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Study of different cleaning methods for solar reflectors used in CSP plants

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Abstract

Soiling and dust accumulation in reflectors for concentrating solar plants (CSP) plants decrease their reflectance and, as a consequence, the solar field efficiency. Minimizing the cost of the cleanliness is a key issue for the solar-plant feasibility. This work is focused on optimizing the cleaning method of solar reflectors for CSP applications under real outdoor conditions in a semi-desert climate. The testing consisted on outdoor exposing of solar reflectors and applying different cleaning methods. According to results obtained, the most effective cleaning method is the one based on demineralized water and a brush, with an average efficiency of 98.8 % in rainy periods and 97.2 % in dry seasons. The innovative cleaning method based on a steam device with a soft tissue was inefficient (efficiency of 97.3 % in a rainy period). If the number of passes applied with the high-pressure demineralized water method is highly enough, this method is as effective as the one based on brushing and the addition of a detergent does not increase its effectiveness.

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Keywords: CSP plants; solar reflectors; maintenance, soiling, cleaning methods.

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Nomenclature

CIEMAT	*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas*
DLR	*Deutsches Zentrum für Luft- und Raumfahrt*
DNI	Direct normal irradiance
O&M	Operation and maintenance
OPAC	Optical Aging Characterization Laboratory
PSA	*Plataforma Solar de Almería*

1. Introduction

Power generation with CSP plants is a current practice increasingly booming in order to contribute to an energy production sustainable with the environment, using the solar resource. Although different technologies are available, the most commonly used are solar towers and parabolic-though collectors. They are basically composed of a power block and a solar field, which concentrates solar energy through solar reflectors. These CSP plants can only use the incoming direct solar radiation, called beam radiation or direct normal irradiance (DNI).

Appropriate site locations for CSP plants are normally in arid to semi-arid regions, where the DNI resource is very high, because acceptable production costs of commercial CSP plants are typically where DNI exceeds between 1700 and 2000 kWh/m^2 year [1]. In addition, the vegetation or other elements like buildings, does not shade the area and therefore the whole surface is receiving the incoming solar radiation. The fact that CSP plants are installed on arid and semi-arid regions involves the existence of important amount of dust and sand in the ambient. Soiling and dust accumulation in solar reflectors of CSP plants causes absorption and scattering of direct solar beams, decreasing mirrors reflectance, and solar field performance and power sales as a result [2]. To guarantee that all solar beams reach the receiver, that is, to keep a suitable average mirror reflectance and a good solar-plant efficiency level, a proper cleaning method has to be frequently applied. As example, around 500,000 m^2 of parabolic-trough reflectors are installed in a typical 50-MW$_e$ commercial CSP plant in South Spain, with a 7.5-hours molten-salt storage system [3]. Hence, collector cleanliness represents one of the most costly expenses of the solar-plant operation and maintenance (O&M), and minimizing this cost is an important issue for the solar-plant economic feasibility [2].

Main action in CSP plants to remove the soiling is based on water, washing the reflecting surface with pressurized water, but depending on the plant location this natural resource can be limited, i.e., on arid or semi-arid regions. Therefore, the necessity of optimizing the cleaning method in every single CSP plant, becomes a very relevant issue.

Although some authors have made a research effort in optimizing the cleaning procedure [4-8], some important technical aspects have not been studied in detail yet. For that reason, this paper focuses on optimizing the cleaning method of solar reflectors under real outdoor conditions, trying to find out the best cost-effective combination.

The test consisted on outdoor exposing and cleaning of several solar reflector samples at the outdoor test area that the Optical Aging Characterization Laboratory (OPAC) has to this purpose at the *Plataforma Solar de Almería* (PSA), in South Spain. OPAC laboratory is a collaborative research project between *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas* (CIEMAT) and *Deutsches Zentrum für Luft- und Raumfahrt* (DLR). PSA is located in Tabernas Desert (South Spain), that is, it has a semi-desert climate.

2. Methodology

Reflector samples were exposed to real outdoor conditions in this semi-desert climate to study the effectiveness of several cleaning methods, including natural cleaning. Different cleaning methods were periodically applied to the reflector samples exposed in separated test benches, during a total test period of 2 years. Reflectance measurements were taken before and after the cleaning tasks to evaluate them. This section describes the methodology followed.

