 1:1 [11] (a), and variant 1:2 (b).

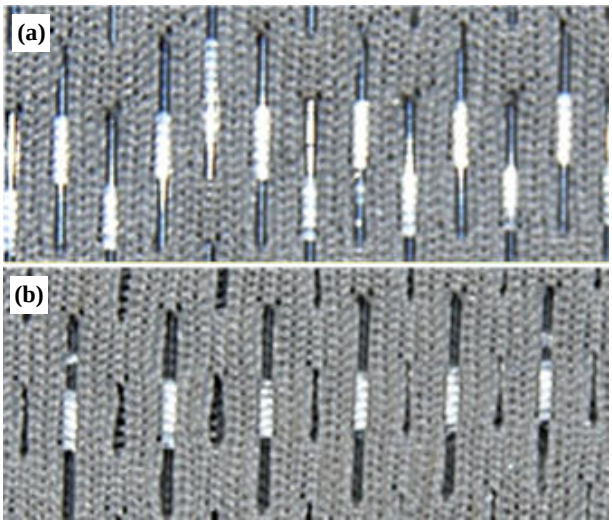

Fig. 8. Weaving optical fibres into the knitted fabric: variant 1:1 (a) and variant 1:2 (b).

The ends of the optical fibres were pulled out of the properly prepared samples in both variants of fibre density. They were derived from the knitted fabric and connected with the system of LEDs. Two types of diode connections have been constructed:

- LEDs connected to the optical fibre bundle,
- LEDs located in the protective tape connected edge-to-edge.

Both types use 10-mW/100-mA LEDs emitting UV-C radiation in the range of 265–280 nm (Fig. 9).

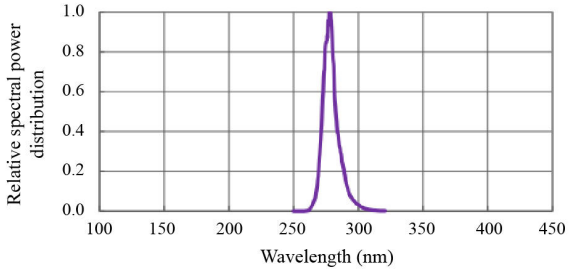

Fig. 9. Spectrum of radiation at the temperature of T = 25 °C [15].

In the first solution (Fig. 10), single optical fibres were grouped into bundles of 11 fibres which were protected with silicone lagging. Next, optical fibres in bundles were cut and their surfaces were ground in order to obtain the best possible contact surface with the front of the diode. The whole bundle (fibre optics bundle with the diode) was placed in a heat shrink tube for protection and permanent immobilization of elements.

The second proposed connection system used a silicone protective tape in which diodes were previously connected (Fig. 11). In this solution, diodes were not in a direct contact with the fronts of the light guides, and radiation was dispersed.

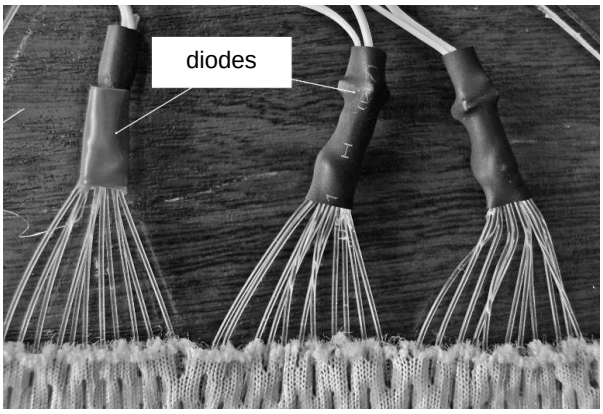

Fig. 10. Diodes connected to the optical fibre bundle.

