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Article

Singular Spectrum Analysis of Pathogenic Microorganisms in a Sanitary Wastewater Treatment System

Ana Beatriz Alves de Araújo [1], Rafael Oliveira Batista [1,*], Stefeson Bezerra de Melo [2], Solange Aparecida Goularte Dombroski [1], Suedemio de Lima Silva [1], Antônio Gustavo de Luna Souto [3], Adler Lincoln Severiano da Silva [1], Daniela da Costa Leite Coelho [1], Fernanda Lima Cavalcante [4] and Daniel Valadão Silva [3]

1 Department of Engineering and Environmental Sciences, Federal University of the Semi-Arid Region (UFERSA), Mossoró 59625-900, RN, Brazil; beatrizufersa@gmail.com (A.B.A.d.A.); solangedombroski@ufersa.edu.br (S.A.G.D.); suedemio@ufersa.edu.br (S.d.L.S.); adler.lincoln@ufersa.edu.br (A.L.S.d.S.); daniela.coelho@ufersa.edu.br (D.d.C.L.C.)
2 Department of Exact Sciences and Information Technology, Federal Rural University of the Semi-Arid Region (UFERSA), Angicos 59515-000, RN, Brazil; stefeson@ufersa.edu.br
3 Department of Agronomic and Forestry Sciences, Federal University of the Semi-Arid Region (UFERSA), Francisco Mota, 572, Costa e Silva, Mossoró 59625-900, RN, Brazil; gusluso@hotmail.com (A.G.d.L.S.); daniel.valadao@ufersa.edu.br (D.V.S.)
4 Federal Institute of Education, Science and Technology of Rio Grande do Norte (IFRN), Campus Mossoró, Raimundo Firmino de Oliveira, 400, Conjunto Ulrick Graff, Mossoró 59628-330, RN, Brazil; fernanda.lima@ifrn.edu.br
* Correspondence: rafaelbatista@ufersa.edu.br

Abstract: The variation in the population of pathogenic microorganisms in wastewater over time can be predicted by single-spectral analysis, which outperforms conventional multivariate methods. This type of information is important for the performance of sewage treatment plants. The objective of this study was to monitor the variability of the population of microorganisms and the removal of microbiological attributes of sanitary wastewater in a treatment plant equipped with a septic tank and solar reactor. Effluent samples were collected monthly upstream of the septic tank and inside the solar reactor, and the effluent was exposed to solar radiation. Total coliforms and *Escherichia coli* were analyzed by means of descriptive analysis and singular spectrum analysis. Solar disinfection obtained bacterial inactivation levels of 99.94%, equivalent to 4 log units for the *Escherichia coli* population, and 99.45%, equivalent to 3 log units for the total coliform population. For the inlet effluent, the prediction showed a trend of growth alternating with periods of stability. For the outlet effluent, the prediction was able to provide regular data up to the first six months, showing error and overestimation of the data for the final six months of the study.

Keywords: environment pollution; mitigation; septic tank; sewage; solar reactor; temporal analysis

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1. Introduction

The legal framework for sanitation aims at the universalization of sanitary sewage, and 90% of the Brazilian population should have sewage collection and treatment by 31 December 2033 [1]. In 2022, about 56% of Brazilian households were connected to the sewage network, and only 52.2% of sewage was being treated, which represents a volume of 5.0 billion m^3 of treated sewage. However, sewage collection and treatment levels in the Northeast region of Brazil are only 31.4% and 34.3%, respectively, below the national levels [2].

In the Brazilian semi-arid regions, water scarcity and inadequate sanitation aggravate the problems of mortality and morbidity of human beings. Under these conditions, diseases such as diarrhea, dysentery, cholera, hepatitis A and typhoid fever are common [3]. Health threats caused by polluted waters generate widespread concern in the population.

Specifically, the high concentration of heavy metals, organic compounds, and pathogens contained in wastewater are threats to human health [4].

Inadequate wastewater treatment is a dangerous situation, not only because of the physicochemical contamination of water sources but also because of the risk of microbiological contamination and the transfer of antibiotic-resistant bacteria into the environment. Urgent modernization or construction of new wastewater treatment plants is needed to mitigate the increasing microbiological contamination of water from springs [5].

Regardless of the types of contaminants present in the water, the aim is to improve the technologies traditionally used in water treatment processes in order to ensure safe water supply to the population and quality effluent for agricultural reuse [6]. The septic tank is a technology most commonly used for wastewater pretreatment, and its basic function is to remove 60% to 80% of the non-soluble material [7].

An important complementary wastewater treatment process is solar radiation disinfection (SODIS), which is a simple, inexpensive, and sustainable domestic treatment suitable for low-income countries or emergency situations [8]. For efficient solar disinfection, characteristics such as type of effluent, reactor material, temperature and reactor size affect the treatment process.

When it comes to solar disinfection, according to Ayoub and Malaeb [9], among the contaminants investigated in their study, *Escherichia coli* (*E. coli*) showed the lowest resistance to ultraviolet A (UVA) radiation, with wavelengths between 320 and 400 nm, while total coliforms were the most resistant. Another interesting result obtained in the study is that the reactor waterproofed with aluminum foil showed more favorable conditions for the inactivation of pathogenic bacteria. Coating the reactor with aluminum foil can also increase the temperature and enhance solar disinfection.

The photoinactivation processes of solar disinfection can follow direct and indirect mechanisms and are strongly affected by the different spectral ranges of ultraviolet (UV) radiation and specific microbiological characteristics of pathogens; protozoa and viruses are mainly photoinactivated by direct endogenous mechanisms caused by the action of ultraviolet B (UVB) radiation, with wavelengths between 280 and 320 nm, while bacteria are damaged by direct and indirect endogenous processes through the action of UVA and UVB [9].

Aimed at bringing a differentiated contribution, the singular spectrum analysis (SSA) technique has been a method of time series analysis in full development. This non-parametric technique is used in a variety of fields, such as signal processing, finance, economics, image processing, meteorology, engineering, medicine, biology, and genetics [10].

Singular spectrum analysis has become a forecasting and preprocessing technique used in time series analysis, being exploited in several monitoring processes, given its greater application and superior performance compared to conventional multivariate methods, such as Principal Component Analysis (PCA) [11].

The capacity to extract relevant information from large datasets is, therefore, of utmost importance. In this context, SSA is a powerful analysis tool that has been gaining momentum [12].

In the treatment of sanitary wastewater involving solar radiation and temperature, the variability of the population levels of microorganisms is noticeable over time. Studying precisely the factors responsible for this variability allows for the generation of information that can improve the performance of sewage treatment plants and improve the quality of the treated effluent for disposal into the environment or for agricultural reuse. The use of SSA to analyze the microbiological attributes of sanitary wastewater allows the decomposition of a time series of data into components, thus allowing a selection of information to maintain the desirable components and remove the undesirable ones, enabling the prediction of scenarios, showing trends and suggesting periodicities.

In view of the above, the objective of the present study was to monitor the removal of microbiological attributes of sanitary wastewater in a treatment plant consisting of a septic tank and solar reactor and to obtain through singular spectrum analysis the behavior of this effluent through a prediction for a period of one year.

