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UV-Accelerated Aging of PLA and PP-Based Biocomposites: A Spectral and Colorimetric Study

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Abstract

In this work, biocomposites of polylactic acid (PLA) and polypropylene (PP) with micronized cellulose (MC) were produced by mold injection and subjected to accelerated aging with ultraviolet (UV) radiation. The tests took place over 10 weeks, during which the produced specimens were exposed to a total of 1050 h of ultraviolet light. During the UV aging test, images were captured, and spectral reflectance and colorimetric measurements were carried out on the specimens exposed to UV and on specimens of the same materials kept in the dark (originals). As expected, only residual color differences were observed in the original specimens with values of ΔE^*_{ab} always below 0.5. On the other hand, spectral reflectance and colorimetric changes were noticed over time in the specimens subjected to UV radiation. In particular, the values of ΔE^*_{ab} increased over time and were found to be higher for PLA with MC compared to PP with MC. Values of ΔE^*_{ab} = 4.7, 9.0, and 10.4 were obtained for weeks 1, 5, and 10, respectively, for the specimens of PLA with MC, whereas ΔE^*_{ab} = 4.5, 6.8, and 7.3 were obtained for weeks 1, 5, and 10, respectively, for the specimens of PP with MC. Therefore, it was found that the specimens of PLA with MC showed greater color fading compared to the specimens of PP with MC when subjected to UV exposure. In addition, it was also found in this work that besides the color differences noted in the tested specimens, those made of PP with MC also showed signs of surface damage.

Keywords: UV radiation; accelerated aging; biocomposites; spectral reflectance and color; CIE 1976 L*a*b*

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1. Introduction

Biocomposites are a category of materials that combine two or more elements, with at least one of them being natural, to form a new material [1]. Biocomposites are usually made of one matrix element and one reinforcement element, which work together to provide a new material with better properties than either individual element alone [1]. Over the years, they have become very popular and, nowadays, they are widely used in many areas and applications, such as the automotive sector, aerospace, medical science, music, furniture, electronics, building and construction, agriculture, cutlery, packaging, and others [1–8].

There are various possible combinations of polymers that can be explored as matrix elements [1–4], and from the available options, polylactic acid (PLA) and polypropylene (PP) are two well-known thermoplastics commonly used and found in many everyday

products [9–13]. As for the reinforcement element, many options are also available [2,4,12], and in particular, plant fibers (cellulose) have recently seen increasing demand due to their green and eco-friendly nature, abundance, and cost-effectiveness [2,4].

Biocomposites, as well as their individual components, are affected by the elements of nature, especially those designed to be used outdoors. In addition to the effects of erosion, mechanical forces, and exposure to humidity and water, sunlight affects biocomposites and many other materials to varying extents [14–16]. When sunlight reaches the surface of the Earth, it has already been absorbed and filtered by the atmosphere, ozone layer, clouds, and other elements that may be present in the air, allowing only a fraction of the total electromagnetic radiation emitted by the sun to pass through [17]. Of the entire solar radiation that reaches the Earth, the portion of it with the strongest irradiance corresponds to visible light, with wavelengths ranging from 400 nm to 760 nm, which comprises the radiation spectrum sensitive to our eyes. Infrared radiation (IR), with longer wavelengths and lower energy, has a wide range, from 760 nm to 1 mm, but it has a much lower irradiance compared to visible light. The last portion of solar radiation that reaches the surface of the planet is ultraviolet (UV) light, which has shorter wavelengths below 400 nm and is the most energetic of the three.

UV can be divided into three different classes: UV-A, from 315 nm to 400 nm; UV-B, from 280 nm to 315 nm; and UV-C, from 100 nm to 280 nm. It is believed that UV-C, the most dangerous of the three classes, is absorbed entirely or almost entirely by the ozone layer and does not reach the surface of the planet except for places located at high altitude [17]. However, the work of Herndon et al. [18] demonstrated that all wavelengths ranging from 200 nm to 400 nm reach the Earth's surface, which is contrary to the widespread perception mentioned earlier. This is clearly a matter of great concern and high importance that should be thoroughly monitored now and in the coming years. As for the remaining two classes, UV-B and UV-A, the first is more dangerous than the second, and it is believed that they are both present on Earth in proportions of around 5% and 95% of the total UV radiation (excluding UV-C) [17]. Although updates to these figures might occur any time, it is clear that UV-A is by far the dominant UV class corresponding to the majority of the ultraviolet light present on Earth.

Another relevant remark about ultraviolet radiation is that it has both benefits and hazards for us all. For instance, in terms of health, it can stimulate the synthesis of vitamin D, which is beneficial for humans, but it can also cause direct damage to deoxyribonucleic acid (DNA) [17]. In materials and medical sciences, it can be used for the curing of coatings [19] or for the disinfection of equipment and reusable utensils [16,20], which is beneficial in a high number of applications, but it can also damage the structure of materials [14–16]. In this latter case, it should be noted that biocomposites and polymers in general are usually very much affected by UV through the process of photodegradation [21], as indicated and explored in several works that can be found in the literature [2,14–16,22–40].

In light of everything mentioned and the importance of studying how ultraviolet light affects everyday materials/products, the current work will also analyze how biocomposites deteriorate when exposed to UV radiation with a particular focus on three key points: (1) the specimens to be tested will be PLA and PP-based biocomposites, which are widely used in a variety of applications; (2) the experiments to be carried out will use the UV-A radiation class, which accounts for the majority of the ultraviolet light that exists on Earth; and (3) the analysis to be conducted will be based in the changes in spectral reflectance and colorimetric characteristics during the UV radiation tests.

Finally, the results obtained in this work will be thoroughly discussed and compared with the results and findings from other works, providing valuable information about the

color changes as well as the overall appearance of two commonly used materials when exposed to accelerated aging.

2. Materials and Methods

2.1. Materials—Biocomposite Samples

Two different types of biocomposite specimens were produced by the industry through mold injection to be tested with our methodologies. For the first, we chose polylactic acid (MFI = 80 g/10 min at 210 °C/2.16 kg) as the matrix element and micronized cellulose as the reinforcement element, which was obtained by milling bleached eucalyptus kraft pulp (BEKP) on specialized equipment kindly provided by the Navigator Company (Aveiro, Portugal). For the second type, we chose polypropylene (MFI = 40 g/10 min at 230 °C/2.16 kg) as the matrix element, and for the reinforcement element, we used the same micronized cellulose plus a coupling agent of maleic anhydride modified polypropylene (MFI = 170 g/10 min at 190 °C/2.16 kg) and a processing additive of a blend of complex, modified fatty acid esters. For both biocomposites, the content of micronized cellulose was maintained at 30 wt.%.

To simplify the reading of the article, from here on, the two produced biocomposites will be referred to as PLA + MC and PP + MC.

2.2. Methods—Biocomposite Manufacturing

The preparation of the biocomposites was carried out using a co-rotation extruder ZSE 35 iMAXX–48 D from Leistritz (Nuremberg, Germany) with a double interpenetrating spindle (L/D = 48, spindle diameter 35 mm), three feeders, and an underwater granulator. The temperatures of the different extrusion zones ranged from 160 °C to 180 °C for the PLA + MC and from 160 °C to 175 °C for the PP + MC. The screw speed was maintained at 135 rpm.

Their injection was performed with a Victory 80T machine from ENGEL (Schwertberg, Austria) to produce rectangular specimens (dimensions: 80 mm length, 10 mm width, 4 mm thickness) and dog-bone specimens (dimensions: 170 mm total length, 30 mm length of grip section, 20 mm width of grip section, 10 mm width of gauge section, 4 mm thickness), using pellets dried before injection at 80 °C for 6 h in the case of the PLA + MC and at 115 °C for 3 h in the case of the PP + MC. The injection temperatures ranged from 170 °C to 210 °C for the PLA + MC and from 160 °C to 190 °C for the PP + MC, while the mold temperature was kept at room temperature.

Four different sets of specimens were taken into consideration in the experimental assays. Two of the four sets consisted of PLA + MC, while the other two consisted of PP + MC. One of each was kept in the dark for the entire duration of the assays (original specimens), and they were only removed from the dark when measurements needed to be taken. The two remaining sets, one made of PLA + MC and the other of PP + MC, were placed inside the UV chamber to undergo accelerated aging.