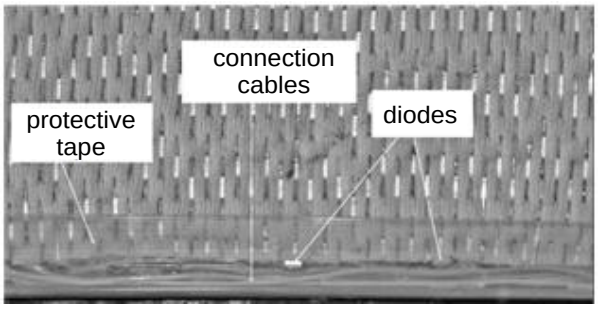

Fig. 11. LEDs located in the protective tape connected edge-to-edge.

In both systems, prior to connection, the diodes were equipped with heat sinks to dissipate heat and were connected to the power supply system. 12- and 24-VDC constant voltage switch mode power supplies with voltage stabilization were selected to power the system. The system allows to adjust the emitted radiation power level by changing the diode current. The current of a single diode was of 80 mA which was 80% of the relative radiation power.

For demonstration purposes, a UV diode emitting visible light with a wavelength λ_d of 360–370 nm was connected to the systems (Figs. 12 and 13).

Fig. 12. System visualization for diodes connected to the optical fibre bundle using visible light radiation.

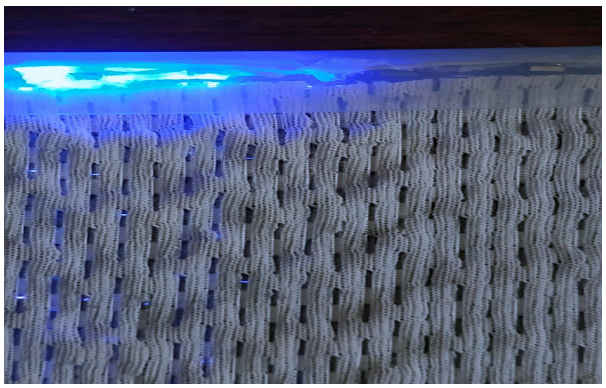

Fig. 13. System visualization for diodes located in the protective tape connected edge-to-edge using visible light radiation.

The light propagation along the optical fibre depends on many factors, among which, apart from the optical fibre material itself, the angle of the light beam entering its core is the most important one. Therefore, for better light propagation, a diode system connected to the optical fibre bundle was chosen.

3. Microbiological testing

Microbiological tests consisted of performing microbiological (quantitative and qualitative) analyses of selected taxonomic groups of microorganisms on the prepared textronic knitted fabrics before and after the irradiation process. They were carried out in the Microbiological Laboratory of the Faculty of Infrastructure and Environment of the Częstochowa University of Technology.

At the beginning, a preliminary assessment of the effectiveness of the proposed methods of removing biological contaminants from the tested materials was performed. Moreover, the bactericidal effectiveness was

determined which was given as a percentage of the tested microorganisms removal. The samples of the modified knitted fabric were prepared in a 1:1 and 1:2 configuration with a woven optical fibre with a diameter of 0.5 mm. The tested material consisted of the prepared fragments of textronic knitted fabrics with connected LEDs. Figure 14 shows examples of materials used in the research. The samples were tested on the experimental stand shown in Fig. 15.

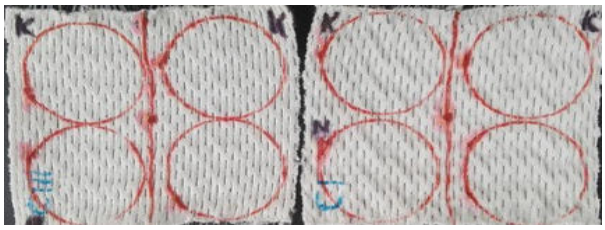

Fig. 14. Examples of textronic knitted fabrics used in the research.