2.1. Experimental set-up

Four metallic test benches were provided by Saint-Gobain to support the reflector samples. A picture of the four metallic test benches is in Fig. 1. The four test benches are labeled structure 1 to 4, from left to right in Fig. 1.

Fig. 1. Structures 1 to 4 (from left to right) at OPAC's outdoor exposing area.

A different cleaning method was applied on each individual test bench. The metallic structures were installed faced to the south and constructed such that the sample were fixed with an angle of 45° above horizontal, near the 37° which corresponds to the latitude of the location. This inclination allows an easy application of the cleaning methods and reflectance measurement.

The design of each metallic test bench is intended to place a total of 20 samples per structure, with two different sizes. That is, a maximum of 10 samples with a size of 400x400 mm^2 (3 mm thickness), and 10 samples of 80x80 mm^2 (3 mm thickness) can be placed on each test bench. Largest samples are arranged in 2 rows and 5 columns, while small ones do it in a single row below the previous one, as can be seen in Fig. 2 (left). In this case, each test bench has received a maximum of 5 different types of solar reflectors. The distribution of each type has been per column as follows: each column contains two large samples per row, and two small ones in the lowest row. For this study were taken into account the two largest reflectors placed in column 4 of each of the 4 structures (Fig. 2 right). The rest of the samples were used for another study.

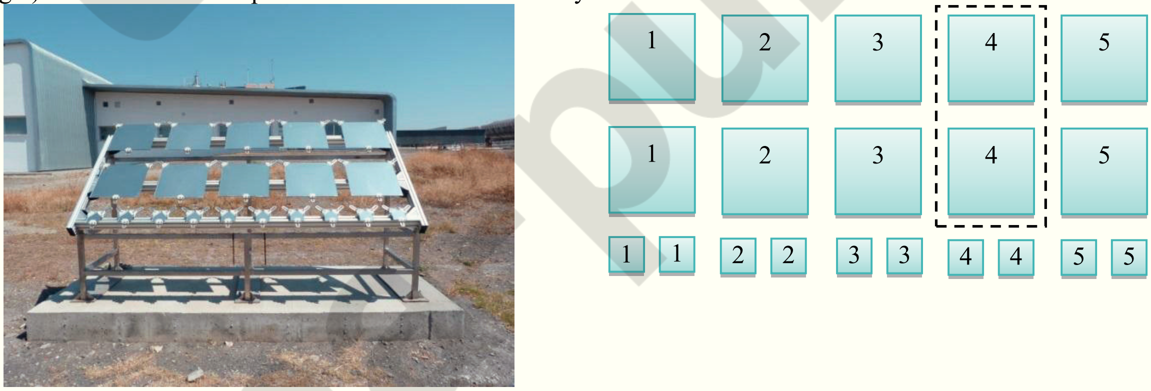

Fig. 2. Structure 2 (left) and distribution of solar reflectors per type in a test bench (right).

2.2. Reflectance measurements

The reflectance is the selected parameter to evaluate the efficiency of the different methods applied to the reflector samples. The efficiency was obtained on the one hand by checking the difference between reflectance before and after cleaning the samples in each test bench, which indicates the ability of the cleaning methods to eliminate the soiling accumulated, and on the other hand by comparing reflectance values obtained after cleaning them, which represent the capability of the cleaning methods to restore the initial reflectance.

The reflectance is defined as the ratio of the radiant flux reflected from a surface to that of the incident radiation [9]. Monochromatic specular reflectance was measured with the portable specular reflectometer model 15R-USB, manufactured by Devices and Services [10]. It is provided with a LED source of wavelength range between 635-685 nm, with a peak on 660 nm (see Fig. 3).

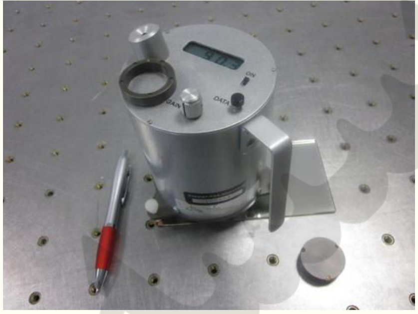

Fig. 3. Portable specular reflectometer 15R-USB by Devices and Services.

It has the possibility to select the acceptance angle for the measurements among 23.0, 12.5 and 7.5 mrad. 12.5 mrad acceptance angle was chosen for all the measurements in this study. First and second surface reflectors can be measured with this device. The instrument itself has a portable calibrated reflector, using it as standard to calibrate the device.