2.3. Methods—UV Aging Chamber

The aging chamber used in our experiments, model IV 43 DF from CITEL (Paris, France), allowed to illuminate the specimens with UV light, subjecting them to accelerated aging for comparison with the original specimens kept in the dark. The experiments that were conducted were based in the recommendations of ISO 4892-1 [41] and ISO 4892-3 [42]. A diagram of the chamber used in the experiments is shown on the right side of Figure 1, displaying its main components, namely, six UV-A light lamps of 15 Watts each, T8 15W BL UV-A G13 Luxtek from Fillday (Vila Nova de Famalicão, Portugal), which illuminated the specimens from above, and the samples stand, made of glass, on which the specimens were

conveniently positioned inside the chamber. Figure 1 also shows the approach followed to achieve uniform irradiation on all samples inside the chamber throughout the test. Specifically, the samples were systematically moved clockwise to occupy each location on the samples stand. Additionally, the samples were flipped in the stand to ensure direct irradiation from both the front and back.

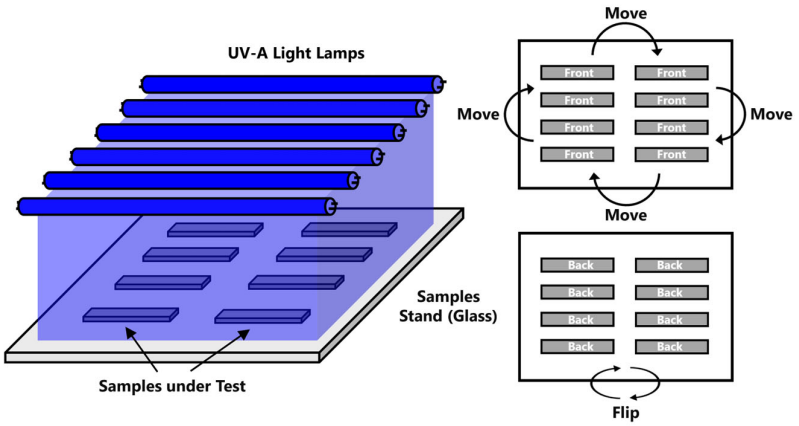


Figure 1. Diagram of the UV aging chamber (**left side**) and approach followed for positioning and flipping of the samples (**right side**).

The UV aging chamber may have also been used to illuminate the samples from both the top and bottom sides. However, only the top side was considered in our experiments for three main reasons: (1) to ensure that the samples are primarily illuminated with direct light (they also receive light from below through reflections that reach the samples from the glass but at a lower percentage); (2) to ensure that the samples are exposed to an adequate amount of UV-A radiation inside the chamber (the total wattage of the UV lamps was $6 \times 15 = 90$ Watts, resulting in a UV-A irradiance of approximately 45 W/m^2); (3) to maintain the temperature inside the chamber at acceptable levels without exposing the specimens to excessive heat.

In relation to the third point, additional information must be provided regarding the operational procedure adopted in the experiment. Specifically, the specimens were exposed to UV-A radiation for a period of ten weeks (total exposure of 1050 h) considering alternating cycles of light and dark. Four light cycles of 4 h, 4 h, 4 h, and 3 h were planned per day, which were alternated with four dark cycles of 1.5 h, 1.5 h, 2 h, and 4 h. The need for a 4 h dark cycle for the proper measurement of all the samples required the other three dark cycles to be adjusted and shortened. During a light cycle, the temperature inside the chamber was 43 ± 2 °C. Conversely, during a dark cycle, the temperature inside the chamber was 24 ± 1 °C. Neither ventilation nor added humidity were considered in the experiments: only the light emitted by the UV-A lamps and the natural heat they generated.

2.4. Methods—Optical System

Images of the PLA + MC and PP + MC specimens were acquired using a customized optical system with multi-chromatic LED lighting. A diagram of the used optical system is shown in Figure 2, displaying its main components: namely, an image detector Alvium 1800 U-2040m from Allied Vision (Stadtroda, Germany), a controlled illumination source composed of an LED lamp Parathom Pro from OSRAM (Augsburg, Germany), and a motorized wheel filter USFW-100 from Newport (CA, USA). This system captures a sequence of images by illuminating the sample with red (630 nm), green (530 nm), blue (460 nm) monochromatic light, and white (400–780 nm) polychromatic light.

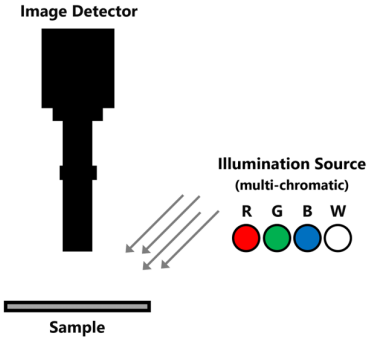


Figure 2. Diagram of the optical system used to acquire images of the samples.

The specimens kept in the dark and those exposed to UV radiation were inspected with this system for comparison purposes. The various images obtained in the process are presented and can be consulted in Section 3 of this article.

2.5. Methods—Spectrophotometer

Throughout the entire duration of the UV accelerated aging test, spectral reflectance and colorimetric measurements in the color space CIE 1976 L*a*b*, ISO/CIE 11664-4 [43] were conducted on the tested specimens. These measurements were used to track any potential changes on the specimens from the beginning of the test to its conclusion. L* denotes lightness, whereas a* and b* denote color coordinates (a* is related with the opponent colors red–green; b* is related with the opponent colors blue-yellow). For this part of the experiment, a spectrophotometer, model Chroma Sensor CS-5, and the corresponding white calibration standard from Datacolor International (Zurich, Switzerland) were used. A simplified diagram of the equipment is shown in Figure 3, displaying its main components. Namely, an illumination source emits light to an integrating sphere that will then pass through two openings: one where the sample is placed and the other which is connected to an array of detectors. All the light collected by the sphere is ultimately decomposed into several spectral bands (400 to 780 nm with a 10 nm step), allowing the measurement of the spectral reflectance distribution of the samples, as well as the corresponding colorimetric data, expressed in the CIE 1976 L*a*b* color space, using the standard illuminant D65 [44] for a standard observer of 2°.

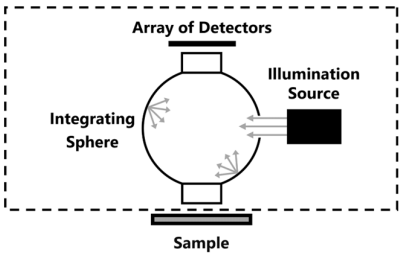


Figure 3. Diagram of the spectrophotometer used for spectral reflectance and colorimetric measurements on the samples.

The principal results obtained with this equipment for all specimens of PLA + MC and PP + MC are presented in the following section.

3. Results and Discussion

Images of the specimens of PLA + MC and PP + MC that were stored in the dark (original specimens), as well as those exposed to UV radiation, were captured using the optical system described in Section 2.3. Figures 4–15 show the images obtained throughout the entire test period (10 weeks). The left side of the figures shows the images of the individual

components of the samples (R—red, G—green, B—blue, and W—white), while the right side shows the corresponding full color images (RGB), resulting from the combination of the different individual components.

