Materials Today Communications 31 (2022) 103690

Contents lists available at ScienceDirect

Materials Today Communications

journal homepage: www.elsevier.com/locate/mtcomm

Evaluation of the degradation of materials by exposure to germicide UV-C light through colorimetry, tensile strength and surface microstructure analyses

Oihane Mitxelena-Iribarren [a,b,*], Beñat Mondragon [b], Eva Pérez-Lorenzo [a,b], Cristian Smerdou [c], Francisco Guillen-Grima [d,e,f,g], J. Enrique Sierra-Garcia [h], Fernando Rodriguez-Merino [i], Sergio Arana [a,b]

[a] CEIT-Basque Research and Technology Alliance (BRTA), Manuel Lardizábal 15, 20018 Donostia-San Sebastián, Spain
[b] Universidad de Navarra, Tecnun, Manuel Lardizábal 13, 20018 Donostia-San Sebastián, Spain
[c] Division of Gene Therapy and Regulation of Gene Expression, Cima Universidad de Navarra and Instituto de Investigación Sanitaria de Navarra (IdISNA), 31008 Pamplona, Spain
[d] Clínica Universidad de Navarra, Dept of Preventive Medicine, Pio XII 36, 3108 Pamplona, Navarra, Spain
[e] Navarra Institute for Health Research (IdiSNA) Irunlarrea s/n, 31008 Pamplona, Navarra, Spain
[f] Dept of Health Sciences Public University of Navarra (UPNA), Avda Barañain s/n, 31008 Pamplona, Spain
[g] Ciber OBN, Instituto de Salud Carlos III, Madrid, Spain
[h] University of Burgos, Dept. of Electromechanical Engineering, Avda Cantabria,09006 Burgos, Spain
[i] Boos Technical Lighting S.L., Santovenia de Pisuerga, Valladolid, Spain

ARTICLE INFO

Keywords:
UV-C germicidal light
Material degradation
UV irradiation
Surface microstructure
Discoloration
Tensile strength

ABSTRACT

Due to the COVID19 pandemic, solutions to automate disinfection using UV-C combined with mobile robots are beginning to be explored. It has been proved that the use of these systems highly reduces the risk of contagion. However, its use in real applications is not being as rapid as it needs to be. One of the main market input barriers is the fear of degrading facilities. For this reason, it is crucial to perform a detailed study on the degradation effect of UV-C light on inert materials. This experimental study proves that, considering exposition times equivalent to several work years in hospital rooms, only the appearance of the material is affected, but not their mechanical functionalities. This relevant result could contribute to accelerate the deployment of these beneficial disinfection technologies. For that purpose, a colorimetry test, tensile strength test, and analysis of the surface microstructure were carried out. The results showed that polymers tend to turn yellow, while fabrics lose intensity depending on the color. Red is hardly affected by UV-C, but blue and green are. Thus, this study contributes to the identification of the best materials and colors to be used in rooms subjected to disinfection processes. In addition, it is shown how the surface microstructure of the materials is altered in most of the materials, but not the tensile strength of the fabrics.

1. Introduction

Due to the current COVID-19 pandemic, the germicidal market experienced a great revolution. As more information about the virus was known, the importance of keeping surfaces disinfected to prevent its spread was increasingly emphasized. That was why, like many other disinfection products, UV-C lamps combined with mobile robots to automate the disinfection process became more prominent than ever. These lamps can continuously irradiate C-band UV and thus eliminate microorganisms from almost any surface by directly damaging their genomic material [1]. Its use in hospitals was already studied and considered [2–4]. With the pandemic, it spread to almost any setting [5,6]. Any scenario where humans can interact with the environment repeatedly, with areas where different people touch the same surface, became a target for UV lamps. These lamps are the perfect element to prevent the spread of the virus and other pathogenic elements by contact with surfaces [6,7]. However, its use in real applications is not being as rapid as it needs to be, due to the fear of degrading facilities, among

* Corresponding author at: CEIT-Basque Research and Technology Alliance (BRTA), Manuel Lardizábal 15, 20018 Donostia-San Sebastián, Spain.
E-mail address: omitxelena@ceit.es (O. Mitxelena-Iribarren).

https://doi.org/10.1016/j.mtcomm.2022.103690
Received 2 March 2022; Received in revised form 6 May 2022; Accepted 14 May 2022
Available online 19 May 2022

Fig. 1. UV-C incidence room, with the Zenzoe lamp from ASTI MOBILE ROBOTICS in the center and the LS126C UV Light Meter.

other reasons. Thus, in order to accelerate its deployment, performing a detailed study on the degradation effect of UV-C light on inert materials is crucial.

UV-C radiation is known to be highly germicidal. It is known that the thymine-containing DNA found in microorganisms absorbs UV-C light. Because of the absorption, the thymine is modified, thus preventing the growth of the bacterium. In this way, the UV light can pass through the cell membrane of the bacteria, thus damaging the bacterial DNA and killing the microorganisms [8]. UV-C radiation can also damage the RNA, which constitutes the genomic material of many viruses, including SARS-CoV-2. In this case, UV-C can cause different types of damage in RNA, including crosslinking, photochemical modification, and oxidative damage [9]. However, just as it can be harmful to microorganisms, it can also be harmful to humans. It is known that overexposure to UV radiation can cause health problems such as skin cancer, premature aging, and other skin damage, cataracts and other eye damage, and immunosuppression, among others [10]. Therefore, germicidal lamps should be used with great caution. In addition, the effect of UV-C light on inert materials must also be investigated, as these can become aesthetically degraded or lose their functionality.

To date, not many studies have been carried out to analyze the effect of UV-C on different materials in-depth, although some studies focused on specific materials. For example, it is known that most polymers, which are made up of covalent bonds, are susceptible to degradation when exposed to UV-C. The high-energy photons have sufficient energy to promote the degradation of the material. They can promote electrons to higher energy levels and thus dissociate or allow the oxidation of covalent bonds [11]. In addition, it is also known that most metals are unaffected by UV light due to the availability of free electrons to absorb photon energy without undergoing energetic bond dissociation transitions [12].

On the other hand, ceramics have tightly bound electrons, so they are generally unaffected by UV irradiation. As for wood, it is known that it tends to undergo photo-oxidative degradation when exposed to UV light, leading to discoloration and surface changes [13]. In this context, in order to boost the deployment of these beneficial disinfection technologies, a deep analysis of the effect that direct UV-C light can have on the appearance and functionality of materials is needed.