2. Materials and Methods

2.1. Experimental Area Location and Characterization

This study comprised the installation and monitoring of a system for the treatment and agricultural use of sanitary wastewater in an experimental area located near the Laboratory of Rural Constructions and Environment (LCRA) of the Federal Rural University of the Semi-Arid Region (UFERSA), located in the municipality of Mossoró, Rio Grande do Norte, Brazil, under the geographic coordinates 5°12′12.90″ South latitude, 37°19′26.97″ West longitude and 20 m altitude.

According to the classification proposed by Köppen-Geiger, the climate of the region is BSh, which is a dry, very hot climate with a rainy season in the summer extending to autumn, with very irregular rainfall, annual average rainfall of 794 mm, and average annual temperature of 26.50 °C [13].

The experimental area was selected because it has sufficient physical space for installing the system for the treatment and agricultural use of sanitary wastewater (Figure 1).

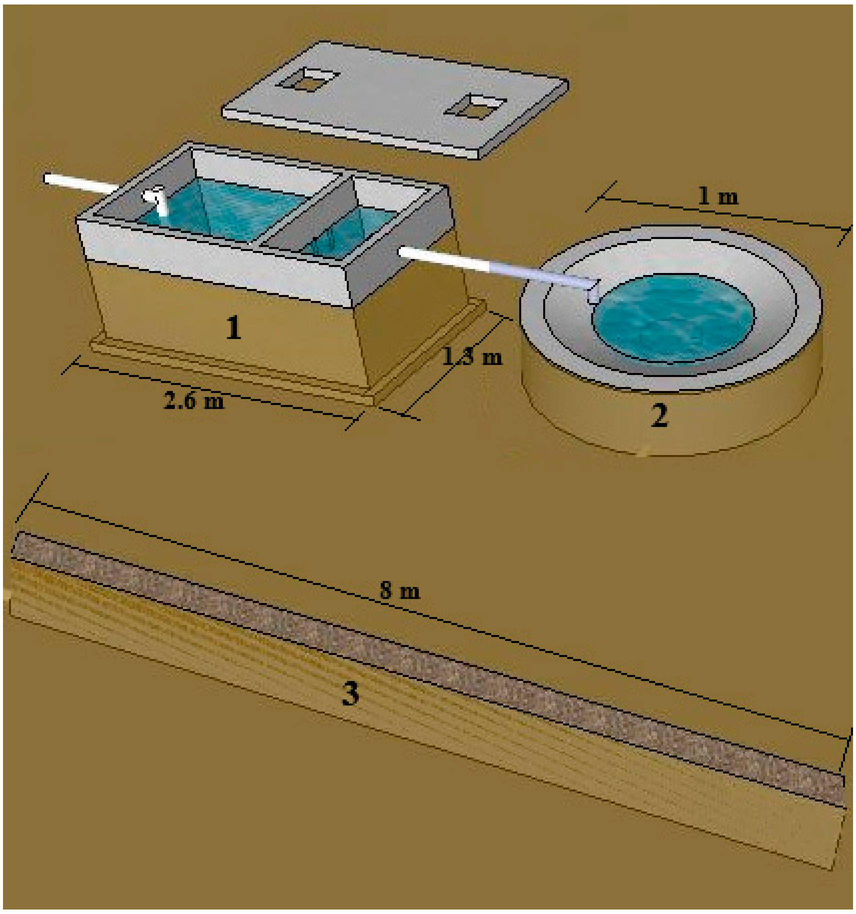


Figure 1. Diagram of three devices in the sanitary wastewater treatment system: septic tank (1), solar reactor (2), and an infiltration trench (3).

LCRA/UFERSA has a network that collects all wastewater generated in the building, as well as an equalization tank, with dimensions of 0.80 m long, 0.70 m wide and 0.25 m deep, for the homogenization of wastewater from the toilets and washbasins of the male and female bathrooms, as well as sinks of the Soil–Machine Interaction Dynamics Laboratory (LDISM), building's classroom, and Materials Testing Laboratory (LEM), and a water distiller installed at LDISM. It is estimated that LCRA/UFERSA has, on average, 61 temporary occupants per day, including professors, students, employees, and outsourced workers of UFERSA.

2.2. Description of the Sanitary Wastewater Treatment System

The sanitary wastewater treatment and agricultural use system consists of a septic tank, a solar reactor, and an infiltration trench designed according to the technical recommendations of both NBR 7229 [14] and NBR 13969 [15].

The septic tank was designed to receive a flow rate of 3.05 m^3 d^{-1}, produced by 61 temporary occupants under school conditions as described in the technical recommendations of NBR 7229 [14] and NBR 13969 [15]. In contrast, the solar reactor was designed to treat a maximum of 0.41 m^3 d^{-1} of sanitary wastewater following the recommendations of Cavalcante et al. [16] and Silva et al. [17].

Figure S1 (Supplementary Materials) shows photographic records of the ecological system for the treatment of sanitary wastewater, highlighting the two-chamber septic tank (Figure S1a), solar reactor (Figure S1b), and infiltration trench (Figure S1c). It should be noted that the equalization tank, septic tank, solar reactor, and infiltration trench were interconnected by PVC pipes with nominal diameters of 40 and 100 mm.

2.3. Septic Tank

The usable volume of the septic tank of 4.73 m^3 was estimated by the equation of NBR 7229 [14]:

$$Vu = (1000 + N \times (C \times T + K \times Lf))/1000 \quad (1)$$

where Vu is the usable volume of the septic tank in m^3, N is the number of people occupying the facility, C is the wastewater contribution in L $occupant^{-1}$ d^{-1}, T is the hydraulic detention in d, K is the sludge accumulation rate in days, and Lf is the sludge contribution in L $occupant^{-1}$ d^{-1}.

In the calculation of Vu, the values of 61 occupants, 50 L $occupant^{-1}$ d^{-1}, 0.83 d, 97 d and 0.20 L $occupant^{-1}$ d^{-1} were used for the parameters N, C, T, K and Lf, respectively.

The purpose of the septic tank is to collect and treat sludge and scum present in sanitary wastewater. This tank was built with two chambers in series, and the partition has three openings. Each opening is 0.10 m wide by 0.20 m high, positioned at 2/3 of the septic tank length. Each chamber has a circular opening with a 0.10 m nominal diameter on the surface of the tank for inspection, collection of effluent samples, and exhaustion of gases (Figure 1).

With a Vu of 4.73 m^3 and considering an internal width (W) of 1.30 m ($W \geq 0.80$ m), as recommended by NBR 7229 [14], and a usable depth (h) of 1.40 m ($1.20 \text{ m} < h < 2.20$ m) for a Vu of 4.73 m^3, also according to NBR 7229 [14], the internal length of the septic tank (Lng) of 2.6 m was finally calculated using the following equation:

$$Lng = Vu/(W \times h) \quad (2)$$

where Lng is the internal length of the septic tank in m, Vu is the usable volume of the septic tank in m^3, W is the internal width of the septic tank in m, and h is the usable depth of the septic tank in m.

Thus, the septic tank used in the present study was built with internal dimensions of 2.60 m long, 1.30 m wide and 1.40 m deep, using brick masonry, precast slab, and internal lining with waterproofing material.

2.4. Solar Reactor

The solar reactor was built in reinforced concrete in the shape of a pyramid trunk (Figure 1), with longest radius of 1.00 m, shortest radius of 0.25 m, and depth of 0.30 m, following the recommendations of Cavalcante et al. [16] and Silva et al. [17].