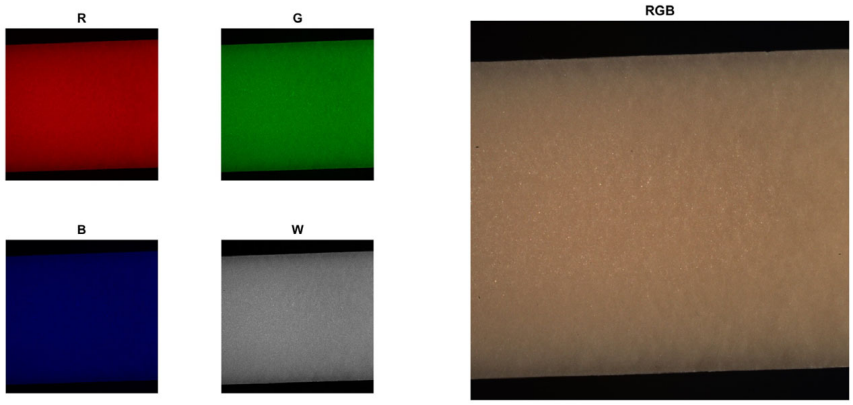


Figure 4. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PLA + MC (original specimen) at the beginning of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

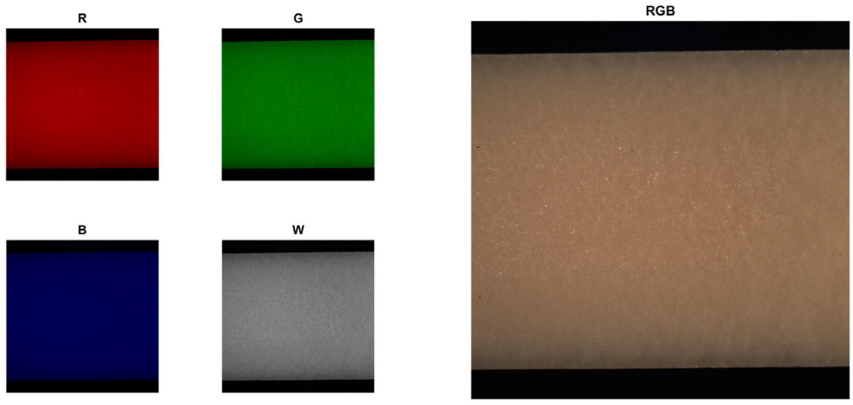


Figure 5. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PLA + MC (original specimen) at week 5 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

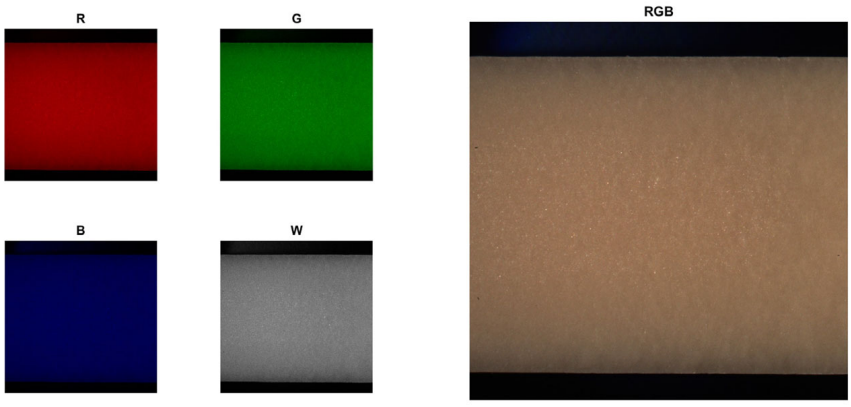


Figure 6. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PLA + MC (original specimen) at week 10 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

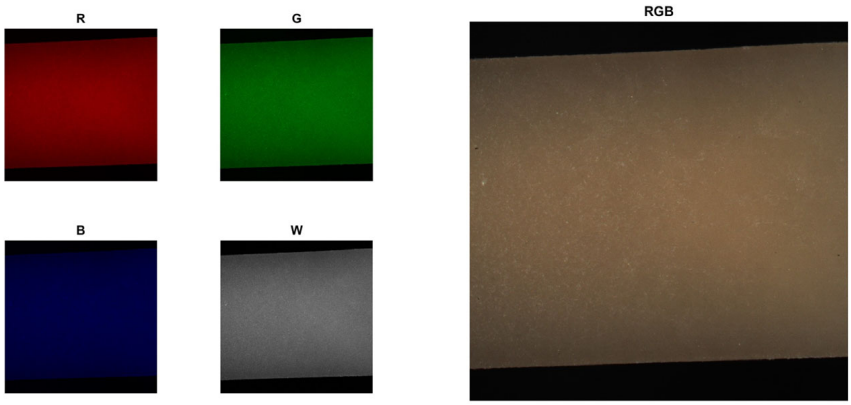


Figure 7. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PP + MC (original specimen) at the beginning of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

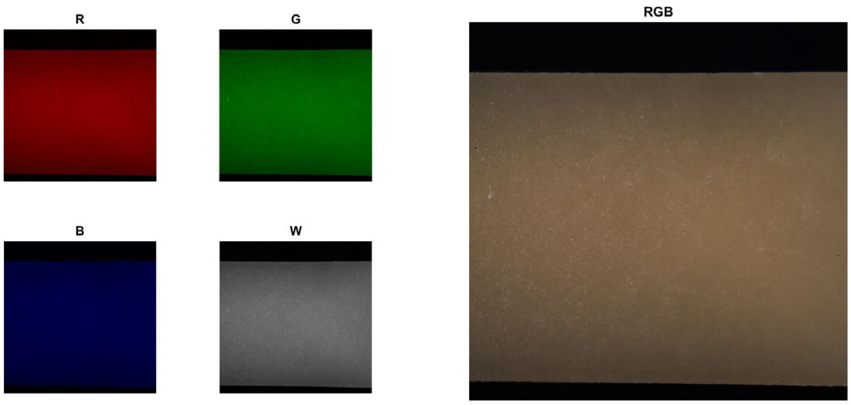


Figure 8. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PP + MC (original specimen) at week 5 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

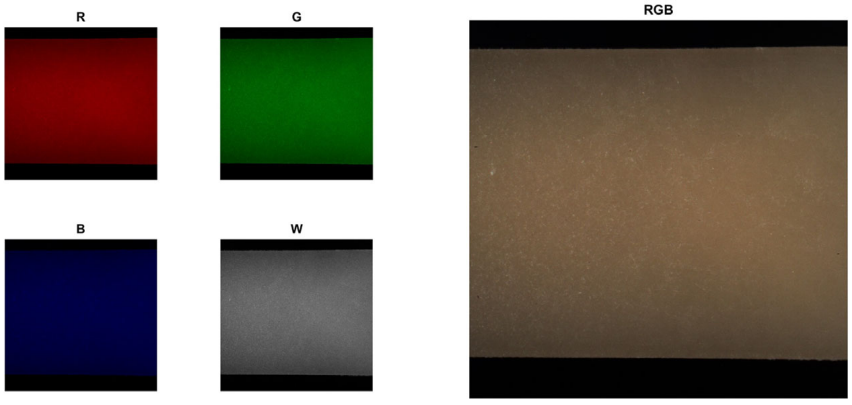


Figure 9. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PP + MC (original specimen) at week 10 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

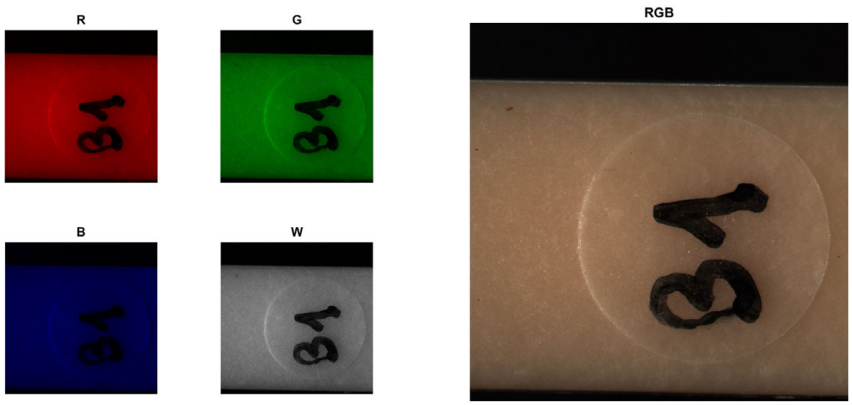


Figure 10. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PLA + MC (specimen exposed to UV radiation) at the beginning of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

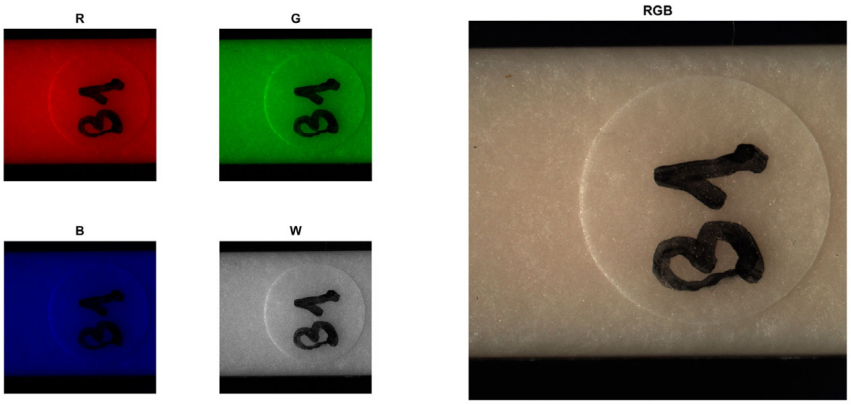


Figure 11. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PLA + MC (specimen exposed to UV radiation) at week 5 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