The Zenzoe UV-C lamp from ASTI MOBILE ROBOTICS and Boos technical Lighting was used to irradiate materials of different nature to determine the effect mentioned above. The main objective of this work was to know the effects of UV-C irradiation on different types of materials that are usually present in healthcare centers. Therefore, different analyses such as colorimetry, tensile stress, and surface analyses were carried out to determine discoloration, a decrease of the tensile strength, and degradation of the surface microstructure suffered by the materials after different treatments. This can help to identify the best materials and colors to be used in rooms subjected to disinfection processes.

Table 1
Materials irradiated with UV-C light.

Material family	Color	Composition or common name
Fabrics	Orange	SILVERTEX: 100% Polyester (Tapestry)
	Grey/blue	Astro from SMART FABRICS: 100% Polyester (Tapestry)
	Black	Orozco from SMART FABRICS: 89% Polyester 11% Cotton (Tapestry)
	Green	Acrylic
	White	Cotton
	Green	
	Blue	Polyester
	Green	
	Red-pink	
	Orange	
	Brown	Leather
Polymers	White	Soft opaline polystyrene
	Transparent	2 mm-thick Polycarbonate
		3 mm-thick Polycarbonate
		5 mm-thick Polycarbonate
	Grey	Acrylonitrile Butadiene Styrene (ABS)
	Blue	
	Green	Polypropylene (PP)
	White	2 mm-thick Teflon
Woods	White	Polyvinyl chloride (PVC)
	Grey	Melamine
	Blue	
	Brown	Uncoated Medium-density fiberboard (MDF)
	Brown	Varnished MDF
	White	Painted MDF
	White	Formica on agglomerated wood
Metals	Gray	Extruded aluminum
	Gray	Stainless steel

2. Materials and methods

2.1. Experimental set-up and materials

The lamp used for the experiments was the Zenzoe lamp from ASTI MOBILE ROBOTICS and Boos Technical Lighting. This lamp integrates 5 fluorescent tubes of UV radiation in the C band, emitting at a wavelength of 254 nm and with a power of 140 W. The Zenzoe lamp is still under development, aiming to disinfect surfaces autonomously through UV-C radiation and thus guarantee sterile conditions in hospital and industrial environments.

The lamp and all the samples were located in a closed room, without windows, to measure only the effect of UV-C radiation obtained from the Zenzoe lamp (Fig. 1). In the room, there were six shelves at different distances from the lamp. After measuring the radiation obtained from the lamp in ten different positions with the LS126C UV Light Meter (Linshang, China), the higher incidence point was chosen to locate the samples.

For this project, materials that are usually present in hospitals were selected. Materials of different families were chosen to determine the effect of UV-C light on different fabrics, polymers, woods, and metals. A total of twenty-eight different materials (Table 1) were continuously exposed to different times: 3.5, 7, 14, 28, and 54 h. These times were equivalent to treating the surfaces once a day with a 36.8 mJ cm^{-2} dose and a velocity of 100 mm/s during 1, 2, 4, 8, and 16 years respectively, according to the radiation measured in the chosen position. The 36.8 mJ cm^{-2} is 10 times more than the average needed levels for photodesactivate 90% of the SARS CoV-2 on the surface [14]. All samples were treated at a frontal distance of approximately one meter from the

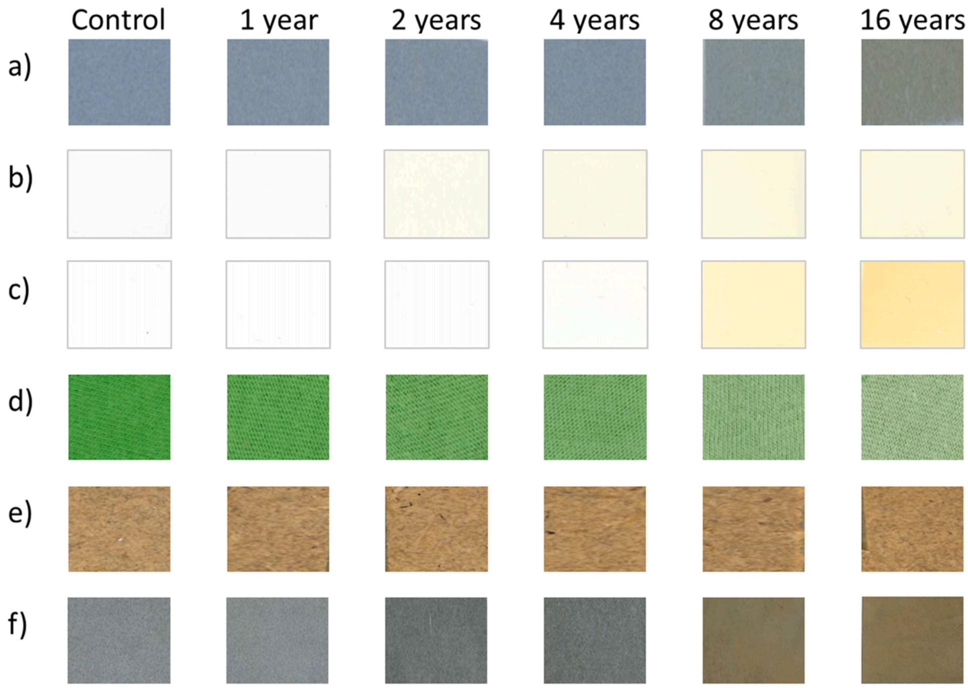

Fig. 2. Evolution of different materials after the equivalent dose of UV-C light exposure times: a) blue ABS, b) soft opaline polystyrene, c) PVC, d) green cotton, e) MDF and f) stainless steel. The times indicated in the image (1, 2, 4, 8 and 16 years) are the equivalent time to daily short irradiations, which in continuous treatment during the experiments were 3.5, 7, 14, 28, and 54 h of exposure.

germicidal lamp. The materials were cut in two different sizes, in order to have the precise amount of each sample for each test. The samples analyzed in the colorimetry test were cut in sizes of 3x3cm. These same samples were then used for the surface microstructure analyses. Finally, the samples afterwards used in the tensile strength study, were cut with a size of 1x10cm. Three samples of each material and size were at least exposed, in order to have a sample size big enough to perform de following statistical analyses.

After, the following tests were carried out to assess the degradation of the materials: colorimetry tests, tensile strength tests, and observation of surface microstructures by SEM microscope.