The solar reactor floor was waterproofed and covered with an asphalt blanket, with an aluminized finish, containing asphalt, polymers, and synthetic structuring agents in its composition, thus avoiding the infiltration of sanitary wastewater and allowing the reflection of sunlight, thus increasing the exposure of pathogenic microorganisms to UVA (320 to 400 nm) and UVB (280 to 320 nm) ultraviolet radiation.

According to Ayoub and Malaeb [9], when aluminum foil was applied to solar reactors, a higher quality of disinfection was obtained compared to solar reactors painted in black. Figure S2 (Supplementary Materials) shows the application of an asphalt blanket with an aluminized finish in the solar reactor.

This system performs tertiary treatment on sanitary wastewater, reducing the population level of total coliforms and *E. coli* due to the synergistic effect of temperature elevation and exposure to UVA and UVB ultraviolet radiation. The maximum height of the solar reactor of 0.30 m was not used in the present study, but a 0.10 m depth of sanitary wastewater for a period of 12 h, as proposed by Cavalcante et al. [16], in order to enhance solar disinfection. The equation below was used to obtain a volume of 0.14 m^3 of sanitary wastewater treated in the solar reactor.

$$V = ((\pi \times h)/3) \times (R^2 + R \times r + r^2) \quad (3)$$

where V is the usable volume of the cone trunk-shaped solar reactor in m^3, R is the radius of the larger base of the cone trunk-shaped solar reactor in m, r is the radius of the smaller base of the cone trunk-shaped solar reactor in m, and h is the height of the cone trunk-shaped solar reactor in m.

2.5. Infiltration Trench

The infiltration trench is a system for disposing of the treated effluent in the solar reactor that guides its infiltration into the soil. It consists of an ordered set with perforated piping enveloped by a gravel support layer [14]. Equation (4) was used in its sizing, and the surface area of the infiltration trench was 12 m^2, considering an infiltration coefficient of 130 L m^{-2} d^{-1} in the soil of the experimental area.

$$As = (N \times C)/Ci \quad (4)$$

where As is the surface area of the infiltration trench in m^2, N is the number of contribution units in inhabitants, C is the contribution of discharges in L $occupant^{-1}$ d^{-1}, and Ci is the infiltration coefficient in L m^{-2} d^{-1}.

This system was built with 8.0 m length (Figure 1) by 1.5 m width and 0.5 m depth, with PVC pipe with a nominal diameter of 100 mm and 0.01 m-diameter perforations, as per Figure S1c (Supplementary Materials). To minimize the obstruction of these perforations, the 100 mm-diameter pipe was enveloped with Gneiss gravel No. 1.

2.6. Monitoring of the Sanitary Wastewater Treatment and Agricultural Use System

2.6.1. Microbiological Attributes

In the monitoring of the performance of the ecological system for treatment and agricultural use of sanitary wastewater, 12 samplings of sanitary wastewater were carried out upstream of the septic tank (P1) and inside the solar reactor (P2), with monthly frequency between May 2018 and April 2019.

For the microbiological attributes, single samples were collected at P1 and P2 after 12 h exposure of the effluent to UVA and UVB ultraviolet radiation. During the period of sampling and transport to the laboratories, the single samples were preserved in an isothermal box at a temperature between 4 and 6 °C to minimize the alteration of biological attributes, following the recommendations of the Standard Methods for the Examination of Water and Wastewater [18].

Microbiological analyses were performed using sterile flasks with a volume of 100 mL at the Environmental Sanitation Laboratory (LASAM) of UFERSA. The choice of these indicators to evaluate the removal of pollutants and the inactivation of microorganisms was based on the studies conducted by Cavalcante et al. [16] and Silva et al. [17].

Identification and quantification of the population levels of total coliform (TC) and *Escherichia coli* were performed using the Colilert system (Idexx Laboratories Inc., Westbrook, ME, USA), which is employed for simultaneous detections and specific and confirmatory identifications of total coliforms and *E. coli*. The samples were mixed with the culture medium (Colilert), and after homogenization, they were transferred to a pack (Quanti-Tray) and sealed in a specific sealer. Then, the packs were incubated at 35 °C for 24 h.

The results were quantified by the Quanti-Tray 2000 Most Probable Number (MPN) statistical table. In the Colilert Quanti-Tray 2000 system, the presence of total coliforms (TC) is indicated by a reaction that changes the color of the reagent to yellow. Yellow wells indicate the presence of total coliforms. If *E. coli* is present, it can be confirmed by exposing total coliform-positive samples to type C ultraviolet radiation (100–280 nm), which reacts and emits blue fluorescence (Idexx Laboratories Inc., Westbrook, ME, USA).

2.6.2. Climatic Variables

The climatic variables' UV radiation and ambient temperature are factors that influence the population levels of pathogenic microorganisms in sewage exposed to atmospheric conditions. In addition, the effect of these two variables enhances the inactivation of these microorganisms; therefore, monitoring these variables is important in analyzing the performance of the treatment system.

In order to better characterize the climatic conditions of the municipality of Mossoró, RN, the records of the climatic variables were obtained using a UVM-30A ultraviolet ray sensor-type temperature sensor (Roxo/Gsens, China), which allows for the detection of the presence of UV radiation with wavelengths between 200 and 370 nm.

The temperature sensor was installed at the edge of the solar reactor, as can be seen in Figure S3 (Supplementary Materials), identifying temperature variations that occurred during the exposure of the effluent to UVA and UVB ultraviolet radiation. Measurements were taken every minute during the 12 h of exposure.

In the experimental area, the first rays of sunlight usually arrived at the solar reactor at 7 a.m. and were monitored until before sunset, around 4 p.m., thus ending the exposure to radiation on the first day; on the second day, the sensor was turned on again at 7 a.m., and the effluent was monitored for more 3 h, thus completing the 12 h of sun exposure. Through monitoring, it was possible to obtain maximum (Max), minimum (Min), and mean (Mean) values of ambient temperature (TAmb) in °C, water temperature (TWater) in °C, relative humidity (RH) as a percentage, and ultraviolet radiation (UR) in W m^{-2}, as can be seen in Tables S1 and S2 (Supplementary Materials). The mean and total ultraviolet radiation (Table S2 in Supplementary Materials) were calculated for 12 h of effluent exposure to UVA and UVB radiation.

2.7. Statistical Analysis

The values of the microbiological attributes of the sanitary wastewater collected at P1 and P2 were subjected to descriptive analysis and singular spectrum analysis (SSA). SSA is a non-parametric technique, i.e., used in time series analysis, which does not require prior knowledge of the behavior of the series, so the technique is based exclusively on data [19].

Thus, SSA is able to decompose a time series into principal components: trends, oscillations, and noise. A major advantage is the fact that the methodology is non-parametric, meaning that it can adapt to the underlying dataset, eliminating the need for pre-modeling. For this reason, it is also known as a model-less approach. The capacity to extract relevant information from large datasets is, therefore, of utmost importance. In this context, SSA is a powerful analysis tool that has been gaining momentum [12].

The main advantages of the SSA method in the field of dynamic time series can be attributed to the resolution of the following issues: finding trends of different resolutions, extracting components with seasonality, smoothing, simultaneous extraction of trends and complex periodicities, extracting periodicities with variable amplitudes, suppressing noise contributions, and extracting information from the components [20].