Each sample was always measured at three different points to determine the homogeneity degree of the measurement. A mask was used while measuring with the reflectometer to measure always the same points on the samples. The final reflectance value of each solar reflector is given by the average of the three independent measurements and the associated standard deviation.

2.3. Cleaning methods

Throughout the test period of 2 years, different phases of 3 months were considered. In each phase, 3 different methods were compared, applying every method in a separated test bench, labeled structure 1 to 3 (see Fig. 1). The corresponding cleaning methods were applied every two weeks.

Different variables are involved in the cleaning task of concentrating solar reflectors for CSP plants, such as type of contact device (brush and soft tissue), water quality (demineralized and tap), water pressure, additives and water state (liquid and steam). Therefore, different cleaning methods considering each one of these factors have been applied to the test benches in order to identify those with more economical and performance advantages. The methodology followed is described below:

1. All reflectors are cleaned with demineralized water and brush (that is, a “perfectly clean” task), as “reset” operation and beginning of the period.
2. Initial reflectance of all reflectors is measured, just after the “perfectly clean” application, to check that maximum reflectance was reached.
3. The cleaning method to be applied in each of the 3 structures is selected, depending on the results of the previous period.
4. Two weeks later, reflectance is measured after this outdoor exposition to the environmental conditions and before being cleaned. These measurements permit to check the soling rate in this interval.
5. Reflectors of every structure are cleaned with the selected method.
6. Reflectance is measured, just after the cleaning process. These measurements give information about the effectiveness of every cleaning method in removing the soiling and also permit to compare the cleaning methods among them.

7. Steps 4 to 6 are repeated during the 3 months period, finishing with the last “dirty” measurement. After the complexion of the 3 months, the procedure starts again in step 1 for the beginning of the next period.

Taking into account the different variables that influence in the cleaning task and the proposed methodology to be followed for the study of its improvement, the cleaning methods selected and applied in the three structures during the six periods were those included in Table 1.

Table 1. Cleaning methods for every structure and period.

Period	Structure 1	Structure 2	Structure 3
1	**High-pressure demineralized water**: maximum pressure around 200 bar; 1 m distance; quantity of water: 0.3-0.7 l/m^2; 2 passes with the water nozzle.	**High-pressure demineralized water with detergent**: as structure 1 but using a 1% solution of a glass cleaner; 2 water with detergent passes plus 3-4 rinse water passes with the water nozzle.	**Demineralized water and a natural horse-hair bristles brush**: there is a direct contact to the glass. The quantity of water: 0.3-0.7 l/m^2; 3 passes with the brush.
2	**High-pressure demineralized water**: equal to period 1 but 3 passes with the water nozzle to increase the effiency.	**High-pressure demineralized water with detergent**: equal to period 1 but 1 water with detergent pass plus 2 rinse water passes with the water nozzle to reduce the water consumption.	**Demineralized water and a natural horse-hair bristles brush**: equal to period 1 but 4 passes to ensure the whole reflector surface is cleaned.
3	**High-pressure demineralized water**: equal to period 2.	**High-pressure demineralized water**: equal to structure 1 but only 2 passes in order to verify whether a lower quantity of water is enough to clean structure 2.	**Demineralized water and a natural horse-hair bristles brush**: equal to period 2.
4	**High-pressure demineralized water + 2% water additive**: maximum pressure around 200 bar; 1 m distance; quantity of water: 0.3-0.7 l/m^2. 2 passes with the water nozzle.	**Demineralized water + natural horse-hair bristles brush + 2% water additive**: 2 passes. No rinse water applied.	**Demineralized water + natural horse-hair bristles brush**: equal to period 3 but 2 passes to reduce water consumption.
5	**High-pressure demineralized water**: equal to period 1.	**Pressurized steam and soft tissue**: 2 passes using the steam cleaner and covering the floor nozzle with a soft tissue.	**Demineralized water + natural horse-hair bristles brush**: equal to period 4.
6	**High-pressure demineralized water**: equal to period 5.	**Pressure demineralized water:** maximum pressure 150 bar; 50 ºC temperature; 1 m distance; quantity of water: 0.3-0.7 l/m^2; 2 passes with the water nozzle.	**Demineralized water + natural horse-hair bristles brush**: equal to period 5.