2.2. Colorimetry test

The colorimetry tests were performed to measure the color change caused in the materials with the different radiation times with respect to the non-radiated control. Due to a lack of colorimeter, a color identification method previously developed and published by this research group was used in this research [15]. Firstly, images of the non-radiated materials were obtained in triplicate (three samples for each material) to ensure that the results were statistically significant. All the digital images were taken in a fixed position, in a special set-up with the same camera position and illumination. All the images were analyzed using RGB color model and the image processing for the numerical quantification of the intensity of the colors was conducted using Matlab (The MathWorks, Inc., Natick, MA, USA). The code developed with MATLAB consisted of reading an image and obtaining the intensity values (a value from 0 to 255) of the three-color channels: red (R), green (G) and blue (B) of each pixel in the image, as it has been done in the literature for several applications [15–17]. These initials named the code as RGB analysis. The values obtained in each color channel were used to objectively quantify the color change between control samples and the treated ones, as the same procedure was followed with all the samples after each time point treatment. To measure the total color change between samples and to homogeneously compare all the samples, the intensities of each color channel at each time point were compared with the control intensity values.

2.3. Tensile strength test

To analyze the harmful effect of radiation on the consistency of fabrics, 10 samples (the fabrics except for the leather, Table 1) were analyzed in the tensile strength test. For the study, the triplicate control samples and the triplicate samples treated with different radiation intensities were analyzed. The study was carried out with a Zwikiline 1.0 traction machine linked to the testXpert III control software (ZwickRoell S.L., Spain) with a loading cell which holds in a range of 5–50 N.

In this case, all samples (cut with a size of 1 $\times$10 cm) were tested before being treated in triplicate. Subsequently, the same tensile tests were carried out on the samples treated at different times. The initial distance between the grips was 50 mm. Once the sample was fixed, these were initially stretched with a speed of 10 mm/min until 0.01 N were reached. Then, the test was performed by moving the upper grip 50 mm/min, while recording all the loading and deformation data with the software. After the tensile strength tests performed with each sample, the maximum force supported by each one was calculated to compare the tensile mechanical properties between different samples.

2.4. Surface microstructure analysis

An analysis of the surface microstructure of the materials was carried out to determine the effect of UV-C light on these surfaces. For this, two steps were carried out in the assays. First, images of the surfaces were obtained using a Phenom G2 26 PRO SEM microscope. Then, two types of measurements were carried out using the ImageJ program. On the one hand, for the fibrous materials, twenty different measurements of the width of the fibers were taken. Measurements are indicated as mean value $\pm$ standard deviation.

On the other hand, for the non-fibrous materials, it was decided to measure the roughness of the material, measuring the grey intensities of the surface using the same image processing software. An approximation of the roughness using this standard deviation was obtained, as the

Table 2
Color change time points, indicating continuous treatment time and the equivalent dose of daily short irradiation.

Materials	Color change time points	
	Continuous treatment	*Equivalent daily short irradiation*
SILVERTEX	No color change after 54 h treatment (16 years)	
Orange SILVERTEX	3.5 h	1 year
Astro from SMART FABRICS	3.5 h	1 year
Orozco from SMART FABRICS	No color change after 54 h treatment (16 years)	
Green acrylic	14 h	4 years
White cotton	No color change after 54 h treatment (16 years)	
Green cotton	3.5 h	1 year
Leather	54 h	16 years
Blue Polyester	3.5 h	1 year
Green Polyester	3.5 h	1 year
Red-pink Polyester	3.5 h	1 year
Orange Polyester	3.5 h	1 year
Soft opaline polystyrene	7 h	2 years
2 mm Polycarbonate	14 h	4 years
3 mm Polycarbonate	14 h	4 years
5 mm Polycarbonate	14 h	4 years
Grey ABS	54 h	16 years
Blue ABS	3.5 h	1 year
PP (Polypropylene)	No color change after 54 h treatment (16 years)	
2 mm Teflon	No color change after 54 h treatment (16 years)	
PVC	14 h	4 years
Grey melamine	No color change after 54 h treatment (16 years)	
Blue melamine	No color change after 54 h treatment (16 years)	
Uncoated MDF	No color change after 54 h treatment (16 years)	
Varnished MDF	3.5 h	1 year
White painted MDF	No color change after 54 h treatment (16 years)	
Formica on agglomerated wood	No color change after 54 h treatment (16 years)	
Extruded aluminum	No color change after 54 h treatment (16 years)	
Stainless steel	28 h	8 years

different heights of the material were represented by different intensities of the grey color. Thus, the more these intensities varied, the rougher the material was.

2.5. Statistical analysis

The statistical significance of the results was determined using a paired t-test for every comparison of the triplicated treated samples to the control. Results were considered significant (p-value less than 0.05 and greater than 0.01), very significant (p-value less than 0.01 and greater than 0.001), and highly significant (p-value less than 0.001). On the other hand, results with p-values greater than 0.05 were considered statistically non-significant.

3. Results and discussion

3.1. Colorimetry test

After treating all the samples for the periods of time indicated in the Materials and Methods section, some changes were visually perceived (as can be distinguished in some of the examples of Fig. 2). For example, green cotton and blue ABS were discolored after 3.5 h of continuous treatment (equivalent to 1 year of daily short irradiation). However, other materials such as Orozco or woods appeared identical to the controls after 54 h of continuous treatment (equivalent dose of 16 years of daily short irradiation). All the visual color change time points are collected in Table 2.

Following the experimental procedure explained earlier, the color of the images taken from the samples before and after UV-C treatment was quantified using the image processing procedure with Matlab. Different behaviors were observed depending on the nature of the materials.

When analyzing the UV-C light effect over the polymers, it was observed that this kind of material tended to get a yellowish color after some exposure time, as occurred in variety of polymers in other works [18–21]. This behavior was observed not only visually but also quantitatively. For example, in the case of blue ABS, the color intensity varied a total of 2.47 points after 3.5 h of UV-C exposure (the equivalent to one year of treatment). As observed in Fig. 3a, the color change was progressive throughout the experiment, reaching a total variation of 37.99 units after 54 h (equivalent to 16 years). Moreover, the change suffered in the three-color channels individually was statistically significant (p-value <0.05). This increasing RGB variation was consistent with the physical changes since it was observed that the material darkened considerably while increasing the exposure time to UV-C light. In this case, the blue ABS progressively lost its bluish color, turning it into brownish. In this context, it was remarkable that the blue channel suffered the highest variation, 38 units out of 255, while the red one underwent almost no variation. The soft opaline polystyrene (Fig. 3b) and the PVC (Fig. 3c) followed the same pattern but showed a yellow color earlier after irradiation. For the soft opaline polystyrene, the color significantly varied shortly after 7 h (equivalent to two years of treatment) and continued varying progressively, reaching a total variation of 15 points.

The results agreed with the visual inspection since the color change was significant in this material from this point in time: instead of being white, it became yellowish after 7 h and acquired some yellow-brown color with the increasing radiation time. This tendency to take on a yellowish color was reflected again in the RGB graph, where the change began to be significant after 7 h (or two years Fig. 3b). Once again, while the red and green channels did not vary excessively, the blue color underwent a significant variation: 32 units out of 255, which turned out to be statistically significant (p-value <0.05).