The basic SSA method for forecasting is composed of three complementary stages: decomposition, reconstruction, and prediction. Window length (L), which is used in the SSA embedding step, plays a key role in the SSA technique because the entire SSA procedure depends on this parameter. In the first stage, the series is decomposed into several components (trend, oscillations, and noise) [10]. The first eigenvalue and its respective eigenvector represent the general trend of the series, while the other eigenvalues represent the main oscillations within the series [21]. In the second stage, the noise-free series is reconstructed and thus used in the third and final stage for the prediction of new data points [22]. Figure S4 (Supplementary Materials) provides an overview of the SSA methodology for prediction.

The computational environment considered for the analysis was Caterpillar through SSA predictions. Caterpillar was developed by a group of researchers from the Department of Mathematics at St. Petersburg University in Russia called the GistaT Group. Information on the development of the SSA technique and the corresponding software is available on the group's official website. In the present study, a temporary license of version 3.4 was used, which is available for download on the homepage of GistaT Group [23].

3. Results

3.1. Climatological Variables

The mean values of air temperature, water temperature, ultraviolet radiation and relative humidity for the collection days are presented in Table 1, which showed that the mean air temperature and standard deviation for the 12 months of the study was 34 ± 2.17 °C, and the minimum and maximum values reached were, respectively, 25 °C and 43 °C. For water temperature, the mean and standard deviation was 35 ± 4.47 °C, with a minimum of 26 °C and a maximum of 51 °C. The mean relative humidity and standard deviation for the 12 months of the study was 53 ± 16.56%, varying with a minimum of 25% and a maximum of 99%.

Table 1. Climatological variables were monitored during the experimental period.

Variables	Mean	Std. Deviation	Minimum	Maximum
Air temperature (°C)	34.05	2.17	25.80	43.20
Water temperature (°C)	35.40	4.47	26.00	51.20
Ultraviolet radiation (W m^{-2})	714.25	90.03	104.00	1100.00
Relative humidity (%)	53.64	16.56	25.30	99.90

In the total period of exposure to solar radiation (12 h from 7:00 a.m. to 4:00 p.m. on the first day and from 7:00 a.m. to 10:00 a.m. on the second day), the mean and standard deviation ultraviolet radiation for the 12 months of the study was 714.25 ± 90.03 W m^{-2}, and the minimum and maximum values reached were 104.00 W m^{-2} and 1100.00 W m^{-2}, respectively.

3.2. Descriptive Analysis of Microbiological Attributes

The *E. coli* and TC variables showed significant differences between P1 and P2 effluents, as can be seen in Table 2.

Table 2. Microbiological variables of effluent samples collected upstream of the septic tank (P1) and inside the solar reactor (P2).

Variables	P1		P2		Removal	P
	Mean	±sd	Mean	±sd	%	5% **
E. coli (MPN 100 mL^{-1})	1.96×10^6 a	2.01×10^6	3.99×10^2 b	4.10×10^2	99.94	0.0027
TC (MPN 100 mL^{-1})	4.55×10^6 a	5.93×10^6	4.24×10^3 b	4.07×10^3	99.45	0.0144

Notes: TC—Total coliforms. ** Different lowercase letters in the columns differ from each other by the *t*-test at 5% probability (P) level and standard deviation (±sd).

After sun exposure to sanitary wastewater for a period of 12 h, an improvement was observed in its microbiological quality, with a reduction of 99.94% in the *E. coli* population level. The mean population level of *E. coli* for the P1 effluent was 1.96×10^6 MPN 100 mL^{-1}, and the mean population level for the P2 effluent was 3.99×10^2 MPN 100 mL^{-1}, with a mean inactivation of 4 log (Table 2).

The mean total coliform population for the P1 effluent was 4.55×10^6 MPN 100 mL^{-1}, and the mean total coliform population for the P2 effluent was 4.24×10^3 MPN 100 mL^{-1}, which corresponded to a reduction of 99.45% in the population level, with a mean reduction of 3 logarithmic units (Table 2).

3.3. Time Series Analysis

As the present study was conducted with 12 samplings, the size of the window L was defined in the embedding phase as 6. Thus, the descending order of the singular eigenvectors was obtained, with the components that represent the variable total coliforms for the inlet effluent (P1). The first component forms 41.69% of the data, being larger than the other eigenvectors, representing the general trend of the series, and the eigenvectors from 2 to 5 show the oscillations of the original time series, with 22.19%, 21.29%, 6.66%, and 6.28% of the data formation, respectively (Figure S5 in Supplementary Materials).

After the decomposition of the original time series into the sum of independent and interpretable components, the time series is reconstructed for the variable total coliforms of the P1 effluent (Figure 2a). The reconstruction of the time series for the variable total coliforms in the P1 effluent allowed the generation of a noise-free series, concentrating the elements with similar characteristics in order to organize them in a homogeneous group.

In the prediction for the variable total coliforms in P1, a variation above zero was obtained, with a cyclical fluctuation and moments of stability alternating with peaks of small growth for the predicted months.

It is possible to identify points that represent the prediction months for the period of one year with the behavior of total coliforms in the P1 effluent (Figure 2b).

For the variable total coliforms of the outlet effluent (P2), the descending order of the singular eigenvectors with the principal components was obtained. The first component explains 65.35% of the data, which is larger than the others representing the general trend of the series. The eigenvectors from 2 to 5 show the oscillations of the original time series, with 17.22%, 12.87%, 3.62%, and 2.85% of the data formation, respectively (Figure S6 in Supplementary Materials).

By decomposing the original time series of the variable total coliforms for the P2 effluent, it was possible to obtain the reconstructed and noise-free time series, which was used to generate the prediction (Figure 3a).

The prediction of the behavior of the P2 effluent for the variable total coliforms for one year was performed after the reconstruction of a smooth time series (Figure 3b). In the first six months, the prediction model remained consistent, while in the other months, the model showed extreme values with zeros and was not able to make the prediction for the P2 effluent.

For the variable *E. coli* of the P1 effluent, the eigenvectors are represented in descending order, with the first component explaining 49.45% of the data, which is larger than the other eigenvectors that represent the general trend of the series. The eigenvectors from 2 to 5 show the oscillations of the original time series, with 16.79%, 13.47%, 11.02%, and 7.01% of the data formation, respectively (Figure S7 in Supplementary Materials).

Figure 4a shows the representation of the original data as well as the noise-free reconstructed time series after decomposition for the variable *E. coli* of the P1 effluent.