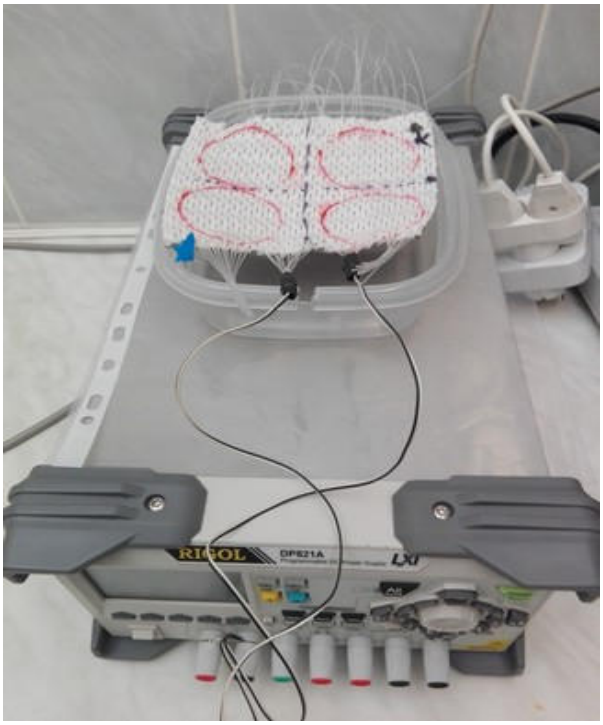

Fig. 15. Test stand: RIGOL power supply and irradiation chamber.

On the tested fabrics specific concentrations of biological contaminants (municipal sewage, dilution ratio of 10^{-3}) were introduced into circular areas marked on the fabric in Figs. 11 and 12. The sewage contains groups of micro-organisms that cause sanitary contamination and a large part of them are groups of pathogens important for nosocomial infections. The reference (control) was made of unmodified and irradiated knitted fabrics. Materials were biologically contaminated within the marked areas by spraying (from the atomizer) with prepared sewage dilutions. In order to limit the contaminated area only to the marked area, dilutions of the wastewater were introduced through a plastic pipe with a diameter of the studied area (it corresponded to the surface of the contact plate with a diameter of 55 mm). Prior to the irradiation, controls were taken using the replica plating method. It is used for the tests involving the collection of a sample from a plate filled with a suitable growth medium with a convex meniscus. This method is used to determine a degree of microbial contamination of various smooth surfaces, packaging materials, and fabric surfaces. In the studies on estimating the number of microorganisms discussed in the paper, during each sampling, the lid was removed from sterile plates (with a substrate appropriate for a given group of microorganisms) and the plate substrate was pressed against the tested surface of the fabric for about 10 s. In order to standardize the sampling in terms of microbiological cleanliness of the surface, an even pressure was applied to the plate surface of 500±50 g for 10±1 s (applicator). Then, the plate was sealed, turned upside down and placed in an incubator at an appropriate temperature and for a period of growth specified for the analysed group of microorganisms. Next, the number of colonies grown on individual plates was counted. The results are given in CFU (colony-forming unit) per 25 cm^2 area (plate area).

In the preliminary tests, two variants of knitwear were irradiated for 30 min at a room temperature of approximately 23 °C. After the irradiation process, samples were taken to determine the degree of reduction in the amount of potentially pathogenic microorganisms on the knitted fabric surface. The total number of mesophilic bacteria was determined. This group of microorganisms includes a majority of potentially pathogenic microorganisms for which the human body temperature is optimal for development. The preliminary test results (Table 1) showed a much higher efficiency of the system based on the 1:1 variant than on 1:2, so this system was subjected to further microbiological tests.

Table 1.
The preliminary test results.

Variant	Reduction of the number of microorganisms after the process [%]
1:2	50
1:1	91.9

In the subsequent studies, 4 variants of the irradiation time of knitted fabrics were used: 15 min, 30 min, 60 min, and 120 min. After the process, the samples were taken to determine the reduction degree in the amount of potentially pathogenic microorganisms on the knitted fabrics surface.