Similarly, in PVC, the results were also significant and consistent with what was visually observed, as the variation in the intensity of the colors occurred exponentially as the brown color increased in the PVC surface. A progressive and slow variation was seen up to 14 h (equivalent to 4 years, Fig. 3c), while the variation became very significant at the equivalent time points of 8 years and 16 years of treatment (p-value < 0.01). As occurred with the previous polymers, the blue channel in the RGB graph also underwent a more pronounced variation than in the other two colors, this being 91 units out of 255. This experiment demonstrated that polymers turned yellowish over time under UV-C irradiation and that the blue channel in the RGB graphs decreased significantly. It was demonstrated that the decrease in the blue color is related to the appearance of the yellow color in the material. This agreed with other studies stating that most polymers undergo chemical reactions when exposed to UV light [22–27]. Consequently, as happened in this study, the polymers discolored since most polymers turned yellow/brown with an increasing radiation time, gradually losing their original color.

In the case of fabrics, the numerical results obtained with the green cotton were also very consistent with the visible results. For example, in this case, it was observed that color variation occurred progressively and from the first time point. In addition, it reached a total intensity variation of 63.15 units at the equivalent 16 years time-point (p-value <0.05), corresponding to a discolored green tissue. As observed in Fig. 3d, the color change was quite fast, with the three channels varying similarly and approaching the maximum value of 255. This was coherent with the effect on the visual color since the white color is made up of a 255 value of the three colors, and it was visually appreciated that the green color was fading over time. As previously published [28–30], fabrics generally undergo apparent changes after being treated with UV-C. In particular, cellulose cotton turns yellow when exposed to UV light. Through the results obtained with the fabrics of this study, it was found that the materials lost their color intensity, which is considered to turn more yellow or white (depending on the original color), in short, to fade.

The behavior of woods after the UV-C light treatment was different

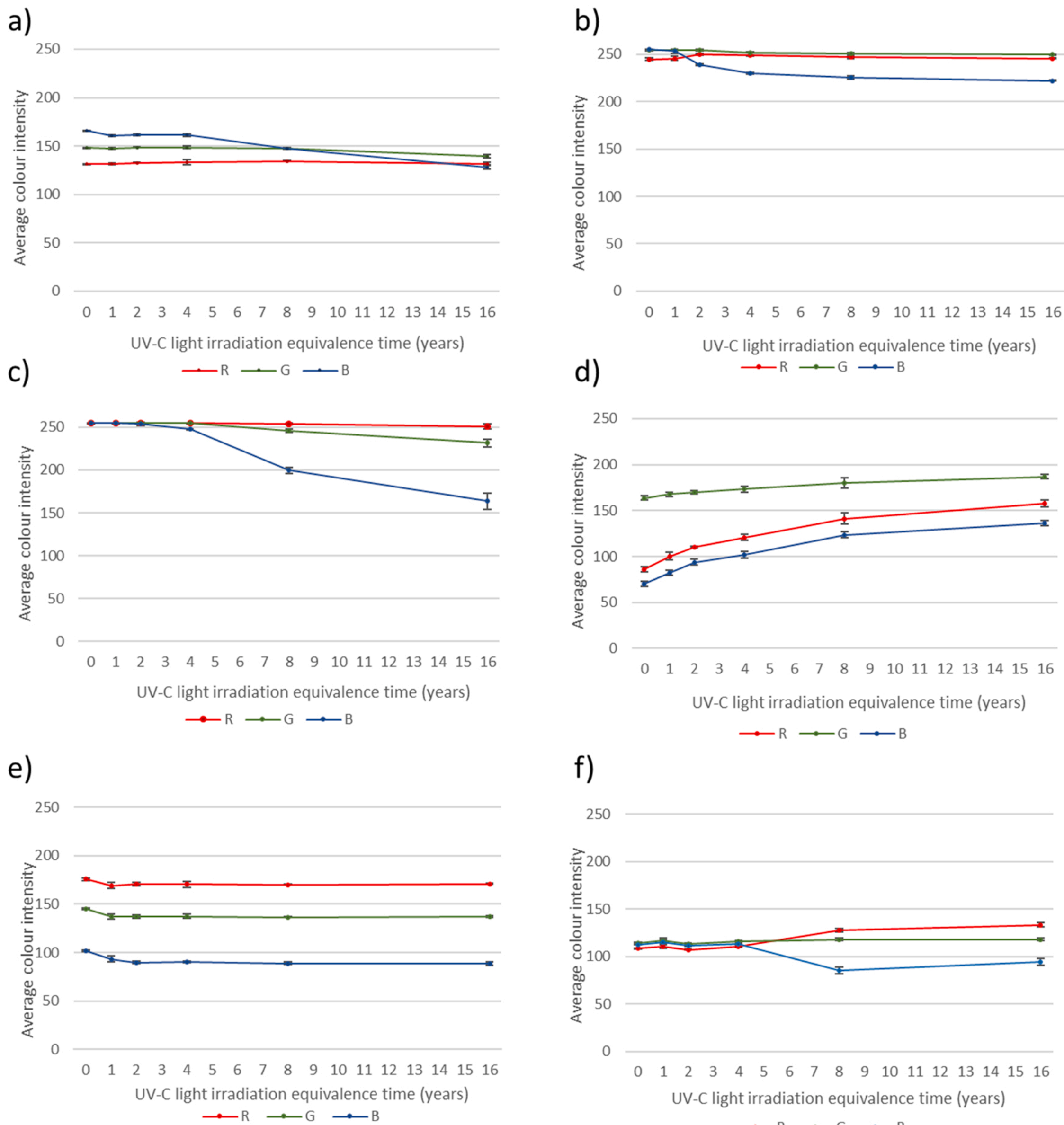

Fig. 3. Evolution of the average level of red (R), green (G), and blue (B) of a) blue ABS, b) soft opaline polystyrene, c) PVC, d) green cotton, e) MDF and f) stainless steel after several UV-C light exposure times (Sample size for the average, n = 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from the one observed with other materials. In uncoated MDF, no color change was observed visually, while numerically, a total intensity change of 10 units was detected. This numerical change was relatively high compared to the change measured in other materials, where a color change was visually detected. It is true that the intensity dropped very quickly in the three channels and remained almost constant during all time points. As found in the literature [31–33], uncoated wood tends to wear out and suffer photo-oxidative degradation when exposed to UV light.