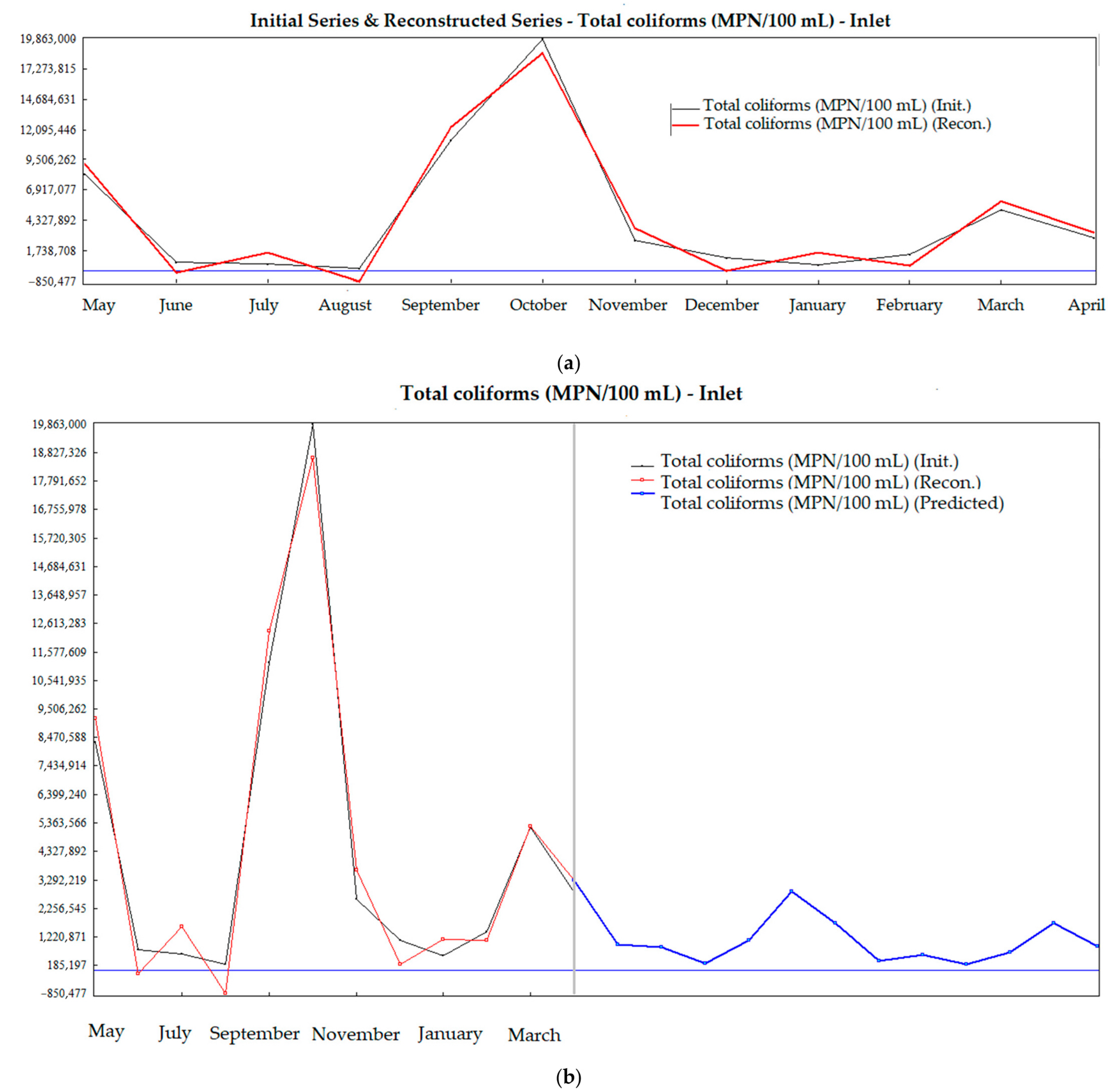
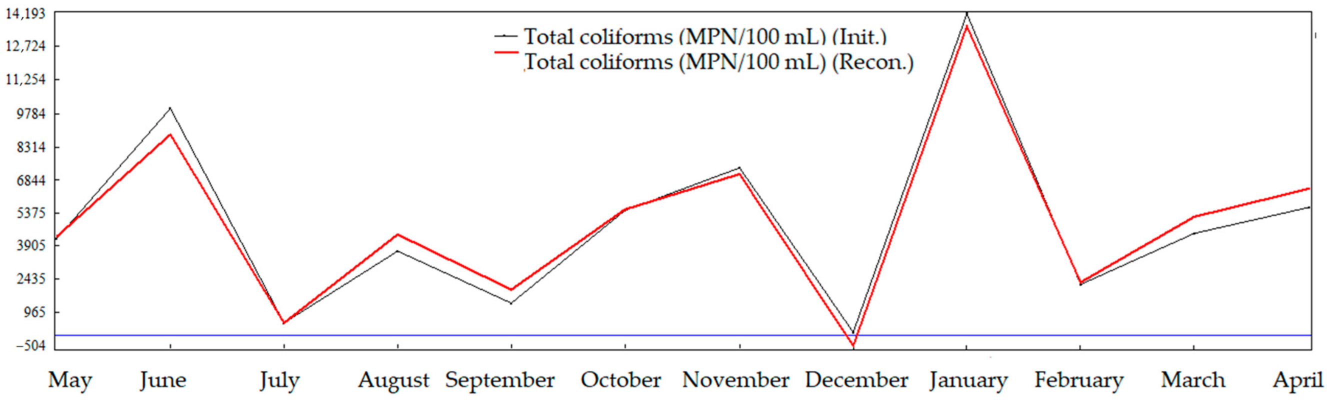


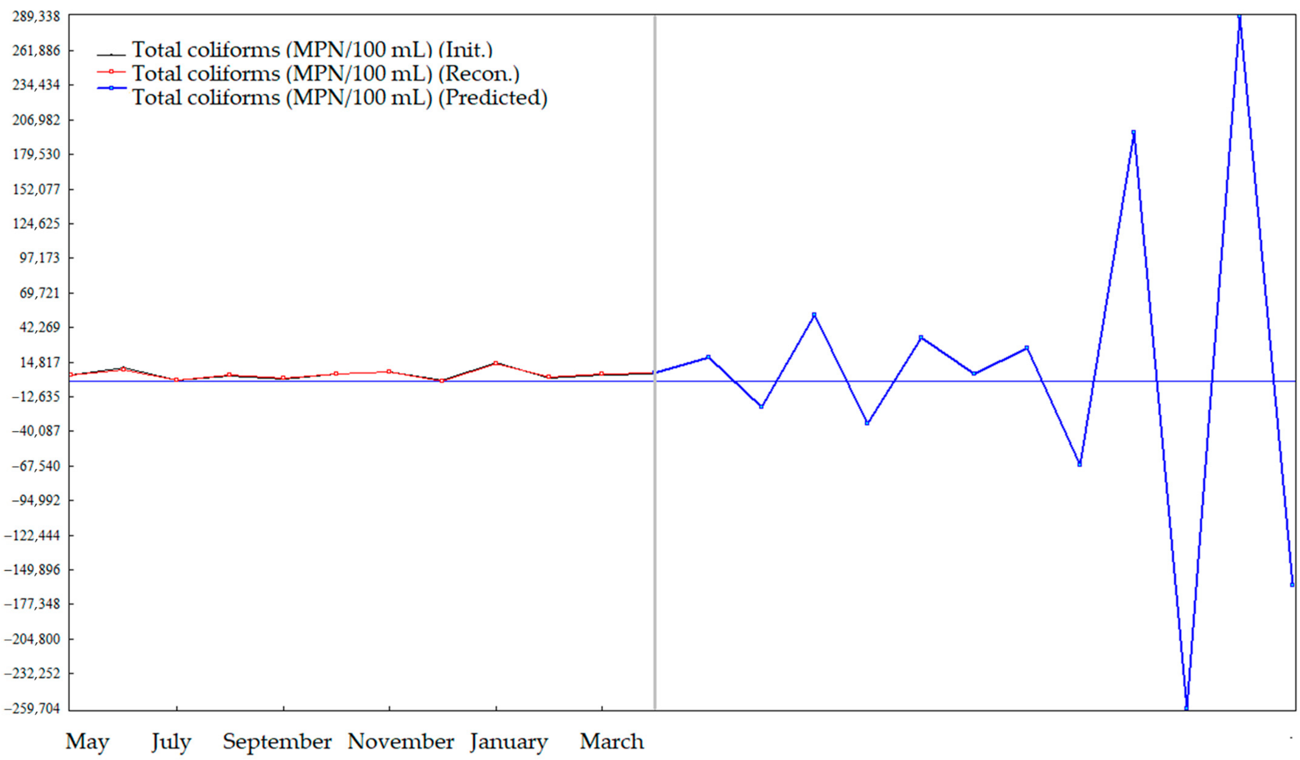
Figure 2. Original data and reconstructed time series for the variable total coliforms of the inlet effluent (**a**) and prediction of the behavior of the variable total coliforms of the inlet effluent for the period of one year (**b**).