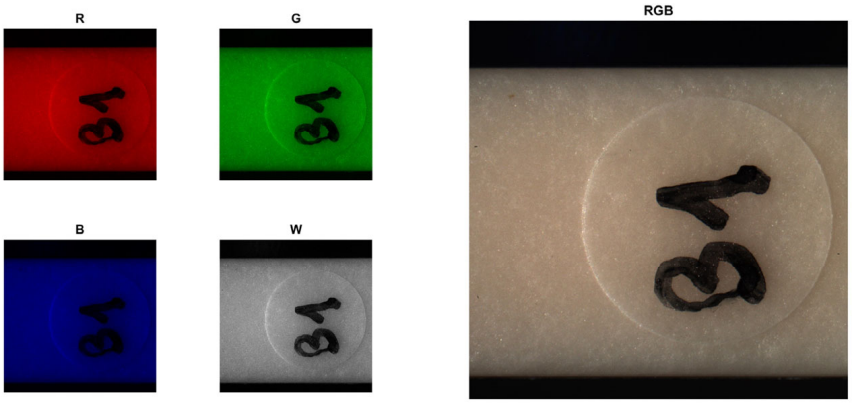


Figure 12. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PLA + MC (specimen exposed to UV radiation) at week 10 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

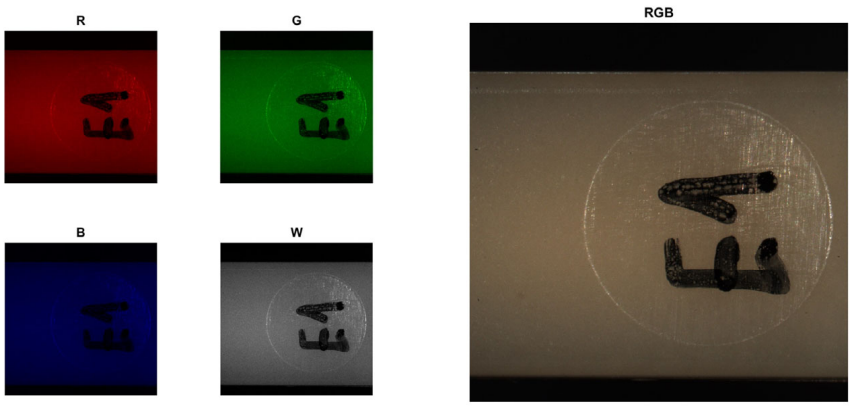


Figure 13. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PP + MC (specimen exposed to UV radiation) at the beginning of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

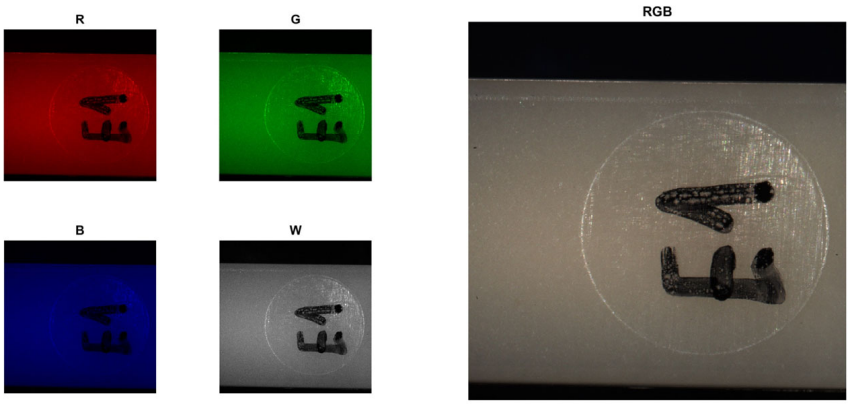


Figure 14. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PP + MC (specimen exposed to UV radiation) at week 5 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

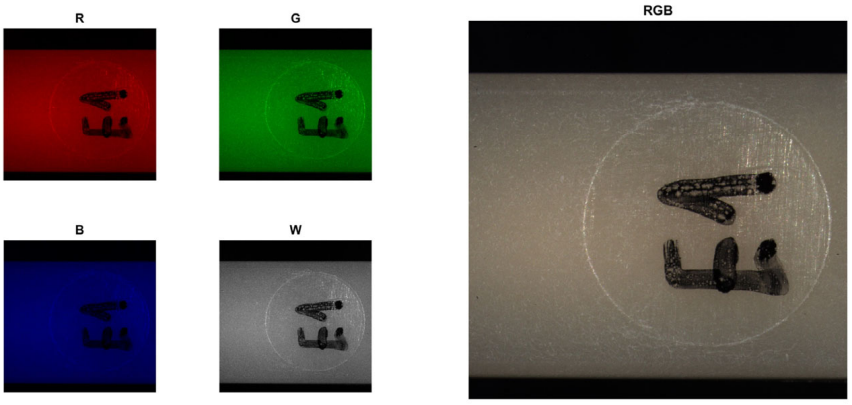


Figure 15. Images obtained in the different components (R, G, B, W) and in full color (RGB) of a specimen of PP + MC (specimen exposed to UV radiation) at week 10 of the UV test (dimensions of the images: width × height = 12 × 12 mm^2).

Through analysis of the images obtained with the optical system, it can be seen in Figures 4–6 that no changes are detected in the appearance of the specimens of PLA + MC kept in the dark (original specimen) for the entire period of the test [45]. Furthermore, the same can also be observed in Figures 7–9 regarding the appearance of the specimen of PP + MC kept in the dark (original specimen) [45]. For the specimens of PLA + MC exposed to UV radiation, images of one of the specimens are presented in Figures 10–12 for

the same three moments. In this case, changes can clearly be seen in the specimen, which is lighter at the end of the UV test (whitish appearance noted over time) [45]. The last three figures of the set (Figures 13–15) show the images obtained for one of the specimens of PP + MC exposed to UV radiation at the beginning, middle and end of the UV test. In this case, changes were also noted in the specimen. In addition to becoming lighter at the end of the UV test (whitish appearance noted over time) [45], the PP + MC specimen also seemed to experience more surface damage, showing a rougher surface and slight crazing [45]. These findings are consistent with other studies that indicated polypropylene as being more susceptible to embrittlement and fractures [21,35]. The study of Niu et al. [23] is particularly interesting because they also investigated accelerated fragmentation of the same thermoplastics (PLA and PP) that were considered in the current study. In their study, they used UV radiation ranging from 300 nm to 400 nm, primarily in the UV-A class, with an irradiance of 60 W/m^2. Additionally, they immersed the samples in seawater. After 57 and 76 days of UV exposure, they observed cracks forming on the surface of polypropylene but not on polylactic acid. They also found that polylactic acid released fewer microplastics than polypropylene, indicating that it was more resistant to fragmentation.

During the entire UV accelerated aging test, spectral reflectance and colorimetric measurements were also carried out with the spectrophotometer described in Section 2.4. The results obtained here are presented in Figures 16–19.

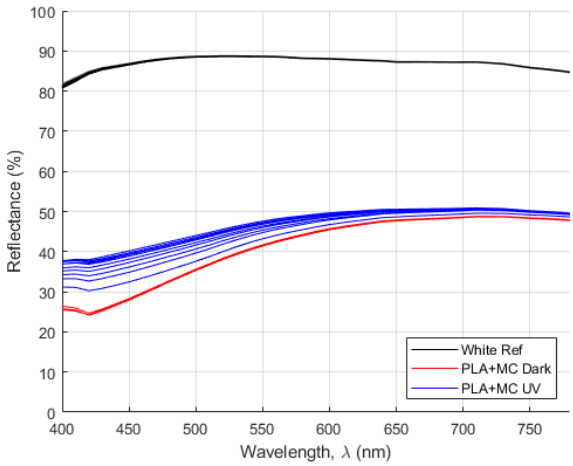


Figure 16. Spectral reflectance measurements in the visible spectrum for the specimens of PLA + MC as well as for the white calibration standard (white reference) during the 10 weeks of the UV accelerated aging test (the full results are shown in Tables A1 and A2 of Appendix A).