As a consequence, the wood suffers effects such as discoloration and loss of shine, among others. Those analyses agree with what was obtained numerically in this study. Although due to the combination of brown tones in the wood used, no changes in color were visually observed, a slight reduction in the material's brightness was appreciated. It should also be noted that this loss of brightness was more noticeable when the wood was varnished.

Last, the effect of the UV-C light on metals was studied with the colorimetry test. Studies found in the literature generally showed that the color of metals (such as nickel or copper) is not affected by exposure to UV light unless the metal is oxidized [34]. In fact, some photo-corrosion was observed in aluminum or steel in some other works [12,35,36]. This was corroborated by this study, as in the stainless-steel case, no significant intensity variation was observed until the equivalent of 8 years of treatment were reached. At this time point, the surface of the material was oxidized (as explained in the literature [36]), a change in the color corresponding to an intensity variation of 19.50 units (p-value <0.05).

3.2. Tensile strength test

To compare the tensile mechanical properties between different textile samples, the maximum force supported by each one was evaluated. In this way, it was possible to determine whether UV-C band radiation affected the mechanical tensile property of the fabrics. Then, the difference between the maximum force of the control sample and the treated ones was calculated. Images of all the samples before and after

Table 3
Changes measured in the tensile strength of fabrics (n = 3).

Materials	Color change (visual)	Maximum force (mean ± standard deviation) [N]	Maximum force variation (mean ± standard deviation) [N]	p-value
Orange SILVERTEX	1 year	27.83 ± 2.45	↑ 0.59 ± 0.002	0.860
Astro from SMART FABRICS	1 year	44.94 ± 0.01	↑ 0.01 ± 0.001	0.084
Orozco from SMART FABRICS	No color change	44.93 ± 0.02	↑ 0.03 ± 0.004	0.338
Green acrylic	4 years	44.93 ± 0.01	↓ 0.01 ± 0.0001	0.807
White cotton	No color change	29.09 ± 1.63	↓ 1.57 ± 0.0012	0.504
Green cotton	1 year	33.63 ± 3.51	↓ 1.92 ± 2.45	0.083
Blue Polyester	1 year	19.85 ± 1.91	↑ 0.32 ± 0.57	0.891
Green Polyester	1 year	44.31 ± 0.56	↑ 0.3 ± 0.005	0.798
Red-pink Polyester	1 year	22.87 ± 1.75	↑ 0.81 ± 0.075	0.073
Orange Polyester	1 year	43.47 ± 0.94	↓ 1.48 ± 0.035	0.266

the tensile strength test can be found in the Supplementary material.

In this study, all the results obtained showed that the observed changes in the load supported by the material did not suffer any statistically significant change at the time point were the color of the sample changed, since all of them had a p-value greater than 0.05. This meant that, although in the colorimetry study, some changes were observed after the 1-year UV-C light exposure equivalent dose, those changes did not affect their mechanical characteristics. As an example, in Table 3, we show the variations in mechanical properties of the different materials at the time points when the color changed compared to non-irradiated controls.

However, it is true that when analyzing the last treatment points (equivalent to 16 years), a reduction of the maximum load supported was observed in all the materials, especially in the cottons and polyesters. This corroborated previous findings [28,37–40], where, for example, it was determined that applying the combination of UV radiation and heat on specific cellulose cotton samples reduced the breaking force of a material. In the case of the green cotton and all the polyesters, in the samples exposed for the equivalent time of 16 years, the breaking force decreased between a 10% and a 25%, being these changes in this time point statistically significant (p-values < 0.041). Therefore, in this study it was established that UV-C light did not have a detrimental effect on the tensile strength of fabrics at the same time point that the appearance of the samples was changed, but it was for the longest tested exposure times. This means that although a color change was observed, the mechanical properties of the materials still.

3.3. Surface microstructure analysis

SEM images were analyzed to determine if the color change was related to the surface microstructure of the material. When visually analyzing the results obtained with the SEM microscope (Fig. 4), apparent differences were observed in the structures of the materials such as PP, varnished MDF or stainless steel.

The numerical analysis of the size of the fibers or the roughness of the materials allowed us to quantify those differences (Table 4). In the case of fibrous materials (mainly fabrics), it was found that the size of the diameter of the fiber did not suffer any significant change for the different dies of the fabrics: the average diameter change was of dozens of nanometers during the different time points. That is to say, C-band UV light did not significantly affect the fiber diameter size of materials, although they had different colors which degraded with the exposure (p-values > 0.05).