Figure 4b shows the prediction of the behavior of the variable *E. coli* of the P1 effluent for the period of one year. Points representing the months of prediction can be identified in Figure 4b, with variation above zero and fluctuations between growth and decay peaks for the behavior of the effluent in the future.

For the variable *E. coli* of the P2 effluent, the eigenvectors are represented with the first component alone, explaining 68.68% of the data, as it is larger than the other eigenvectors that represent the general trend of the series. The eigenvectors from 2 to 5 show the oscillations of the original time series, which are 17.37%, 10.24%, and 1.94% of the data formation, respectively (Figure S7 in Supplementary Materials).



(**a**)



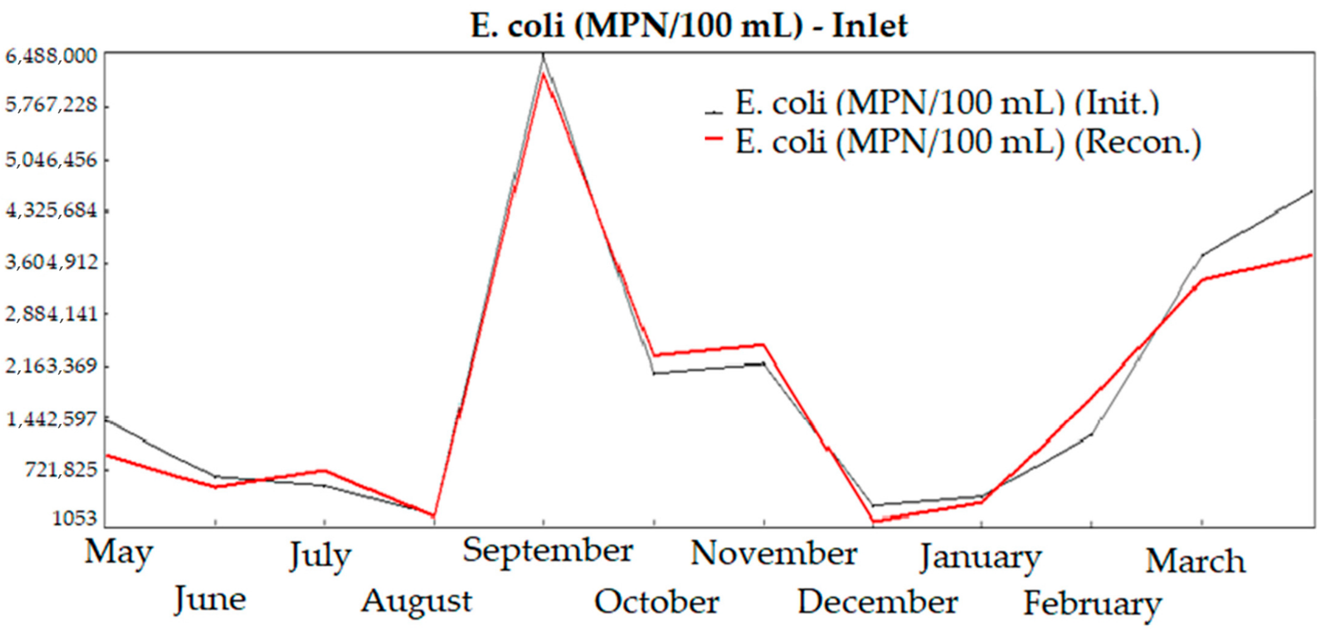
(**b**)

Figure 3. Original data and reconstructed time series for the variable total coliforms of the outlet effluent (**a**) and prediction of the behavior of the variable total coliforms of the outlet effluent for the period of one year (**b**).

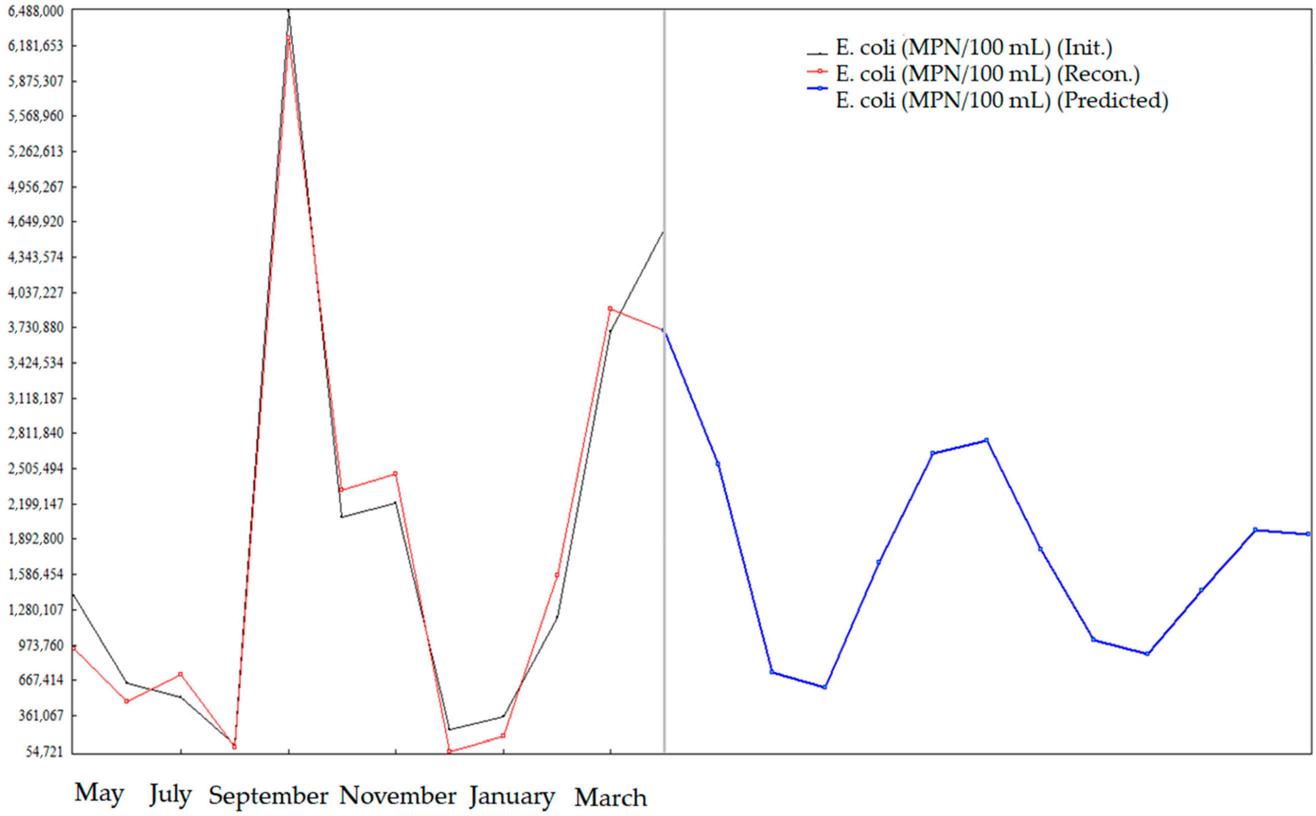
After the decomposition of the original time series into additive components, the reconstructed time series for the variable *E. coli* of the P2 effluent was obtained. After this step, the original series is reconstructed without noise.