Through analysis of the measurements carried out with the spectrophotometer equipment, the specific characteristics of each tested sample can be immediately evidenced in the graphs. In particular, it can be seen in Figure 16 that all the spectral reflectance curves of the white reference, identified in the graph as "White Ref", are very similar. Many of the lines are overlapping, creating the thick black line at the top of the graph. This suggests that the equipment used is highly reliable, as it did not show relevant deviations in the measurements obtained throughout the entire test period. In Figure 16, three red lines can also be seen very close to each other, corresponding to the spectral reflectance curves of the PLA + MC kept in the dark (original specimens), which are identified in the graph as "PLA + MC Dark". The three curves represent the three moments at which the PLA + MC Dark was measured: beginning of the test (week 1—DK 01), at the middle (week 5—DK 05), and the end (week 10—DK 10). Since these three red curves are very similar, it indicates that the PLA + MC specimens stored in the dark did not experience relevant spectral reflectance and color changes throughout the entire test period. Finally, the blue lines in the graph of

Figure 16, identified as "PLA + MC UV", correspond to the spectral reflectance curves of the PLA + MC specimens that were exposed to UV radiation. There are ten different curves on the graph representing the various moments (10 weeks—WK 01 to WK 10) when these samples were measured. The blue curves are all located above the red curves, showing a tendency of approximation toward the white reference. This indicates a color fading or a lighter appearance of the samples over time [45]. The same observation can also be made in the graphs of Figure 17 in the CIE 1976 L*a*b* color space [43], which show the blue spots moving toward the black spot of the white reference (L* = 100, a* = 0, b* = 0).

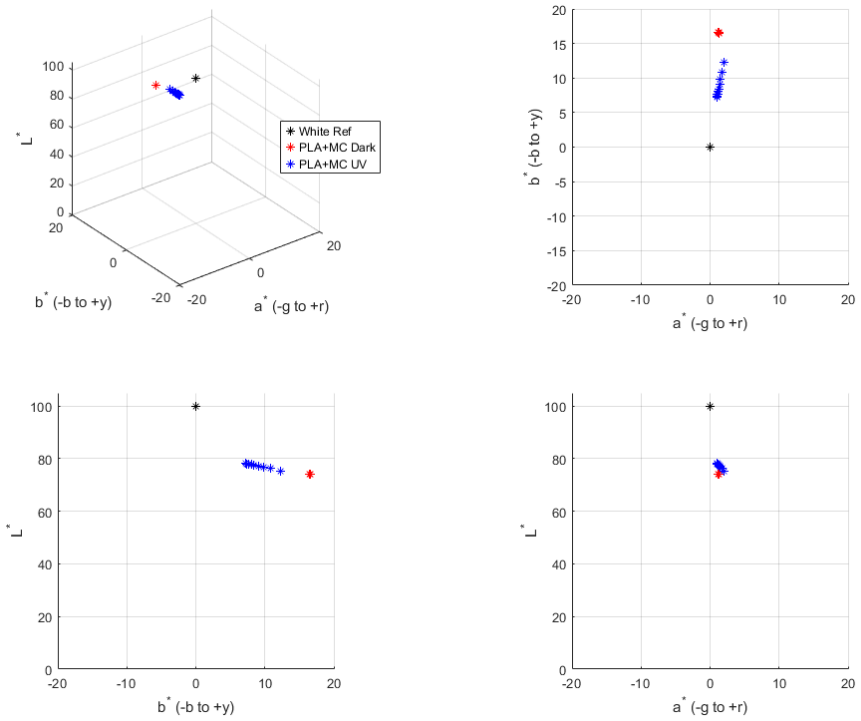


Figure 17. Colorimetric representations in the CIE 1976 L*a*b* color space [43] for the specimens of PLA + MC as well as for the white calibration standard (white reference) during the 10 weeks of the UV accelerated aging test (the full results are shown in Table A4 of Appendix A).

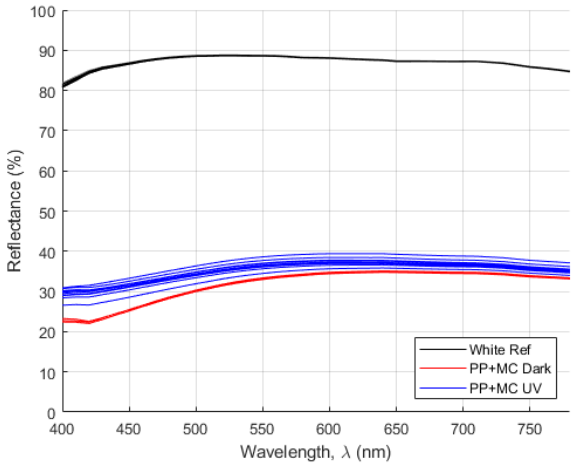


Figure 18. Spectral reflectance measurements in the visible spectrum for the specimens of PP + MC as well as for the white calibration standard (white reference) during the 10 weeks of the UV accelerated aging test (the full results are shown in Tables A1 and A3 of Appendix A).

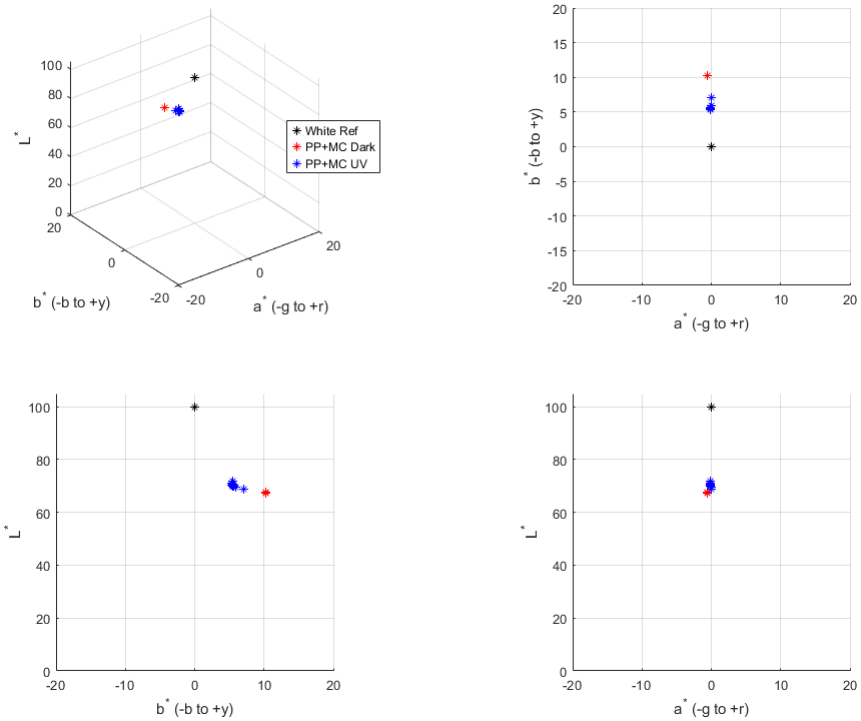


Figure 19. Colorimetric representations in the CIE 1976 L*a*b* color space [43] for the specimens of PP + MC as well as for the white calibration standard (white reference) during the 10 weeks of the UV accelerated aging test (the full results are shown in Table A5 of Appendix A).

Figures 18 and 19 present exactly the same but in this case for the PP + MC specimens instead of the PLA + MC specimens. The conclusions drawn earlier are equally valid for the PP + MC specimens. However, there is one difference between the samples that must be highlighted. In particular, the blue curves shown in Figure 18 and the blue dots shown in Figure 19 are closer to each other compared to the PLA + MC case. This means that the PP + MC specimens showed less dispersion in the spectral reflectance and colorimetric results throughout the entire UV test period, indicating that they experienced less color fading.

All of the effects mentioned above can also be observed through the corresponding color differences (ΔL^*, Δa^*, Δb^*, ΔE^*_{ab}) [43] calculated for the two types of biocomposites tested (PP + MC and PLA + MC) stored in the dark and exposed to UV radiation. These results are summarized in Tables 1 and 2 (results are shown in Tables A4 and A5 of Appendix A).