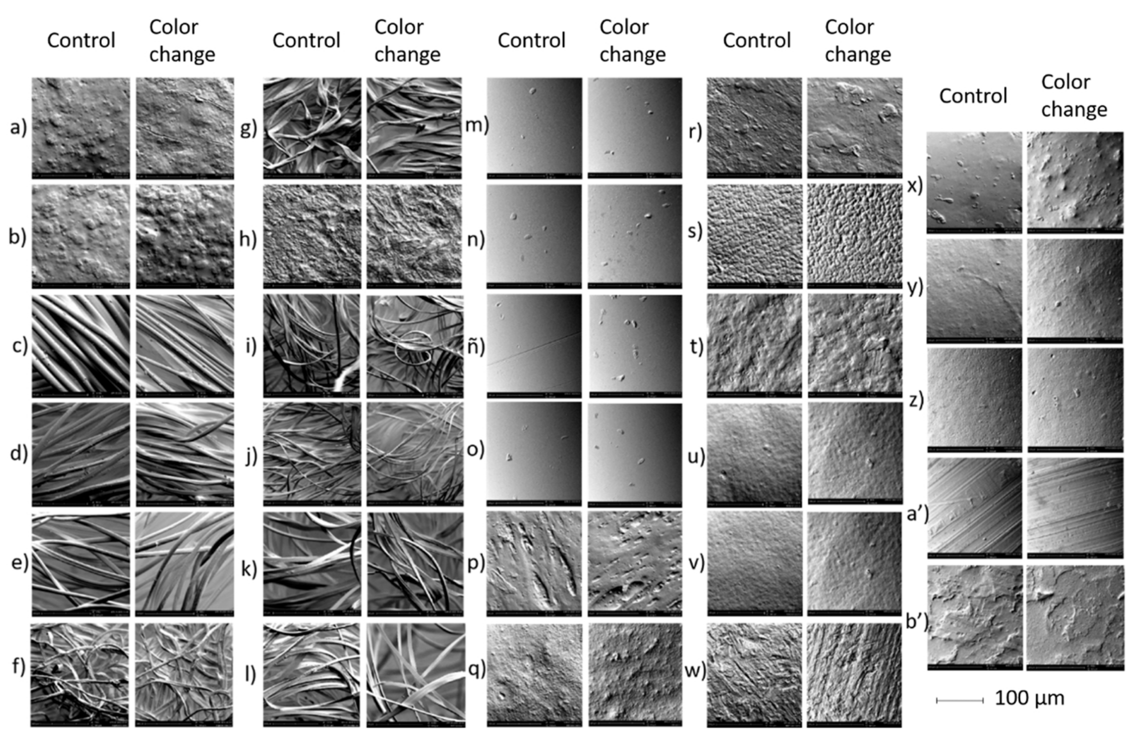

Fig. 4. Surface microstructure comparison between control and color change time point of a) SILVERTEX, b) orange SILVERTEX, c) Astro from SMART FABRICS, d) Orozco from SMART FABRICS, e) Green acrylic, f) White cotton, g) Green cotton, h) Leather, i) Blue PET, j) Green PET, k) Red-pink PET, l) Orange PET, m) Soft opaline polystyrene, n) 2 mm PC, ñ) 3 mm PC, o) 5 mm PC, p) Grey ABS, q) Blue ABS, r) PP, s) PTFE (Teflon), t) PVC, u) Grey melamine, v) Blue melamine, w) Uncoated MDF, x) varnished MDF, y) white painted MDF, z) Formica on agglomerated wood, a') Extruded aluminum, b') Stainless steel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Changes measured in the rugosity or fiber size of the different materials (n = 3).

Materials	Rugosity (%) or fiber size (μm)		Variation	p-value
	Before radiation	After radiation		
SILVERTEX	38.32%	46.53%	8.21	2.81×10^{-20}
Orange SILVERTEX	34.42%	42.82%	8.40	3.89×10^{-217}
Astro from SMART FABRICS	15,833 μm	13,637 μm	-2.20	0.305
Orozco from SMART FABRICS	14,071 μm	13,500 μm	-0.57	0.377
Green acrylic	21,964 μm	19,104 μm	-2.86	0.128
White cotton	15,101 μm	14,26 μm	-0.84	0.511
Green cotton	15,586 μm	16,425 μm	0.84	0.647
Leather	64.81%	70.73%	5.92	0.246
Blue Polyester	38.32%	46.53%	8.21	0.935
Green Polyester	34.42%	42.82%	8.40	0.818
Red-pink Polyester	15,833 μm	9637 μm	-6.20	0.391
Orange Polyester	6829 μm	7554 μm	0.73	0.168
Soft opaline polystyrene	No rugosity. The small particles observed are from the sputtered material (Pd)			
2 mm Polycarbonate	No rugosity. The small particles observed are from the sputtered material (Pd)			
3 mm Polycarbonate	No rugosity. The small particles observed are from the sputtered material (Pd)			
5 mm Polycarbonate	No rugosity. The small particles observed are from the sputtered material (Pd)			
Grey ABS	60.95%	50.09%	-10.87	5.04×10^{-05}
Blue ABS	60.76%	35.46%	-25.3	1.23×10^{-38}
PP (Polypropylene)	48.14%	42.95%	-5.20	2.50×10^{-45}
2 mm Teflon	6829 μm	7554 μm	0.73	7.13×10^{-05}
PVC	58.99%	46.23%	-12.76	7.27×10^{-23}
Grey melamine	54.02%	33.46%	-20.56	2.83×10^{-58}
Blue melamine	35.34%	32.53%	-2.81	2.26×10^{-35}
Uncoated MDF	71.68%	71.18%	-0.50	1.78×10^{-10}
Varnished MDF	47.32%	42.13%	-5.20	1.00×10^{-08}
White painted MDF	39.66%	31.91%	-7.75	3.34×10^{-191}
Formica on agglomerated wood	39.41%	31.85%	-7.57	2.65×10^{-30}
Extruded aluminum	35.84%	29.03%	-6.81	2.88×10^{-19}
Stainless steel	65.88%	44.35%	-21.53	5.22×10^{-11}

In contrast, in the case of rough materials, the roughness of the surfaces changed significantly. Woods irradiated with UV-C light showed a reduced roughness, providing a polishing effect to the surfaces. Although not all of the studies in the literature evaluated surface degradation by measuring microstructures with SEM imaging, some publications state that wood undergoes surface degradation when exposed to UV light [13]. In this case, the results obtained in this test showed that wood suffers a highly significant reduction in roughness (p-values $< 1 \times 10^{-8}$), corroborating what previous studies had published.

A similar effect was also observed in polymers. Previous studies demonstrated that their surface degrades with UV light, becoming flattened (losing roughness) [41–44]. Our study corroborated this effect, as a highly significant surface degradation (p-values $< 7 \times 10^{-5}$) was observed in the polymers analyzed. All the polymers suffered a rough reduction of at least five points between one treatment and the next. In this case, the reduction of the roughness could be related to the color change suffered by these materials, as they tended to get yellowish with the treatment and this could be linked with the "polishing" of the surface.

4. Conclusions

After evaluating the color, tensile strength, and surface of the different material families, the main conclusion of this study is that all materials were altered when irradiated with C-band UV light, although this alteration was variable. On the one hand, both colored fabrics and plastics were found to be discolored by UV-C light. However, woods and metals did not suffer from this effect. As for the tensile strength of the fabrics, it was not modified at those time-points. In other words, although the materials changed the color, the changes suffered in the capacity to withstand a maximum load of 45 N were not statistically significant. This means that the first time the color change was detected in the sample, the maximum load supported by the material was almost the same as in control. It can be concluded that the material did not change its loading property although the color had changed. Finally, the results obtained with the surface analysis test demonstrated that when the color change was detected, most materials showed a significant change in their surface microstructure. This change was especially significant in non-fibrous materials. Although the changes in the surface microstructure were indeed noticeable, they did not impact the mechanical behavior of the samples. Only color change had a noticeable impact. Therefore, it could be concluded that treating different materials with a UV-C light lamp would only affect their appearance, but not their structure, not risking their functionalities.

CRediT authorship contribution statement

Oihane Mitxelena-Iribarren: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing. **Beñat Mondragon**: Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing. **Eva Pérez-Lorenzo**: Investigation; Resources; Visualization; Writing – review & editing. **Cristian Smerdou**: Investigation; Project administration; Writing – review & editing. **Francisco Guillen-Grima**: Conceptualization; Investigation; Project administration; Resources; Writing – review & editing. **J. Enrique Sierra-Garcia**: Conceptualization; Funding acquisition; Project administration; Resources; Writing – review & editing. **Fernando Rodriguez-Merino**: Conceptualization; Funding acquisition; Project administration; Resources; Writing – review & editing. **Sergio Arana**: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

This research was partially funded by the Spanish Ministry of Science and Innovation under the contract COI-20201089.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.mtcomm.2022.103690.