As can be seen in Table 1, after each period the efficiency of the methods is evaluated and new methods are proposed for the next period, in order to improve the previous one. Number of passes is reduced or additive removed, for example, to reach this aim.

2.4. Cleaning devices

The pressure washing device used to apply the different cleaning methods was the model HDS 10/20-4M manufactured by KARCHER (see Figure 4). This machine allows working with pressurized water at a pressure range between 30 and 200 bar. In addition, thanks to a temperature controller, water can be applied from ambient temperature to 98 ºC, and up to 150 ºC into steam phase. Water flow rate selected was 16.7 l/min, working at the maximum value in all the experiments.

Fig. 4. Pressure washing device with hand spray nozzle accessory (1), water-fed natural horse-hair bristle brush accessory (2), steam cleaner (3), demineralized water tank (4), and additives tank (5).

The washer is connected to a 500-l demineralized water tank (number 4 in Figure 4) and a 60-l additives tank (number 5 in Figure 4). Different additives have been included in the study. The set is assembled on a trailer to carry them to the location of the test benches. The additional washing accessories used in the different methods are the following:

- Hand spray nozzle to apply both cold and hot pressurized water (number 1 in Figure 4).
- Water-fed natural horse-hair bristle brush, from the HiFlo^{TM} family manufactured by Unger Global (number 2 in Figure 4).

In addition, a steam cleaner, model SC 1.020 manufactured by KARCHER, was also used in the experiments (see number 3 in Fig. 4). This device provides a maximum steam pressure of 3.2 bar due to its 1500 W heating output and 1-l boiler/tank. From the standard accessories included in the set, the steam hose with a floor nozzle has been used in this study. The floor nozzle has been covered with a soft tissue to protect reflector samples from any possible damage. This soft tissue was perfectly washed after every experiment.

3. Results and discussion

All results obtained during this 2-year study about the effectiveness of different cleaning methods in a semi-desert climate are presented in this section. Fig. 5 and 6 and Table 2 show the results achieved in the study. In figures 5 and 6, abscises axis is the date and black arrows indicate the days when rainfall occurred, being the length of the arrows proportional to the rainfall quantity. These arrows allow checking the influence of a natural cleaning method (rainfall) in reflectance of the samples.

In Fig. 5 and 6, the ordinate axis is the reflectance value normalized to the maximum reflectance. Fig. 5 includes the curves corresponding to the three structures where the different artificial cleaning methods were applied (structures 1 to 3), divided by the different periods established in Table 1. Therefore, it presents an effectiveness comparison among the different artificial cleaning methods considered in this study. In this case, reflectance was measured just after the application of the cleaning method. As can be seen in Fig. 5, reflectance is recovered to more than the 96% of its maximum value during the whole extension of the study, except in the summer of 2012, when cleaning methods applied in structure 1 and 3 could not really clean the reflector samples.

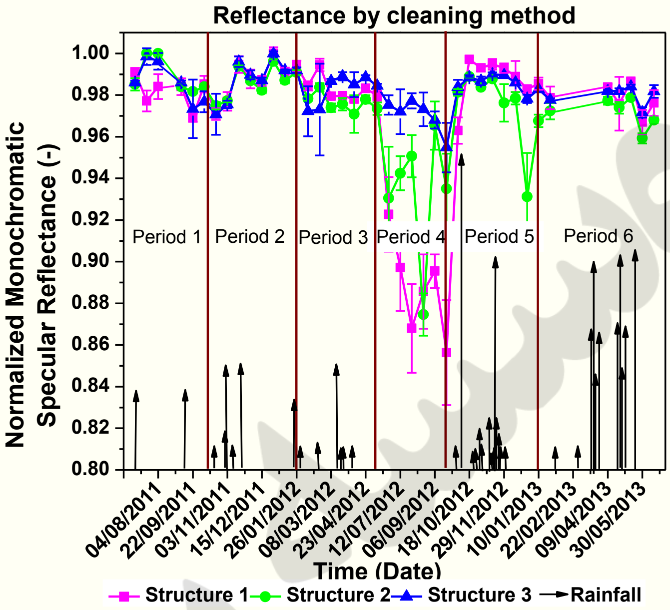

Fig. 5. Normalized monochromatic specular reflectance for the different cleaning methods applied, after cleaning (structures 1 to 3).