Table 1. Color differences calculated for the PLA + MC and PP + MC specimens stored in the dark (original specimen) in week 5 relative to week 1 (DK 05 vs. DK 01), in week 10 relative to week 5 (DK 10 vs. DK 05), and in week 10 relative to week 1 (DK 10 vs. DK 01).

Color Differences	DK 05 vs. DK 01		DK 10 vs. DK 05		DK 10 vs. DK 01	
	PLA + MC	PP + MC	PLA + MC	PP + MC	PLA + MC	PP + MC
ΔL^*	0.1	0.3	0.0	−0.3	0.2	0.0
Δa^*	0.0	0.0	0.0	0.0	−0.1	0.0
Δb^*	−0.3	−0.4	0.1	0.2	−0.1	−0.2
ΔE^*_{ab}	0.3	0.5	0.1	0.4	0.2	0.2

Table 2. Color differences calculated for the PLA + MC and PP + MC specimens exposed to UV radiation compared to the specimens stored in the dark (original specimens) in week 1 (WK 01 vs. DK 01), week 5 (WK 05 vs. DK 01), and week 10 (WK 10 vs. DK 01).

Color Differences	WK 01 vs. DK 01		WK 05 vs. DK 01		WK 10 vs. DK 01	
	PLA + MC	PP + MC	PLA + MC	PP + MC	PLA + MC	PP + MC
ΔL*	1.7	1.8	3.8	3.5	4.6	4.6
Δa*	0.7	0.6	0.1	0.4	−0.2	0.4
Δb*	−4.3	−4.1	−8.1	−5.8	−9.3	−5.6
ΔE^*_{ab}	4.7	4.5	9.0	6.8	10.4	7.3

The tables reveal that in fact, the specimens stored in the dark consistently show low color differences, with ΔE^*_{ab} values always below 0.5. As for the specimens exposed to UV radiation, they exhibit increasing ΔE^*_{ab} values over time. For PLA + MC, the values are higher compared to PP + MC with values of 4.7, 9.0, and 10.4 for weeks 1, 5 and 10 in the first case and values of 4.5, 6.8, and 7.3 for weeks 1, 5 and 10 in the second case in comparison to the corresponding specimens stored in the dark. DK 01 was selected for the calculations mentioned above, although any of the three (DK 01, DK05 or DK10) could have been used as they are all similar and would not have affected the final results.

4. Conclusions

In this work, biocomposites of two commonly used thermoplastics, polylactic acid (PLA) and polypropylene (PP), were examined for their resistance to ultraviolet (UV) light. They were exposed to a total of 1050 h of UV-A radiation, and were analyzed by image, spectrally and colorimetrically. The specimens exposed to UV radiation were then compared to specimens of the same materials stored in the dark.

In our experiments, the following was found:

1. As expected, the specimens that did not receive any UV radiation showed no relevant color changes throughout the entire UV test period.
2. On the other hand, the specimens that were exposed to UV radiation showed noticeable changes, revealing color fading and a lighter appearance over time.
3. This effect was observed in the images captured from the tested samples as well as in the spectral reflectance and colorimetric measurements taken during the 10 week test period.
4. The color fading was more pronounced in the PLA + MC specimens compared to the PP + MC specimens.
5. The images captured during the UV test revealed that in addition to the color fading experienced by the PP, the specimens of this material also exhibited signs of surface damage. There was a slight crazing present on the surface of the specimens that were exposed to UV light, which was consistent with other research found in the literature on this topic.

In terms of future work, additional studies are already underway to thoroughly investigate the mechanical properties of samples exposed to UV compared to samples stored in the dark, to explore the effects of a more prolonged UV radiation exposure on these materials, specifically in terms of spectral reflectance, colorimetric characteristics surface damages, and their evolution over time, and to examine the impact of UV stabilizers on these materials when they are exposed to UV radiation.

Author Contributions: Conceptualization, A.d.O.M. and P.T.F.; methodology, A.d.O.M., P.T.F. and A.G.; software, A.d.O.M. and P.T.F.; validation, A.d.O.M. and P.T.F., formal analysis, A.d.O.M. and P.T.F.; investigation, A.d.O.M., P.T.F., V.L.D.C., J.C.V., P.E.M.V., M.J.R.M.N., J.M.R.C., M.E.A. and A.P.C.; resources, A.d.O.M., P.T.F., V.L.D.C., P.E.M.V., M.J.R.M.N., A.G., P.P., J.B., J.C.V., J.M.R.C., M.E.A. and A.P.C.; data curation, A.d.O.M. and P.T.F.; writing—original draft preparation, A.d.O.M. and P.T.F.; writing—review and editing, A.d.O.M., P.T.F., A.G., P.P. and J.B.; visualization, A.d.O.M., P.T.F., V.L.D.C., P.E.M.V., M.J.R.M.N., J.C.V., J.M.R.C., M.E.A. and A.P.C.; supervision, P.T.F., A.G. and P.P.; project administration, P.T.F., A.P.C., J.M.R.C., M.E.A., A.G. and P.P.; funding acquisition, P.T.F., A.P.C., J.M.R.C., M.E.A., A.G. and P.P. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript (alphabetically):

B	blue
CIE	International Commission on Illumination
DK	dark
DNA	deoxyribonucleic acid
G	green
h	hour(s)
IR	infrared
ISO	International Organization for Standardization
MC	micronized cellulose
MFI	melt flow index
PLA	polylactic acid
PP	polypropylene
R	red
Ref	reference
RGB	red–green–blue
rpm	revolutions per minute
UV	ultraviolet
UV-A	ultraviolet subtype A

UV-B	ultraviolet subtype B
UV-C	ultraviolet subtype C
vs.	versus
W	white
WK	week

Appendix A

The following Tables A1–A5 present the spectral reflectance and colorimetric data obtained with the spectrophotometer used in the present work.

Table A1. Spectral reflectance measurements obtained from 400 to 780 nm for the white calibration standard (white reference) at three different moments (weeks 1, 5, and 10) considered for the samples stored in the dark (DK 01, DK 05, and DK 10) and during the 10-week period of the UV aging test (WK 01 to WK 10).