Quantitative and qualitative analyses of micro-organisms important for nosocomial infections were performed. The total number of bacteria, the total number of bacteria from the *Enterobacteriaceae* family (this group includes, among others, *Klebsiella pneumoniae* bacteria), and the total number of bacteria from the so-called coli group, including *Escherichia coli*, were determined. Additionally, the total amount of fungi and actinomycetes, which can also cause lesions in humans, was determined.

Microbiological tests of the knitted fabrics surfaces were carried out in accordance with the recommendations of PN-EN ISO 18593:2018-08 and the European Pharmacopoeia [16,17].

The following substrates (BioMaxima SA contact plates) were used for the study intended for each group of the analysed microorganisms (selectively differentiating):

- VRBG LAB-AGAR™ + Letheen + Tween (contact plates) medium is used to isolate and determine the total amount of bacteria from the *Enterobacteriaceae* family,
- Sabouraud Dextrose with Chloramphenicol IRRLAB-AGAR™ + Letheen + Tween is used to isolate and determine the total number of fungi,
- TSA IRR LAB-AGAR™ + Letheen + Tween/box medium is used to isolate and determine the total number of bacteria,
- Actinomycete LAB-AGAR™/250 g medium is used to isolate and determine the total amount of actinomycetes,
- TBX LAB-AGAR™ medium is used to isolate and quantify the total amount of (β-D-glucuronidase-positive) *Escherichia coli* and coliform bacteria.

After sampling the knitted fabrics, the plates were incubated at 28 °C for 24–48 h (determination of the total number of bacteria) and 1–3 days (determination of the total number of fungi and actinomycetes).

The plates were incubated at 37 °C to determine the total number of bacteria from the *Enterobacteriaceae* family and coliforms (for 24–48 h). The research was carried out in three replications, and the mean values are used in the results. For each type of bacteria, 6 samples were prepared: 3 control and 3 irradiated. The percentage of reduction was calculated from Eq. (1):

$$R = \frac{A_0 - A}{A_0} \cdot 100\%, \tag{1}$$

where A_0 is the mean number of colonies in a control sample, and A is the mean number of colonies in a sample after irradiation.

The percentage uncertainty of reduction was calculated using Eq. (2):

$$\Delta R = \frac{\Delta A}{A_0} \cdot 100\%, \tag{2}$$

where ΔA is the standard deviation of the colonies number after irradiation. Examples of contact tests are shown in Figs. 16–20.

4. Research data analysis

Tables 2–5 show the number of microbial colonies in the control and irradiated samples and the percentage reduction, as well. The mean and standard deviation were given which was taken as a measure of the measurement uncertainty. The reduction uncertainty does not exceed 10%, and, in most cases, it is below 5%.

The results presented in Tables 2–5 showed that the total reduction of all tested microorganisms in relation to the controls was the following for the 4 tested exposure times, respectively:

- after 15 min: 68%,
- after 30 min: 78%,
- after 60 min: 93%,
- after 120 min: 99%.

Knitted fabric modification proved effective in reducing the amount of potentially pathogenic microorganisms.

Fig. 16. Example of a comparison of the determination of the total amount of bacteria (from the left) isolated from the control knitted fabric and irradiated under a 30-min exposure, lower part of the contact plate.

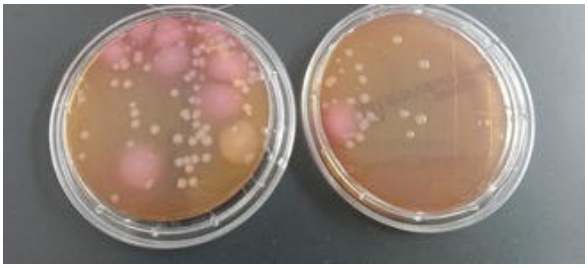

Fig. 17. Example of a comparison of the determination of the total number of bacteria from the *Enterobacteriaceae* family (from the left), isolated from the control knitted fabric and irradiated for 30 min: lower part of the contact plate.