Figure 5a shows the representation of the original data and the deconstructed and reconstructed time series for the variable *E. coli* in the outlet effluent.

In the prediction for the period of one year of the behavior of *E. coli* of the P2 effluent, it is possible to identify that the model remained stable in the first six months and showed errors in the other months, generating an overestimated result, which tended to resemble an increasing line, which represents the prediction of the behavior of the variable *E. coli* of the outlet effluent, for a period of one year (Figure 5b). This result can be explained by the fact that the values of *E. coli* in the P2 effluent became lower and more constant during the 12 months of collection after treatment with solar disinfection.



(**a**)



(**b**)

Figure 4. Original data and reconstructed time series for the variable *E. coli* of the inlet (**a**) and prediction of the behavior of the variable *E. coli* of the inlet effluent for the period of one year (**b**).

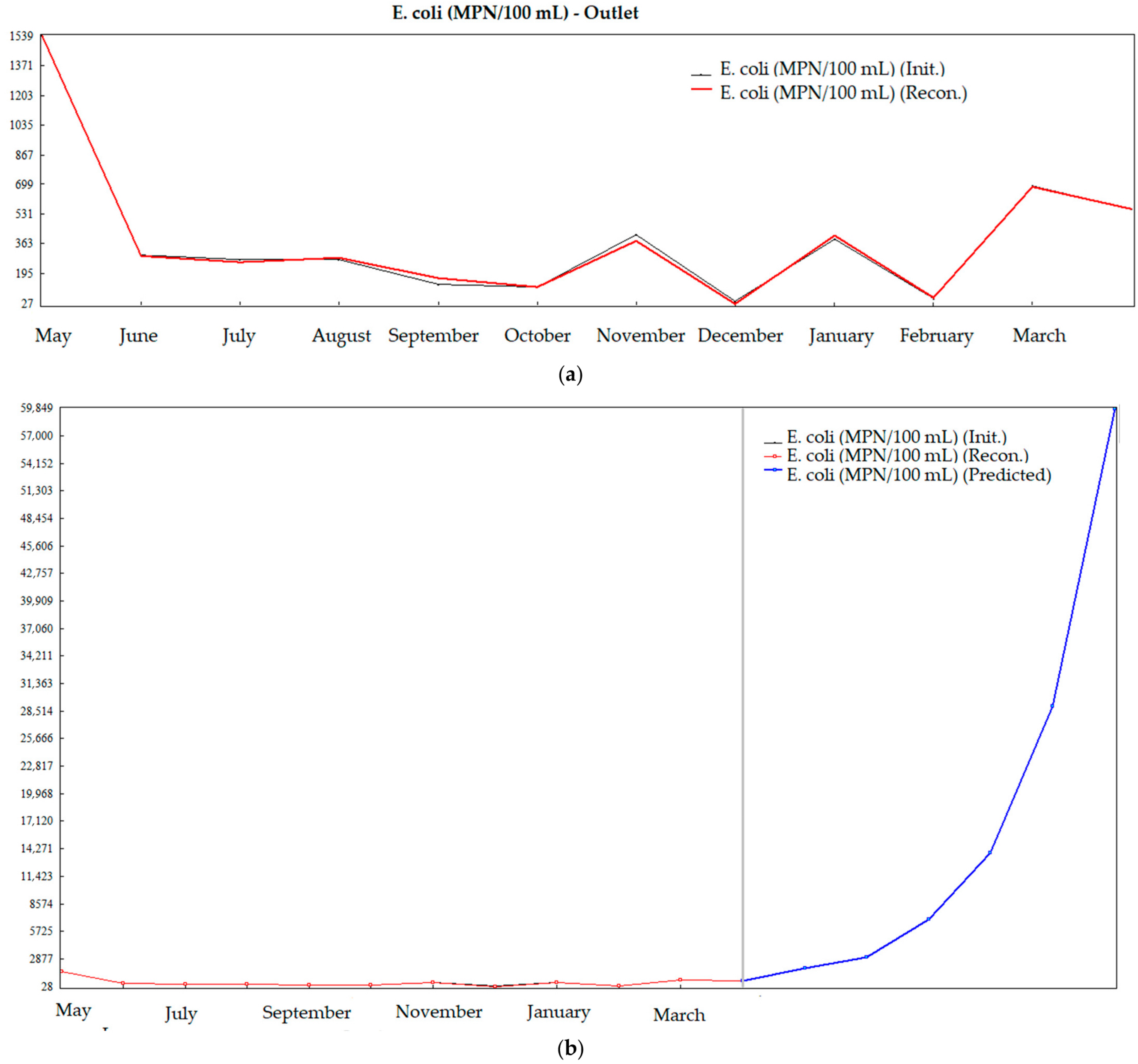


Figure 5. Original data and reconstructed time series for the variable *E. coli* of the outlet effluent (**a**) and prediction of the behavior of the variable *E. coli* of the outlet effluent for the period of one year (**b**).

4. Discussion

4.1. Effect of Reactor Waterproofing on the Disinfection Process

The solar reactor was waterproofed with an asphalt blanket with an aluminized finish, so it is understood that reflection surfaces (provided by shiny surfaces of reflective panels) influence water temperature and exposure to ultraviolet rays [24]. The average temperature of wastewater in the solar reactor ranged from 26.00 to 51.20 °C during the experimental period (Table 1). Heat treatment is one of the oldest and simplest methods used to disinfect sewage, as exposure to high temperatures can result in the denaturation or coagulation of vital cellular components, causing loss of viability [25].

As observed by McMichael et al. [26] in their experiment, total coliforms reached undetectable levels within 12 h of exposure to temperatures ranging from 27 to 46 °C, occasionally exceeding 50 °C, with the fastest inactivation rate at the highest temperature. According to Fernandes et al. [24], sample temperatures above 45 °C enhance solar disinfection. In the present study, there was no synergistic effect between ultraviolet radiation and temperature (heat) throughout the experimental period, thus leading to a reduction in the efficiency of solar disinfection. In this study, disinfection can be attributed more to the effect of ultraviolet radiation since sample temperatures above 45 °C occurred only in the months of June 2018 and April 2019 (Table S1 in Supplementary Materials), requiring further studies of devices that cause an increase in the temperature of the wastewater treated in the solar reactor.