References

[1] W.Y. Leung, V. Murray, The influence of DNA methylation on the sequence specificity of UVB- and UVC-induced DNA damage, J. Photochem. Photobiol. B Biol. 221 (2021), 112225, https://doi.org/10.1016/J.JPHOTOBIOL.2021.112225.
[2] B. Casini, B. Tuvo, M.L. Cristina, A.M. Spagnolo, M. Totaro, A. Baggiani, G.P. Privitera, Casini_2019_Evaluation of an Ultraviolet C (UVC) Light-Emitting Device for Disinfection of High Touch Surfaces in Hospital Critical Areas_130._HA pdf.pdf, (2019).
[3] D. Menzies, J. Popa, J.A. Hanley, T. Rand, D.K. Milton, Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: Double-blind multiple crossover trial, Lancet 362 (2003) 1785–1791, https://doi.org/10.1016/S0140-6736(03)14897-0.
[4] F. Memarzadeh, R.N. Olmsted, J.M. Bartley, Applications of ultraviolet germicidal irradiation disinfection in health care facilities: effective adjunct, but not stand-alone technology, Am. J. Infect. Control 38 (2010) S13–S24, https://doi.org/10.1016/J.AJIC.2010.04.208.
[5] I.H. Hamzavi, A.B. Lyons, I. Kohli, S. Narla, A. Parks-Miller, J.M. Gelfand, H. W. Lim, D.M. Ozog, Ultraviolet germicidal irradiation: possible method for respirator disinfection to facilitate reuse during the COVID-19 pandemic, J. Am. Acad. Dermatol. 82 (2020) 1511–1512, https://doi.org/10.1016/j.jaad.2020.03.085.
[6] D.M. Ozog, J.Z. Sexton, S. Narla, C.D. Pretto-Kernahan, C. Mirabelli, H.W. Lim, I. H. Hamzavi, R.J. Tibbetts, Q.S. Mi, The effect of ultraviolet C radiation against different N95 respirators inoculated with SARS-CoV-2, Int. J. Infect. Dis. 100 (2020) 224–229, https://doi.org/10.1016/j.ijid.2020.08.077.
[7] D. Reid, K. Ternes, L. Winowiecki, C. Yonke, B. Riege, F. Fregoli, D. Passey, M. Stibich, R.N. Olmsted, Germicidal irradiation of portable medical equipment: Mitigating microbes and improving the margin of safety using a novel, point of care, germicidal disinfection pod, Am. J. Infect. Control 48 (2020) 103–105, https://doi.org/10.1016/j.ajic.2019.07.021.
[8] Desincash, Desincash, desinfección de Billetes y Monedas - Desinfección de Billetes y Monedas, (2020).
[9] W. EJ, W. SL, RNA under attack: cellular handling of RNA damage, Crit. Rev. Biochem. Mol. Biol. 44 (2009) 34–49, https://doi.org/10.1080/10409230802594043.
[10] EPA, Efectos de la radiación UV en la salud | EPA en español | US EPA, (2015).
[11] UV Degradation Effects in Materials – An Elementary Overview " UV Solutions, (n. d.). ⟨https://uvsolutionsmag.com/articles/2019/uv-degradation-effects-in-materials-an-elementary-overview/⟩ (accessed June 10, 2021).
[12] T.D. Burleigh, C. Ruhe, J. Forsyth, Photo-corrosion of different metals during long-term exposure to ultraviolet light, Corrosion 59 (2003) 774–779, https://doi.org/10.5006/1.3277606.
[13] D.N.S. Hon, S.T. Chang, Surface degradation of wood by ultraviolet light, J. Polym. Sci. A1. 22 (1984) 2227–2241, https://doi.org/10.1002/pol.1984.170220923.
[14] M. Heßling, K. Hönes, P. Vatter, C. Lingenfelder, Ultraviolet irradiation doses for coronavirus inactivation – review and analysis of coronavirus photoinactivation studies, Doc08, GMS Hyg. Infect. Control 15 (2020), https://doi.org/10.3205/DGKH000343.
[15] O. Mitxelena-Iribarren, J. Zabalo, S. Arana, M. Mujika, Improved microfluidic platform for simultaneous multiple drug screening towards personalized treatment, Biosens. Bioelectron. 123 (2019), https://doi.org/10.1016/j.bios.2018.09.001.
[16] A. Al-Naji, A.B. Fakhri, S.K. Gharghan, J. Chahl, Soil color analysis based on a RGB camera and an artificial neural network towards smart irrigation: a pilot study, Heliyon 7 (2021), e06078, https://doi.org/10.1016/J.HELIYON.2021.E06078.
[17] R. Xiao, P. Polaczyk, B. Huang, Measuring moisture damage of asphalt mixtures: the development of a new modified boiling test based on color image processing, Measurement 190 (2022), 110699, https://doi.org/10.1016/J.MEASUREMENT.2022.110699.
[18] R.L. Clough, G.M. Malone, K.T. Gillen, J.S. Wallace, M.B. Sinclair, Discoloration and subsequent recovery of optical polymers exposed to ionizing radiation, Polym. Degrad. Stab. 49 (1995) 305–313.
[19] M. Tworek, Ł. Skowroński, E. Makarewicz, J. Kowalik, Properties of poly (vinyl chloride) membranes containing cadmium pigments, irradiated with UV radiation, Sci, 2021, Reports 111 (11) (2021) 1–11, https://doi.org/10.1038/s41598-021-96713-w.
[20] B.W. Hutzler, L.D.B. MacHado, A.B. Lugão, A.L.C.H. Villavicencio, Properties of irradiated PVC plasticized with non-endocrine disruptor, Radiat. Phys. Chem. 57 (2000) 381–384, https://doi.org/10.1016/S0969-806X(99)00472-7.
[21] A. Kömmling, E. Chatzigiannakis, J. Beckmann, V. Wachtendorf, K. Von Der Ehe, U. Braun, M. Jaunich, U. Schade, D. Wolff, Discoloration effects of high-dose γ -irradiation and long-term thermal aging of (U)HMW-PE, Int. J. Polym. Sci. (2017) (2017), https://doi.org/10.1155/2017/1362491.
[22] B.P. Bustamante, B.P. Bustamante, La degradación del concreto armado, Rev. Univ. EAFIT. 30 (2012) 83–98. ⟨https://publicaciones.eafit.edu.co/index.php/revista-universidad-eafit/article/view/1417⟩ (accessed June 10, 2021).
[23] J. Kowalonek, Surface studies of UV-irradiated poly(vinyl chloride)/poly(methyl methacrylate) blends, Polym. Degrad. Stab. 133 (2016) 367–377, https://doi.org/10.1016/j.polymdegradstab.2016.09.016.