λ (nm)	DK 01	DK 05	DK 10	WK 01	WK 02	WK 03	WK 04	WK 05	WK 06	WK 07	WK 08	WK 09	WK 10
400	80.87	81.82	80.71	80.85	80.85	80.76	80.78	80.86	81.16	81.53	80.92	81.05	80.72
410	82.57	83.45	82.39	82.51	82.53	82.48	82.44	82.50	82.82	83.13	82.57	82.62	82.44
420	84.30	84.98	84.22	84.34	84.29	84.36	84.30	84.41	84.62	84.73	84.24	84.37	84.25
430	85.30	85.86	85.35	85.41	85.31	85.36	85.31	85.48	85.55	85.76	85.37	85.41	85.29
440	85.90	86.39	85.93	85.96	85.95	85.97	85.92	86.04	86.13	86.27	85.91	85.94	85.93
450	86.52	86.94	86.50	86.53	86.51	86.56	86.56	86.62	86.71	86.84	86.51	86.54	86.52
460	87.14	87.49	87.13	87.18	87.11	87.16	87.19	87.20	87.28	87.43	87.17	87.15	87.12
470	87.60	87.96	87.65	87.67	87.64	87.65	87.65	87.68	87.79	87.88	87.67	87.67	87.63
480	88.00	88.32	88.01	88.04	88.01	88.04	88.05	88.06	88.17	88.21	88.06	88.08	88.01
490	88.27	88.56	88.29	88.34	88.26	88.32	88.32	88.35	88.44	88.49	88.33	88.37	88.30
500	88.46	88.69	88.50	88.51	88.46	88.47	88.49	88.51	88.60	88.68	88.52	88.56	88.46
510	88.54	88.73	88.57	88.55	88.53	88.51	88.58	88.54	88.64	88.73	88.57	88.62	88.51
520	88.60	88.81	88.64	88.65	88.63	88.61	88.68	88.63	88.73	88.81	88.65	88.69	88.60
530	88.58	88.81	88.63	88.66	88.65	88.62	88.67	88.65	88.72	88.80	88.65	88.69	88.59
540	88.53	88.76	88.59	88.61	88.60	88.59	88.61	88.62	88.67	88.76	88.61	88.65	88.55
550	88.52	88.75	88.57	88.57	88.58	88.58	88.57	88.59	88.65	88.71	88.58	88.63	88.55
560	88.48	88.69	88.52	88.51	88.50	88.52	88.52	88.52	88.60	88.64	88.52	88.59	88.49
570	88.32	88.52	88.36	88.37	88.33	88.37	88.36	88.35	88.44	88.48	88.36	88.44	88.31
580	88.08	88.28	88.11	88.11	88.10	88.15	88.12	88.13	88.20	88.23	88.11	88.18	88.09
590	88.04	88.26	88.08	88.08	88.05	88.10	88.10	88.09	88.16	88.19	88.08	88.13	88.07
600	87.98	88.17	88.02	88.02	87.97	88.01	88.04	88.04	88.10	88.11	88.02	88.06	88.00
610	87.87	88.04	87.89	87.90	87.84	87.89	87.94	87.92	87.97	87.98	87.88	87.93	87.87
620	87.75	87.90	87.73	87.74	87.69	87.74	87.77	87.74	87.81	87.82	87.72	87.76	87.72
630	87.59	87.78	87.61	87.60	87.55	87.61	87.64	87.61	87.69	87.69	87.58	87.62	87.58
640	87.45	87.66	87.51	87.49	87.45	87.50	87.54	87.48	87.57	87.60	87.47	87.51	87.48
650	87.18	87.38	87.24	87.22	87.20	87.24	87.28	87.20	87.30	87.32	87.21	87.26	87.22
660	87.19	87.38	87.20	87.21	87.19	87.23	87.26	87.19	87.28	87.30	87.19	87.26	87.20
670	87.21	87.37	87.21	87.22	87.21	87.23	87.27	87.21	87.29	87.31	87.21	87.27	87.22
680	87.18	87.34	87.20	87.20	87.19	87.20	87.25	87.19	87.25	87.28	87.19	87.23	87.20
690	87.15	87.30	87.19	87.18	87.18	87.17	87.23	87.18	87.22	87.26	87.17	87.19	87.18
700	87.15	87.32	87.22	87.20	87.19	87.19	87.25	87.20	87.23	87.27	87.20	87.20	87.21
710	87.15	87.33	87.24	87.22	87.21	87.20	87.27	87.22	87.25	87.28	87.23	87.21	87.25
720	86.92	87.12	87.02	86.99	86.98	86.98	87.05	86.99	87.03	87.05	87.00	86.98	87.02
730	86.69	86.90	86.80	86.76	86.74	86.75	86.82	86.76	86.82	86.82	86.78	86.76	86.80
740	86.22	86.44	86.33	86.29	86.28	86.29	86.36	86.29	86.37	86.37	86.31	86.33	86.32
750	85.73	85.96	85.84	85.79	85.78	85.81	85.87	85.81	85.89	85.90	85.81	85.85	85.82
760	85.42	85.65	85.52	85.48	85.45	85.50	85.55	85.50	85.56	85.59	85.50	85.53	85.50
770	85.06	85.28	85.11	85.11	85.07	85.12	85.15	85.13	85.16	85.21	85.12	85.14	85.15
780	84.64	84.84	84.66	84.67	84.64	84.68	84.72	84.71	84.72	84.77	84.69	84.70	84.73

Table A2. Spectral reflectance measurements obtained from 400 to 780 nm for the PLA + MC (original specimen) at three different moments (weeks 1, 5, and 10) considered for the samples stored in the dark (DK 01, DK 05, and DK 10) and for the PLA + MC exposed to UV during the 10-week period of the UV aging test (WK 01 to WK 10).

λ (nm)	DK 01	DK 05	DK 10	WK 01	WK 02	WK 03	WK 04	WK 05	WK 06	WK 07	WK 08	WK 09	WK 10
400	24.57	25.44	24.73	30.33	32.15	33.45	34.37	35.17	36.14	36.83	36.24	36.84	36.86
410	24.19	24.98	24.35	30.23	32.16	33.52	34.53	35.39	36.38	37.05	36.55	37.13	37.17
420	23.03	23.66	23.29	29.43	31.57	33.01	34.10	35.13	35.99	36.56	36.27	36.82	37.02
430	24.08	24.63	24.34	30.04	32.18	33.56	34.67	35.72	36.49	37.05	36.86	37.32	37.61
440	25.38	25.85	25.62	30.78	32.92	34.27	35.41	36.39	37.16	37.67	37.52	37.98	38.30
450	26.65	27.08	26.90	31.59	33.68	35.02	36.15	37.10	37.84	38.32	38.22	38.66	38.99
460	28.09	28.48	28.34	32.52	34.54	35.80	36.94	37.83	38.57	39.04	38.97	39.39	39.70
470	29.53	29.91	29.81	33.48	35.43	36.64	37.75	38.61	39.31	39.75	39.70	40.13	40.42
480	31.00	31.35	31.26	34.49	36.38	37.53	38.60	39.43	40.09	40.49	40.47	40.88	41.16
490	32.38	32.72	32.63	35.49	37.29	38.39	39.43	40.20	40.86	41.23	41.23	41.62	41.89
500	33.76	34.10	34.03	36.57	38.28	39.33	40.34	41.01	41.66	42.02	42.01	42.37	42.65
510	35.04	35.37	35.31	37.66	39.30	40.26	41.22	41.83	42.45	42.79	42.77	43.13	43.38
520	36.33	36.66	36.60	38.86	40.40	41.29	42.17	42.74	43.31	43.63	43.60	43.94	44.18
530	37.52	37.84	37.80	40.02	41.45	42.26	43.08	43.58	44.11	44.40	44.37	44.68	44.90
540	38.62	38.92	38.90	41.08	42.43	43.16	43.91	44.37	44.85	45.11	45.06	45.37	45.58
550	39.62	39.91	39.89	42.02	43.30	43.96	44.66	45.06	45.51	45.74	45.68	45.98	46.19
560	40.55	40.82	40.82	42.88	44.08	44.67	45.35	45.68	46.12	46.29	46.26	46.54	46.72
570	41.36	41.63	41.61	43.62	44.73	45.27	45.90	46.19	46.60	46.77	46.72	47.00	47.15
580	42.13	42.40	42.37	44.30	45.35	45.85	46.41	46.67	47.04	47.19	47.13	47.40	47.55
590	42.89	43.16	43.14	44.98	45.96	46.41	46.94	47.15	47.50	47.63	47.55	47.80	47.96
600	43.56	43.81	43.79	45.57	46.48	46.88	47.39	47.55	47.87	47.99	47.91	48.13	48.29
610	44.10	44.34	44.32	46.05	46.91	47.26	47.74	47.87	48.18	48.28	48.18	48.40	48.54
620	44.60	44.83	44.78	46.50	47.31	47.61	48.05	48.16	48.45	48.52	48.41	48.63	48.76
630	45.06	45.28	45.23	46.91	47.67	47.94	48.36	48.43	48.71	48.77	48.65	48.86	48.98
640	45.49	45.71	45.66	47.32	48.05	48.28	48.67	48.71	48.98	49.03	48.90	49.11	49.21
650	45.69	45.90	45.85	47.51	48.21	48.41	48.78	48.80	49.06	49.10	48.96	49.16	49.25
660	45.89	46.09	46.03	47.70	48.36	48.54	48.90	48.90	49.15	49.18	49.03	49.23	49.32
670	46.02	46.20	46.14	47.83	48.47	48.62	48.99	48.97	49.20	49.21	49.09	49.26	49.36
680	46.16	46.33	46.27	47.97	48.59	48.72	49.07	49.05	49.27	49.28	49.15	49.32	49.41
690	46.30	46.45	46.40	48.11	48.71	48.82	49.16	49.14	49.34	49.34	49.21	49.37	49.46
700	46.47	46.61	46.55	48.28	48.86	48.94	49.27	49.25	49.44	49.43	49.29	49.46	49.54
710	46.63	46.77	46.71	48.45	49.02	49.07	49.39	49.37	49.54	49.52	49.38	49.54	49.63
720	46.62	46.76	46.69	48.44	48.98	49.02	49.33	49.31	49.48	49.45	49.31	49.47	49.54
730	46.61	46.75	46.67	48.42	48.95	48.97	49.27	49.24	49.42	49.38	49.23	49.39	49.46
740	46.45	46.59	46.49	48.26	48.76	48.78	49.06	49.03	49.21	49.17	49.01	49.19	49.23
750	46.26	46.41	46.30	48.07	48.56	48.57	48.83	48.80	48.98	48.95	48.78	48.96	48.98
760	46.15	46.30	46.17	47.95	48.42	48.44	48.69	48.67	48.82	48.80	48.63	48.81	48.82
770	45.98	46.13	46.00	47.76	48.24	48.27	48.51	48.48	48.62	48.60	48.43	48.59	48.62
780	45.77	45.92	45.78	47.54	48.02	48.05	48.28	48.26	48.39	48.37	48.20	48.33	48.39

Table A3. Spectral reflectance measurements obtained from 400 to 780 nm for the PP + MC (original specimen) at three different moments (weeks 1, 5, and 10) considered for the samples stored in the dark (DK 01, DK 05, and DK 10) and for the PP + MC exposed to UV during the 10-week period of the UV aging test (WK 01 to WK 10).