Solar disinfection in sanitary wastewater applied in the different seasons of the year showed that, with the increase in radiation in the summer, this inactivation occurred between radiations of 200 W m^{-2} to 1200 W m^{-2}, but the incidence of 1200 W m^{-2} proved to be necessary to prevent the bacteria from growing again; when the irradiance is below 900 W m^{-2}, there is a possibility of a rebound effect and new growth of bacteria. In addition, faster inactivation was observed at higher temperatures [27].

Cloudiness is a factor that interferes with the performance of the solar reactor since reducing the dose of UV radiation requires increasing the time of exposure to solar radiation. Similarly, physical parameters of sewage, such as turbidity and color, can also reduce the dose of UV radiation, influencing the efficiency of the inactivation of microorganisms in the solar reactor [17,24].

In solar disinfection, the reduction of the population of pathogenic microorganisms occurs through the combined action of UV and infrared radiation from the sun. UV radiation promotes the modification of the DNA of microorganisms, and infrared radiation causes the water to heat to a temperature above 50 °C, thus making the medium incompatible with the development of most pathogenic microorganisms. The germicidal action of UV radiation is associated with the structural changes it causes in the DNA of cells, a consequence of photochemical reactions triggered by the absorption of radiation by the molecules that make up DNA [18,24]. Furthermore, with disinfection by UV radiation, the pH value affects the solubility of metals and carbonates. It is worth noting that a neutral pH offers optimal conditions for the development of bacteria, but pH values classified as acidic or alkaline can affect these microorganisms [24].

4.2. Effluent Quality Indicators

The World Health Organization (WHO) indicates that the quality of the effluent should reach values $\leq 10^3$ MPN 100 mL^{-1} for *E. coli*, thus allowing for unrestricted agricultural reuse [28]. In their study, Munasinghe-Arachchige et al. [29] used a solar reactor to inactivate pathogenic bacteria in wastewater and achieved an average reduction of 5.5 log for *E. coli*, proving the efficiency of disinfection.

In Brazil, there are still no national parameters and standards for agricultural reuse established for sanitary wastewater. However, this information exists for some Brazilian states, such as the state of Ceará in the semiarid region, which has Coema Resolution No. 02/2017, which presents parameters and standards for agricultural and forestry reuse. This resolution provides for the absence of thermotolerant coliforms in sanitary wastewater treated for fertigation of crops consumed raw and $\leq 10^3$ MPN 100 mL^{-1} of thermotolerant coliforms for fertigation of other crops [30].

When analyzing sanitary wastewater, O'Dowd and Pillai [27] found total coliform inactivation of four logarithmic units, showing the effectiveness in disinfection and decontamination of the effluent, especially with more resistant microorganisms, and pH, temperature and radiation play key roles in the efficiency of this process.

In the present study, solar disinfection reduced the population level of *E. coli* in the treated wastewater after 12 h of exposure to UV radiation to an average value of 3.99×10^2 MPN 100 mL^{-1} (Table 2), a value lower than the WHO [28] standard and what is found in the Brazilian semiarid region [30].

4.3. Singular Spectrum Analysis (SSA)

To analyze the structure (Figure S5 in Supplementary Materials), there is no point in choosing a window length greater than half of the set [30]. Similar to PCA, the idea of SSA is to decompose a time series into components. The goal, therefore, is to keep components that have desired properties and filter out components that have undesired Properties [22].

SSA is capable of decomposing a time series into the principal components of trend and oscillations, making it possible to signal the extraction and reduction of noise [12]. In the reconstruction stage (Figure 2a), interpretable components are reconstructed and can be used to predict new data points [10].

With the reconstruction of the time series without noise, it is understood that a model was constructed, thus allowing the prediction of the behavior of total coliforms for the P1 effluent. According to Aguilar et al. [19], a prediction can only be made if a model has been constructed. The model should be derived from the data or at least checked against the data. When using SSA to obtain results on the evolution of COVID-19 in some countries, Kalantari [10] also found a periodic structure with an evident upward trend in some countries, alternating with countries where the prediction showed some stability.

It was observed that the model was not able to generate a prediction of the behavior of the *E. coli* variable for a period of one year (Figure 3b) due to insufficient data. This result indicates that the experiment should be repeated with a larger time series. And that the ideal prediction for this volume of data is 4 to 6 months. Longer prediction periods require more data, i.e., a larger time series. Kalantari [10] also found a deficiency in his study when providing 40 days ahead point forecasts for the top ten countries affected by COVID-19, using data from eight months of the pandemic for prediction. This author obtained negative values that clearly made no sense, and to solve this problem, he considered the negative values as missing data.

The contributions of SSA components to a complex process allow the creation of a simplified statistical model to remove the noise associated with observation conditions [31]. Noise filtering is based on the removal of singular vectors with small eigenvalues from the decomposition [31].

The inability of the model to predict the behavior of *E. coli* during the one-year evaluation period (Figure 5b) may be associated with statistical errors in the SSA model, as found by Dabbakuti et al. [20], with overestimated values for the analysis of ionospheric variability, highlighting that time series data are often characterized by the existence of significant noise, and filtering this noisy data is considered one of the most challenging tasks when analyzing time series data modeling and forecasting.

According to Kalantari [10], highly right-skewed time series have a high probability of extreme values. The SSA application to hydrological data fields provided filtering of faulty values and improved the quality of interpolation and data smoothing, providing a reliable statistical averaging for a data volume consisting of 51,300 measurements, which were obtained every 2 min over a period of 3 months [31].

5. Conclusions

Solar disinfection of sanitary wastewater obtained bacterial inactivation levels of 99.94%, equivalent to 4 log units for the *E. coli* population, and 99.45%, equivalent to 3 log units for the total coliform population, promoted by the synergy between temperature and ultraviolet radiation.

The present study is a pioneer in the use of singular spectrum analysis to predict the behavior of treated sanitary effluent in the semi-arid region, bringing the possibility of optimizing the analysis and time management processes. For the inlet effluent, the behavior of the *E. coli* and total coliform population levels for one year predicts that this effluent will have an upward trend alternating with stable cycles.

The behavior of the *E. coli* and total coliform population levels for the outlet effluent showed a tendency to error and overestimation of the final data when predicting a volume of data for the period of one year, with stable and consistent data for the evaluation of a prediction period of up to six months. This study requires a longer time series so that the prediction of the outlet effluent can be performed for a period of one year. The recommendation is to conduct a study with a larger volume of samples.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16192754/s1. Figure S1. Images of the sanitary wastewater treatment system, highlighting the two-chamber septic tank (a), solar reactor (b), and infiltration trench (c); Figure S2: Application of asphalt blanket with aluminized finish in the solar reactor; Figure S3: UVM-30A ultraviolet ray sensor-type temperature sensor (a and b); Figure S4: Stages of Singular Spectral Analysis (SSA) methodology for prediction; Figure S5: Scatter plots of the paired harmonic eigenvectors for the variable total coliforms of the inlet effluent (P1); Figure S6. Scatter plots of the paired harmonic eigenvectors for the variable fecal coliforms of the outlet effluent; Figure S7. Scatter plots of the paired harmonic eigenvectors for the variable *E. coli* of the inlet effluent; Figure S8. Scatter plots of paired harmonic eigenvectors for the variable *E. coli* of the outlet effluent. Table S1: Summary of climate data for the period from May 2018 to April 2019, for the days of collection; and Table S2. Solar radiation measured from May 2018 to April 2019 for the days of collection.

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