[24] D. Irving, D.A. Lamprou, M. Maclean, S.J. MacGregor, J.G. Anderson, M.H. Grant, A comparison study of the degradative effects and safety implications of UVC and 405 nm germicidal light sources for endoscope storage, Polym. Degrad. Stab. 133 (2016) 249–254, https://doi.org/10.1016/j.polymdegradstab.2016.09.006.
[25] I.A. Joneidi, A.A. Shayegani, H. Mohseni, Influence of ultra violet radiation on the surface and leakage current of silicone rubber insulator, Int. J. Phys. Sci. 6 (2011) 5109–5120, https://doi.org/10.5897/IJPS11.681.
[26] Honeywell International, Effect of UVC Exposure on Non-Metallic Materials in HVAC Systems, 2000.
[27] A. Nekeb, A. Haddad, N. Harid, H. Griffiths, R. Waters, Effects of UV irradiation on textured silicone rubber material, Proc. Univ. Power Eng. Conf. (2012). ⟨https://doi.org/10.1109/UPEC.2012.6398436⟩.
[28] M. Yatagai, S.H. Zeronian, Effect of ultraviolet light and heat on the properties of cotton cellulose, Cellulose 1 (1994) 205–214, https://doi.org/10.1007/BF00813508.
[29] M. Khazova, J.B. O'Hagan, K.J.L. Grainger, Radiation and chemical degradation of UVR protection characteristics of fabrics, Radiat. Prot. Dosim. 123 (2007) 369–377, https://doi.org/10.1093/rpd/ncl151.
[30] K. O'Hearn, S. Gertsman, M. Sampson, R. Webster, A. Tsampalieros, R. Ng, J. Gibson, A.T. Lobos, N. Acharya, A. Agarwal, S. Boggs, G. Chamberlain, E. Staykov, L. Sikora, J.D. McNally, Decontaminating N95 and SN95 masks with ultraviolet germicidal irradiation does not impair mask efficacy and safety, J. Hosp. Infect. 106 (2020) 163–175, https://doi.org/10.1016/j.jhin.2020.07.014.
[31] L.M. Shao, H.W. Guo, L. Li, Y.L. Liu, Y. Liu, Influence of different wave-lengths artificial light on surface discoloration of dyed veneer, Adv. Mater. Res 189–193 (2011) 711–715, https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMR.189-193.711.
[32] Y. Liu, L. Shao, J. Gao, H. Guo, Y. Chen, Q. Cheng, B.K. Via, Surface photo-discoloration and degradation of dyed wood veneer exposed to different wavelengths of artificial light, Appl. Surf. Sci. 331 (2015) 353–361, https://doi.org/10.1016/J.APSUSC.2015.01.091.
[33] Y. Kataoka, M. Kiguchi, R.S. Williams, P.D. Evans, Violet light causes photodegradation of wood beyond the zone affected by ultraviolet radiation, 23–27, Holzforschung Vol. 61 (61) (2007) 23–27, https://doi.org/10.1515/HF.2007.005.
[34] S. Deng, H. Lu, D.Y. Li, Influence of UV light irradiation on the corrosion behavior of electrodeposited Ni and Cu nanocrystalline foils, 2020, Sci. Rep. 101 (10) (2020) 1–16, https://doi.org/10.1038/s41598-020-59420-6.
[35] H.R. Riazi, I. Danaee, M. Peykari, Influence of ultraviolet light irradiation on the corrosion behavior of carbon steel AISI 1015, 2013, Met. Mater. Int. 192 (19) (2013) 217–224, https://doi.org/10.1007/S12540-013-2014-1.
[36] L. Song, X. Ma, Z. Chen, B. Hou, The role of UV illumination on the initial atmospheric corrosion of 09CuPCrNi weathering steel in the presence of NaCl particles, Corros. Sci. 87 (2014) 427–437, https://doi.org/10.1016/J.CORSCI.2014.07.013.
[37] B. Aksakal, K. Koç, Ö. Yargi, K. Tsobkallo, Effect of UV-light on the uniaxial tensile properties and structure of uncoated and TiO2 coated Bombyx mori silk fibers, Spectrochim. Acta - Part A Mol. Biomol. Spectrosc. 152 (2016) 658–665, https://doi.org/10.1016/j.saa.2015.01.131.
[38] W. Al Azzawi, J.A. Epaarachchi, J. Leng, Investigation of ultraviolet radiation effects on thermomechanical properties and shape memory behaviour of styrene-based shape memory polymers and its composite, Compos. Sci. Technol. 165 (2018) 266–273, https://doi.org/10.1016/j.compscitech.2018.07.001.
[39] G.R. Cobb, R.P. O'Hara, R.A. Kemnitz, V.P. Sabelkin, B.M. Doane, Quantifying the effects of ultraviolet type C radiation on the mechanical and electrical properties of carbon nanotube sheet for space-based applications, Mater. Today Commun. 18 (2019) 7–13, https://doi.org/10.1016/j.mtcomm.2018.10.016.
[40] M.M. Shokrieh, A. Bayat, Effects of ultraviolet radiation on mechanical properties of glass/polyester composites, J. Compos. Mater. 41 (2007), https://doi.org/10.1177/0021998307075441.
[41] J. Kowalonek, I. Vuković-Kwiatkowska, D. Moszyński, H. Kaczmarek, Surface properties of poly(lactic acid)/polyacrylate semi-interpenetrating networks – Effect of UVC radiation, Polym. Degrad. Stab. 131 (2016) 71–81, https://doi.org/10.1016/j.polymdegradstab.2016.07.008.
[42] W.G. Lindsley, S.B. Martin, R.E. Thewlis, K. Sarkisian, J.O. Nwoko, K.R. Mead, J. D. Noti, Effects of ultraviolet germicidal irradiation (UVGI) on N95 respirator filtration performance and structural integrity, J. Occup. Environ. Hyg. 12 (2015) 509–517, https://doi.org/10.1080/15459624.2015.1018518.
[43] C. Qu, J. Hu, X. Liu, Z. Li, Y. Ding, Morphology and mechanical properties of polyimide films: The effects of UV irradiation on microscale surface, in: Materials, 10, Basel, 2017, https://doi.org/10.3390/ma10111329.
[44] T. Lu, E. Solis-Ramos, Y. Yi, M. Kumosa, UV degradation model for polymers and polymer matrix composites, Polym. Degrad. Stab. 154 (2018) 203–210, https://doi.org/10.1016/j.polymdegradstab.2018.06.004.