A cleaning efficiency parameter has been extracted from the study to have a clearer understanding of the results obtained. This parameter indicates the percentage of the reflectance recovering, that is the reflectance measured after the cleaning application related to the maximum reflectance. Table 2 includes the average efficiency percentage of each cleaning method for each period.

Table 2. Cleaning efficiency parameter obtained after cleaning (structures 1 to 3) for all the periods included in the study.

	Structure 1	**Structure 2**	**Structure 3**
Period 1	98.2	98.9	98.6
Period 2	98.8	98.6	98.8
Period 3	98.3	97.6	98.3
Period 4	89.8	94.0	97.2
Period 5	98.9	97.3	98.5
Period 6	97.8	97.1	98.0

To analyze results presented in this Fig 5 and Table 2 in a better way, they are studied by periods as follow:

- Period 1. Washing with detergent (structure 2) seemed to be the most effective cleaning method, with an average efficiency percentage of 98.9 %, followed by the one based on brushing (structure 3), with 98.6 %. It seems like 2 passes of high-pressure demineralized water (structure 1) were insufficient, with an average efficiency percentage of 98.2 %. As a consequence, the number of passes of high-pressure demineralized water was increased in the next period. To reduce the cost of the washing with detergent (structure 2), the number of passes was decreased in the next period.
- Period 2. The three cleaning methods applied were almost equally effective (at least in this winter season). If curves are studied more in detail, it can be appreciated that the methods based on brushing (structure 3) and on high-pressure demineralized water (structure 1) were most effective methods, with an average efficiency percentage of 98.8 % and finally the high-pressure demineralized water with detergent (structure 2), with 98.6 %.

Because the effectiveness of methods applied in structures 1 and 2 (involving both the same number of passes) are really similar and the addition of the detergent of the water (structure 2) involves an additional cost, it was decided to remove this method from the study. Therefore, no detergent was applied to structure 2 in the next period and this structure was dedicated to check if the number of passes can be reduced in the method with the high-pressure demineralized water (structure 1).

- Period 3. In general, cleaning methods based on brushing (structure 3) and on high-pressure demineralized water with 3 passes (structure 1) seemed to be the most effective cleaning methods, with an average efficiency percentage of 98.3 %. As it was expected, the effectiveness of 2 passes in the method with the high-pressure demineralized water (structure 2), with 97.6 % of average efficiency percentage, is lower than the corresponding to 3 passes (structure 1). However, it necessary to take into account that the cost of the method considerably increases with the number of passes. In the next period, it was considered useful to investigate more in detail the cleaning method based on the brushing, by adding a detergent to the water (structure 2). As a new and innovative detergent was available, it was also added to the high-pressure demineralized water (structure 1).
- Period 4. This period was the most extreme one concerning weather conditions because a hard summer was suffered. Therefore, the cleanliness level obtained by the methods applied was lower than in the rest of the study. Comparing the cleaning method based on brushing only with water (structure 3) and with water and additive (structure 2), with an average efficiency percentage of 97.2 % and 94 %, respectively, the first one had the best response. Therefore, it was concluded that it is not interesting to add detergent to the method based on brushing. And concerning the method based on high-pressure demineralized water with additive (structure 1), it presented the worst results of the whole study, with 89.8 %. A new cleaning method using a steam device with a soft tissue was studied in the next period (in structure 2). This new method was compared with the ones which presented the best response in the previous periods that is high-pressure demineralized water (structure 1) and demineralized water with a brush (structure 3).
- Period 5. The method based on a steam device with a soft tissue (structure 2) was inefficient, with an average efficiency percentage of 97.3 %. The main problem using it was an incomplete cleaning of the sample surface due to a progressive soiling of the tissue. Method in structure 1 is the best one, with an average efficiency percentage of 98.9 %, followed by method based on brushing (structure 3), with 98.5 %. In the next period, cleaning methods applied in structure 1 and 3 was kept, and they were compared with the best method concluded in [6] (pressure demineralized water at 150 bar and 50 ºC).
- Period 6. Results obtained with the pressure demineralized water at 150 bar and 50 ºC (structure 2), with an average efficiency percentage of 97.1 %, were slightly lower than the other methods. Method based on brushing (structure 3) is the best one, with an average efficiency percentage of 98.0 %, followed by method in structure 1, with 97.8 %. However, a further economic analysis is required, because this method could to be cheaper.