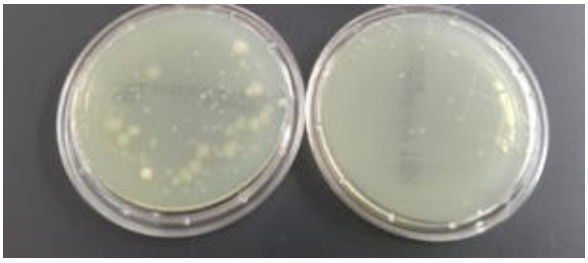

Fig. 18. Exampleof the comparison of the determination of the total amount of coliform bacteria (from the left) isolated from the control knitted fabric and irradiated under a 30-min exposure, lower part of the contact plate.

Fig. 19. Example of a comparison of the determination of the total number of fungi (from the left) isolated from the control knitted fabric and irradiated under a 30-min exposure, bottom part of the contact plate.

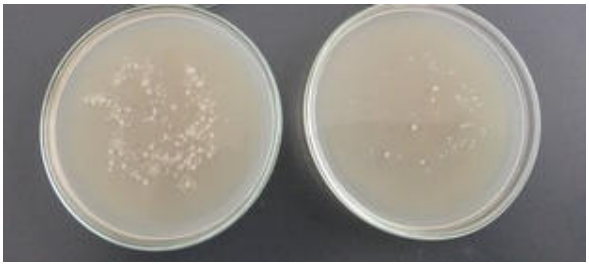

Fig. 20. Example of a comparison of the determination of the total number of actinomycetes (from the left) isolated from the control knitted fabric and irradiated under a 30-min exposure, lower part of the contact plate.

Table 2.
The results of the microbiological analysis of the knitted fabrics surface after 15 min of irradiation.

Type of marking	Number of microbial colonies isolated from 25 cm^2 of the knitted fabric surface		Reduction of microorganisms after the process [%]
	Control (C) without exposure	Exposed	
Total number of bacteria	96±3.6	21±1.8	78±2
Total number of bacteria from the *Enterobacteriaceae* family	19±2.6	3±0.8	84±4
Total number of coliform bacteria	137±3.0	59±3.3	57±2
Total number of bacteria of the genus *Escherichia coli*	12±1.4	4±0.6	67±5
Total number of fungi	15±0.7	8±1.4	47±9
Total number of actinomycetes	17±1.4	4±1.1	77±6

Table 3.
The results of the microbiological analysis of the knitted fabrics surface after 30 min of irradiation.

Type of marking	Number of microbial colonies isolated from 25 cm^2 of the knitted fabric surface		Reduction of microorganisms after the process [%]
	Control (C) without exposure	Exposed	
Total number of bacteria	62±3.2	5±0.9	92±1
Total number of bacteria from the *Enterobacteriaceae* family	172±2.8	53±1.9	69±1
Total number of coliform bacteria	50±1.9	13±1.4	74±3
Total number of bacteria of the genus *Escherichia coli*	5±1.1	0	100
Total number of fungi	13±1.17	7±0.9	46±7
Total number of actinomycetes	61±1.6	8±0.8	87±1

Table 4.
The results of the microbiological analysis of the knitted fabrics surface after 60 min of irradiation.

Type of marking	Number of microbial colonies isolated from 25 cm^2 of the knitted fabric surface		Reduction of microorganisms after the process [%]
	Control (C) without exposure	Exposed	
Total number of bacteria	51±2.3	7±1.2	86±2
Total number of bacteria from the *Enterobacteriaceae* family	20±1.9	1±0	95±0
Total number of coliform bacteria	81±2.1	7±1.4	91±2
Total number of bacteria of the genus *Escherichia coli*	6±0.75	0	100
Total number of fungi	32±2	2±0.4	94±1
Total number of actinomycetes	17±1.4	1±0	94±4

Table 5.
The results of the microbiological analysis of the knitted fabrics surface after 120 min of irradiation.