λ (nm)	DK 01	DK 05	DK 10	WK 01	WK 02	WK 03	WK 04	WK 05	WK 06	WK 07	WK 08	WK 09	WK 10
400	19.91	21.03	20.01	24.81	26.61	27.48	27.56	27.66	28.36	28.48	28.12	28.47	28.65
410	19.82	20.85	19.90	24.93	26.81	27.72	27.81	27.91	28.62	28.68	28.41	28.73	28.94

Table A3. *Cont.*

λ (nm)	DK 01	DK 05	DK 10	WK 01	WK 02	WK 03	WK 04	WK 05	WK 06	WK 07	WK 08	WK 09	WK 10
420	19.38	20.20	19.54	24.77	26.81	27.76	27.90	28.00	28.59	28.59	28.40	28.68	29.02
430	20.32	21.03	20.47	25.39	27.40	28.28	28.48	28.55	29.07	29.01	28.93	29.16	29.55
440	21.38	22.05	21.54	25.98	27.98	28.82	29.06	29.09	29.62	29.50	29.46	29.68	30.10
450	22.35	22.99	22.52	26.61	28.58	29.43	29.65	29.65	30.19	30.04	30.06	30.25	30.68
460	23.43	24.02	23.56	27.28	29.20	30.01	30.24	30.23	30.76	30.58	30.65	30.86	31.30
470	24.46	25.03	24.59	27.94	29.81	30.56	30.81	30.79	31.31	31.13	31.19	31.43	31.90
480	25.46	26.00	25.57	28.59	30.41	31.14	31.40	31.36	31.88	31.70	31.79	32.03	32.51
490	26.37	26.87	26.43	29.22	30.97	31.68	31.95	31.91	32.44	32.24	32.36	32.59	33.09
500	27.24	27.72	27.31	29.86	31.55	32.23	32.52	32.44	32.98	32.80	32.90	33.14	33.69
510	28.01	28.47	28.08	30.43	32.07	32.72	33.03	32.93	33.48	33.31	33.42	33.66	34.24
520	28.74	29.22	28.82	31.05	32.61	33.23	33.54	33.44	33.99	33.81	33.95	34.18	34.78
530	29.38	29.85	29.46	31.58	33.06	33.66	33.97	33.87	34.41	34.22	34.39	34.62	35.22
540	29.92	30.37	30.00	32.02	33.45	34.02	34.31	34.22	34.75	34.56	34.74	34.97	35.59
550	30.38	30.81	30.45	32.39	33.77	34.31	34.59	34.49	35.03	34.83	35.02	35.26	35.89
560	30.79	31.21	30.84	32.71	34.03	34.54	34.84	34.72	35.26	35.05	35.25	35.48	36.14
570	31.14	31.54	31.17	32.98	34.25	34.72	35.03	34.90	35.43	35.23	35.43	35.67	36.33
580	31.44	31.84	31.46	33.18	34.41	34.87	35.17	35.04	35.55	35.36	35.55	35.79	36.46
590	31.71	32.12	31.74	33.39	34.56	35.01	35.30	35.16	35.68	35.49	35.68	35.91	36.59
600	31.90	32.30	31.93	33.51	34.64	35.07	35.36	35.21	35.72	35.53	35.72	35.95	36.64
610	32.03	32.43	32.06	33.58	34.67	35.08	35.38	35.21	35.72	35.52	35.72	35.95	36.65
620	32.13	32.52	32.13	33.62	34.68	35.06	35.36	35.19	35.70	35.49	35.69	35.92	36.63
630	32.21	32.60	32.21	33.64	34.67	35.04	35.33	35.16	35.67	35.47	35.65	35.88	36.61
640	32.28	32.66	32.28	33.67	34.67	35.03	35.31	35.13	35.64	35.45	35.63	35.86	36.59
650	32.21	32.59	32.20	33.56	34.54	34.89	35.17	34.99	35.50	35.29	35.49	35.73	36.44
660	32.14	32.52	32.12	33.48	34.43	34.77	35.06	34.87	35.37	35.17	35.36	35.61	36.32
670	32.06	32.43	32.04	33.39	34.33	34.65	34.94	34.76	35.24	35.04	35.24	35.49	36.20
680	32.00	32.37	31.98	33.31	34.23	34.55	34.83	34.66	35.13	34.94	35.13	35.38	36.09
690	31.94	32.30	31.91	33.24	34.13	34.44	34.72	34.57	35.02	34.84	35.02	35.28	35.99
700	31.91	32.26	31.87	33.19	34.06	34.37	34.65	34.50	34.95	34.77	34.95	35.21	35.92
710	31.88	32.22	31.84	33.14	33.98	34.30	34.57	34.44	34.88	34.70	34.87	35.14	35.85
720	31.74	32.09	31.70	33.00	33.82	34.13	34.40	34.27	34.71	34.53	34.69	34.97	35.67
730	31.61	31.96	31.56	32.86	33.65	33.96	34.23	34.10	34.54	34.36	34.52	34.81	35.50
740	31.36	31.72	31.30	32.59	33.36	33.66	33.94	33.81	34.24	34.07	34.22	34.53	35.20
750	31.11	31.46	31.04	32.32	33.08	33.39	33.65	33.53	33.95	33.79	33.94	34.25	34.91
760	30.93	31.29	30.85	32.13	32.89	33.21	33.45	33.33	33.74	33.59	33.75	34.04	34.70
770	30.75	31.10	30.67	31.92	32.69	33.03	33.25	33.12	33.53	33.38	33.56	33.81	34.48
780	30.56	30.91	30.47	31.71	32.49	32.83	33.04	32.90	33.31	33.16	33.35	33.58	34.26

Table A4. Colorimetric representations obtained in the CIE 1976 L*a*b* color space [43] for the PLA + MC (original specimen) at three different moments (weeks 1, 5, and 10) considered for the samples stored in the dark (DK 01, DK 05, and DK 10) and for the PLA + MC exposed to UV during the 10-week period of the UV aging test (WK 01 to WK 10).

CIE1976	DK 01	DK 05	DK 10	WK 01	WK 02	WK 03	WK 04	WK 05	WK 06	WK 07	WK 08	WK 09	WK 10
L*	72.81	72.96	72.99	74.55	75.45	75.90	76.38	76.65	76.93	77.06	77.07	77.25	77.41
a*	1.32	1.29	1.26	2.07	1.87	1.68	1.53	1.41	1.33	1.28	1.21	1.19	1.12
b*	16.49	16.24	16.38	12.20	10.78	9.79	9.09	8.35	7.92	7.59	7.57	7.32	7.19

Table A5. Colorimetric representations obtained in the CIE 1976 L*a*b* color space [43] for the PP + MC (original specimen) at three different moments (weeks 1, 5, and 10) considered for the samples stored in the dark (DK 01, DK 05, and DK 10) and for the PP + MC exposed to UV during the 10-week period of the UV aging test (WK 01 to WK 10).

CIE1976	DK 01	DK 05	DK 10	WK 01	WK 02	WK 03	WK 04	WK 05	WK 06	WK 07	WK 08	WK 09	WK 10
L*	65.09	65.41	65.12	66.85	68.01	68.44	68.68	68.59	69.00	68.82	69.00	69.18	69.72
a*	−0.64	−0.60	−0.63	−0.01	−0.12	−0.19	−0.21	−0.23	−0.25	−0.21	−0.25	−0.25	−0.26
b*	11.32	10.92	11.12	7.23	6.08	5.56	5.60	5.47	5.40	5.38	5.52	5.49	5.72

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