Fig. 6 represents the curve corresponding to the structure where no artificial cleaning method was applied (structure 4). Thus, it permits to analyze the efficiency of natural cleaning without any intervention of artificial cleaning. In this case, reflectance was measured in the same day when Fig. 5 values were taken, but not after applying the cleaning method because this structure was unwashed.

As can be seen in Fig. 6, in summer seasons (both in 2011 and in 2012) reflectance showed a massive decrease, reaching values even lower than 0.20 in 2012. This was due to the absence of rain, the very dry ambient and the huge amount of particles present in the air which were deposited on the sample surfaces. However, just after summer seasons, reflectance was recovered up to around a 90 % of its maximum value thanks to the positive effect of the abundant rainfall. As a consequence, the high effectiveness of the rain as natural cleaning method was proved in this study.

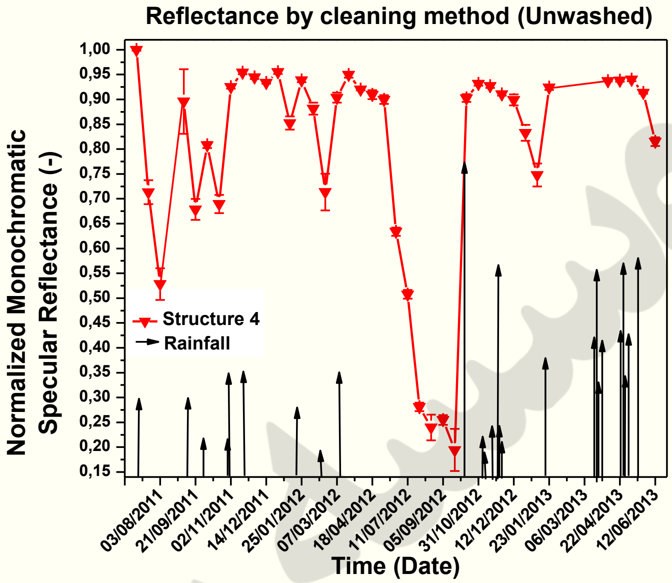

Fig. 6. Normalized monochromatic specular reflectance for the different cleaning methods applied, after cleaning (structure 4).

4. Conclusions

A deep study about the effectiveness of different cleaning methods, including natural cleaning, has been performed during 2 years in a semi-desert climate. Different cleaning methods were periodically applied to several reflector samples exposed in 4 separated test benches Monochromatic specular reflectance measurements were taken before and after applying the cleaning methods.

Reflectance differences between the measurements done before and after the cleaning application were more marked in summer seasons than in the rest of the year because soiling accumulated on reflector samples is considerably higher. On the other hand, during the winter seasons reflectance differences are really small because soiling accumulated on the reflector samples is quite little.

- If the number of passes applied with the high-pressure demineralized water method is highly enough (that is, 3 passes), the addition of a detergent does not implicate an increase of its effectiveness, because the average efficiency parameter obtained is 98.8 % without detergent and 98.6 % with detergent.
- The effectiveness of 2 passes in the method with the high-pressure demineralized water (average efficiency of 97.6 %) is a bit lower than the corresponding to 3 passes (average efficiency of 98.3 %). However, the cost of the method considerably increases with the number of passes.
- The method based on a steam device with a soft tissue was inefficient (average efficiency of 97.3 % in a rainy period).
- The cleaning method based on demineralized water and a brush has proved to be the most effective one because the average efficiency obtained was the highest in all the period where it was applied. It is not interesting to add detergent to the method based on brushing. In addition, in very dry periods, this method is the only effective one.
- In rainy periods, the high-pressure demineralized water method (200 bar and ambient temperature) is as effective as the method based on demineralized water and a brush.
- Results obtained with the pressure demineralized water at 150 bar and 50 ºC were slightly lower than the corresponding to high-pressure demineralized water (200 bar and ambient temperature) and demineralized water with a brush (average efficiency of 97.1 % against 97.8 %). However, a further economic analysis is required, because this method could to be cheaper.

In the structure where no artificial cleaning method was applied, reflectance showed a massive decrease in summer seasons, reaching values even lower than 0.20. However, just after summer seasons, reflectance was recovered up to around a 90 % of its maximum value thanks to the positive effect of the abundant rainfall.

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