Type of marking	Number of microbial colonies isolated from 25 cm^2 of the knitted fabric surface		Reduction of microorganisms after the process [%]
	Control (C) without exposure	Exposed	
Total number of bacteria	44±1.7	1±0	98±0
Total number of bacteria from the *Enterobacteriaceae* family	91±2.7	0	100
Total number of coliform bacteria	15±2.6	0	100
Total number of bacteria of the genus *Escherichia coli*	6±1.1	0	100
Total number of fungi	21±2.3	0	100
Total number of actinomycetes	37±3.3	1	97±2

The percentage reduction in individual taxonomic groups of the analysed microorganisms depended on the exposure time. Figure 21 shows the percentage reduction of microorganisms in relation to the control sample after 15, 30, 60, 120 min: bacteria, *Enterobacteriaceae*, coliforms, *Escherichia coli*, fungi, and actinomycetes.

The data analysis in Table 2 shows that the reduction for individual groups of microorganisms after 15 min of irradiation ranged from 47% for fungi to 84% for bacteria of the *Enterobacteriaceae* genus. Along with the extension of the exposure time, the percentage reduction of pathogenic forms usually increased (Tables 3–5). The mean total number of active microorganisms decreased with time, and the reduction degree was of 78%, 92%, 86%, 98% for the exposure times of 15, 30, 60, and 120 min, respectively. The observed mean reduction in the number of all tested microorganisms in total increased and amounted to 68%,78%, 93%, and 99% for 15, 30, 60 and 120 min of UV-C exposure, respectively. Certain deviations in the dynamics of reduction result from the inability to prepare identical samples (nonuniform distribution of microorganisms in the environment). The quickest reaction to the irradiation was observed for the bacteria of the genus *Escherichia coli*. Already after 30 min of UV-C treatment, the reduction in the amount of these conditional pathogens was of 100% (Table 3). The research

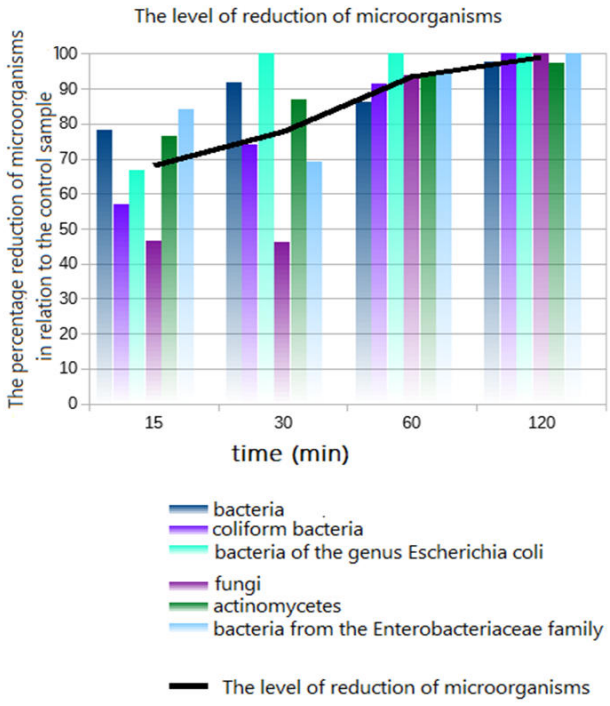

Fig. 21. Percentage reduction of microorganisms in relation to the control sample after 15-, 30-, 60-, 120-min exposure including: total amount of bacteria, bacteria from the *Enterobacteriaceae* family, coliforms, *Escherichia coli*, fungi, and actinomycetes.

confirmed earlier reports [18] that bacteria are among the microorganisms most susceptible to UV-C radiation, whereas fungi are destroyed to a lesser extent by the irradiation.

5. Conclusions

Potentially dangerous microorganisms with which we come into contact very often include coliform bacteria and *enterococci* (formerly *faecal streptococci*). Most often, these microorganisms cause infections of the digestive system. Sometimes these bacteria, especially drug-resistant, can also cause sepsis, which is potentially extremely life-threatening. In turn, weakened organisms can also easily succumb to viral infections and be more prone to serious health complications [19,20]. Bacteria of the *Enterobacteriaceae* family (which also often exhibit drug resistance to many antibiotics) are also a particular health hazard [21,22].

The article discusses the assumptions and methods of implementing the microbiological reduction system. By selecting the appropriate elements, such as optical fibre type and size, spacer fabric type, optical fibres density, and technology of their connection to the UV-C light generator, the source of which was LED diodes of appropriate power and radiation range, various system configurations were considered and tested in order to find the optimal solution. This solution ensures, thanks to the appropriate propagation of the UV-C radiation through optical fibres, the highest sterilization effect while maintaining the functional properties of the knitted fabric. It is worth mentioning that the tests did not detect any degradation of the knitted fabric under the UV-C radiation influence.

According to the presented analysis of the research results, the applied modification of the knitted fabric turned out to be effective in reducing the amount of potentially pathogenic microorganisms. The percentage reduction of individual taxonomic groups of the analysed microorganisms depended on the exposure time, but after 15 min the reduction was achieved from 47% for fungi to 84% for *Enterobacteriaceae*. With time, the reduction typically increased so that after 60 min it was of about 90% and after 2 h it was close to 100% for all types of the tested microorganisms. The fastest reduction is achieved in the *Escherichiacoli* genus: after 30 min the reduction was of 100%. The results indicate that the presented method has a great potential and could be used in the sterilization of textile materials.

Authors' statement

Research concept and design, E. Łada-Tondyra and A. Jakubas; collection and/or assembly of data, E. Łada-Tondyra, A. Jakubas, B. Jabłońska, E. Stańczyk-Mazanek; data analysis and interpretation, E. Łada-Tondyra, A. Jakubas, B. Jabłońska, E. Stańczyk-Mazanek; writing the article, E. Łada-Tondyra; critical revision of the article, B. Jabłońska, E. Stańczyk-Mazanek, A. Jakubas; final approval of article, E. Łada-Tondyra and A. Jakubas.

Acknowledgements

The research was supported by the Polish Agency for Enterprise Development (PARP), grant no. POIR.02.03.02-10-0022/18, 2019-2020.

References

[1] Gniotek, K. & Krucinska, I. The basic problems of textronics. *Fibres Text. East. Eur.***12**, 13–16 (2004).

[2] Łada-Tondyra, E. & Jakubas, A. Modern applications of textronic systems. *Przegląd Elektrotechniczny* **94**, 198–201 (2018). [in Polish]. https://doi.org/10.15199/48.2018.12.44

[3] Strus, M. Mechanisms of action of physical factors on micro-organisms. *Roczniki Państwowego Zakładu Higieny* **3**, 263–268 (1997). [in Polish]

[4] Diston, D., Ebdon, J. E. & Taylor, H. D. The effect of UV-C radiation (254 nm) on candidate microbial source tracking phages infecting a human-specific strain of *Bacteroides fragilis* (GB-124). *J. Water Health* **10**, 262–270 (2012). https://doi.org/10.2166/wh.2012.173

[5] Wolska, A., Wisełka, M. & Pawlak. A. Reducing the risk of COVID-19 through the use of ultraviolet radiation. https://m.ciop.pl/CIOPPortalWAR/file/89579/202003206928&Covid-PROMIENIOWANIE-UV-Komunikat-3.pdf (2020). [in Polish]

[6] Statement on the CIE position on ultraviolet (UV) radiation as a measure to reduce the risk of the spread of COVID-19. https://cie.co.at/files/CIE%20Position%20Statement%20-%20UV%20radiation%20(2020)_PL_0.pdf (2020). [in Polish]

[7] Kowalski, W. J., Petraitis, V. & Walsh, T. J. *2020 COVID-19 Coronavirus Ultraviolet Susceptibility*. (PurpleSun, Inc, New York, 2020).

[8] Beretsou, V. G. *et al.* A chemical, microbiological and (eco) toxicological scheme to understand the efficiency of UV-C/H2O2 oxidation on antibiotic-related microcontaminants in treated urban wastewater. *Sci. Total Environ.* **744**, 140835 (2020). https://doi.org/10.1016/j.scitotenv.2020.140835

[9] Woo, H. *et al*. Efficacy of inactivation of human enteroviruses by dual-wavelength germicidal ultraviolet (UV-C) light emitting diodes (LEDs). *Water* **11**, 1131 (2019). https://doi.org/10.3390/w11061131

[10] Phattarapattamawong, S., Chareewan, N. & Polprasert, C. Comparative removal of two antibiotic resistant bacteria and genes

by the simultaneous use of chlorine and UV irradiation (UV/chlorine): Influence of free radicals on gene degradation. *Sci. Total Environ.* **755**, 142696 (2021). https://doi.org/10.1016/j.scitotenv.2020.142696

[11] Lada-Tondyra, E. & Jakubas, A. The Concept of a Textronic System Limiting Bacterial Growth. in *2018 Progress in Applied Electrical Engineering (PAEE)* 1–4 (IEEE, Koscielisko, Poland, 2018). https://ieeexplore.ieee.org/document/8441107

[12] Cysewska-Sobusiak, A., Prokop, D.& Jukiewicz, M. Development Trends and Application Areas Fibre Optic Techniques. In *Poznan University of Technology Academic Journals. Electrical Engineering* **89**, 205–217 (2017). [in Polish]

[13] Brochure of transparent polymer-TPXTM, *Mitsui Chemicals America, Inc.* www.mitsuichemicals.com/tpx_proc.htm

[14] Armakan, D. M. & Roye, A. A study on the compression behavior of spacer fabrics designed for concrete applications. *Fibres Polym*. **10**, 116–123 (2009). https://doi.org/10.1007/s12221-009-0116-7

[15] ProLight PB2D-1CLA-TC 1W UV Power LED Technical Datasheet. *ProLight Opto* https://www.tme.eu/Document/5559cb9280c8f6735ea54eeee3067a39/PB2D-1CLA-TC.pdf (2021).

[16] ISO 18593:2018 *Microbiology of the food chain — Horizontal methods for surface sampling*. (2018).

[17] *European Pharmacopoeia*, 10th Edition. https://www.edqm.eu/en/work-programme-bsp (2021).

[18] Hardjawinata, K., Setiawati, R. & Dewi,W. Bactericidal efficacy of ultraviolet irradiation on *Staphylococcus ureus*. *Asian J. Oral Maxillofac. Surg*. **17**, 157–161 (2005). https://doi.org/10.1016/S0915-6992(05)80043-3

[19] Xu, Z.*et al*. First report of class 2 integron in clinical *Enterococcus faecalis* and class 1 integron in *Enterococcus faecium* in South China. *Diagn. Microbiol. Infec. Dis.* **68**, 315–317 (2010). https://doi.org/10.1016/j.diagmicrobio.2010.05.014

[20] Stańczyk-Mazanek, E., Pasoń, Ł. & Kępa, U. Effect of mesophilic fermentation of sewage sludge on drug-resistant bacterial count of the *Enterococcus* genus. *Desalination Water Treat.* **134**, 86–91 (2018). https://doi.org/10.5004/dwt.2018.22672

[21] Stępniak, L., Pasoń, Ł., Stańczyk-Mazanek, E. & Lach, J. Analysis of the presence and drug resistance of bacteria from the *Enterobacteriaceae* family and the genus of *Enterococcus* in treated wastewater from a selected wastewater treatment plant. *Desalination Water Treat.* **134**, 23–29 (2018). https://doi.org/10.5004/dwt.2018.22592

[22] Jarząb, A., Górska-Frączek, S., Rybka, J. & Witkowska, D. *Enterobacteriaceae* infection-diagnosis, antibiotic resistance and prevention. *Postepy Hig. Med. Dosw.* **65**, 55–72 (2011). [in Polish] https://doi.org/10.5604/17322693.933273