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Aqualuz: a new solar disinfection device for treatment of cistern water

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ABSTRACT

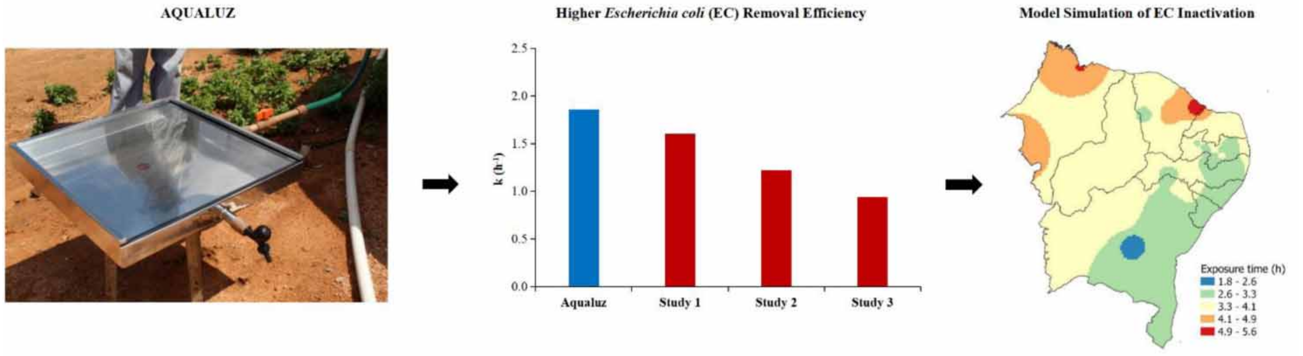
We conducted field, laboratory and modeling studies to evaluate the efficiency of a new solar disinfection (SODIS) device called Aqualuz for the removal of *Escherichia coli* (EC) from cistern water in the Brazilian semiarid, for different solar exposure–water temperature conditions. The results indicated EC contamination (100–300 MPN/100 mL) in all tests performed. As compared to the literature, lower exposure times (2.5–4.0 h) and solar radiations (250–410 W/m^2) were sufficient for EC elimination. Then, assuming the complete-mix approach and first-order kinetics, it was possible to adjust EC decay rate constants (*k*) considering three different models: constant *k*-value, *k* as a function of water temperature and a new formulation for *k* as a function of both solar radiation and water temperature. All models performed well with normalized root mean squared logarithmic error (NRMSLE) lower than 20%, but the best fitting was obtained with the new approach. A new relationship between solar radiation and water temperature was also obtained, which allowed model simulations of EC decay for 34 municipalities in the Brazilian northeast, resulting in a color map for the region depicting the exposure periods of 1.8–5.6 h for reaching a 3-log reduction.

Key words: bacterial decay, drylands, *Escherichia coli*, solar water disinfection, water quality

HIGHLIGHTS

- We conducted field, laboratory and modeling studies to evaluate the efficiency of a new solar disinfection device called Aqualuz for the removal of *Escherichia coli* (EC) from cistern water in the Brazilian semiarid.
- We carried experiments in different solar exposure-water temperature conditions.
- Assuming the complete-mix approach and first-order kinetics, it was possible to adjust EC decay rate constants (k).

GRAPHICAL ABSTRACT



1. INTRODUCTION

The availability of water is essential for public health, economic and social development. In this context, the semiarid region in the northeastern Brazil is characterized by a critical situation, as approximately 15 million inhabitants in the rural areas lack appropriate water supply infrastructure (Aleixo *et al.* 2016; Santos & de Farias 2017; IBGE 2020). To minimize this issue worldwide, the collection and use of rainwater is seen as a suitable remedy for adverse effects of drought among small-scale farmers (Odhiambo *et al.* 2021). In Brazil, since the One Million Cisterns Program (P1MC) created in 2003, more than 1.5 million cisterns has been implemented in this region, which are considered a simple and inexpensive social technology, capable of storing rainwater for rural families that are most affected by water scarcity (Doss-Gollin *et al.* 2016). The use of cisterns, however, requires caution, as the stored water may be contaminated with *Escherichia coli* (EC). Previous studies have shown that most cisterns evaluated in diverse regions of the globe present water quality issues (Crabtree *et al.* 1996; Jordan *et al.* 2008; Abbasi & Abbasi 2011; Ahmed *et al.* 2011; Al-Salaymeh *et al.* 2011; Palta *et al.* 2016; Leong *et al.* 2017; Ayed *et al.* 2018). This problem is even more severe in the Brazilian northeast, where above 90% of cistern water samples presented EC contamination (Souza *et al.* 2011; Xavier *et al.* 2011) and thus were considered inadequate for human consumption (WHO 2019).

A simple alternative to treat water for human consumption is solar disinfection (SODIS), which uses UV radiation to inactivate pathogens present in the water. Although, technically, SODIS can use glass containers, due to the greater weight, fragility and expense of this material, traditionally, users tend to reuse polyethylene tetraphlanate (PET) bottles – mostly of 1.5 or 2 L – or even plastic bags, since these resources are more easily accessed by lower income communities (Acra *et al.* 1984; Wegelin *et al.* 1994; Reed 1997; Sommer *et al.* 1997; Oates *et al.* 2003; Dessie *et al.* 2014; Jin *et al.* 2020). Previous studies indicated exposure times required for 100% of pathogen removal spanning from about 3 to 48 h, depending on the intensity of sunlight, pathogen concentration, turbidity and cloud cover conditions (McGuigan *et al.* 2012; Haider *et al.* 2014). However, it is advisable that solar disinfected water should be consumed within 24 h to minimize the risk of bacteria re-growth (Vivar & Fuentes 2016). To clarify the advances of SODIS technology worldwide and demonstrate the space conquered by these devices in the last decades as a solution for access to drinking water by diffuse communities, an overview of the SODIS method based on 20 years of research and practice is presented by Luzi *et al.* (2016). In this study, we present a new SODIS technology called Aqualuz for treating cistern waters (Beserra 2017). This technology consists of a stainless-steel box covered with a glass sheet, which is connected to the cistern through a pipeline equipped with a filter to reduce turbidity. Because of the rectangular and slim shape of the box, it is expected that Aqualuz present an EC removal efficiency higher than conventional SODIS devices. It has been installed in dozens of cisterns throughout the Brazilian semiarid region to promote water treatment at a rate of about 30 L/day. Preliminary laboratory tests revealed absence of EC after 2–4 h of operation in sunny days. As a result, the technology has been internationally recognized through awards, such as the UN Water Challenge, at the World Water Forum in 2018 and the Young Champions of the Earth, also by the UN in 2019 (https://www.youtube.com/watch?v=MZ7GU2dqIdU). However, in order to optimize its operation and predict its efficiency in different locations, it is necessary to evaluate the time evolution of EC inactivation for different solar exposure–water temperature conditions.

Apart from the SODIS technology itself, it is also important to understand the processes involved in pathogen removal from the water. Several studies reported that coliform concentration levels in natural waters are affected by climatic factors (Bravo *et al.* 2017; Fraga *et al.* 2020). Thus, modeling of bacterial decay under different climatic conditions can help not only improve the understanding of coliform survival in water, but also provide predictive information to support decision-making for effective public health management (Cho *et al.* 2012). Previous mathematical models for coliform dynamics in water usually assume the complete-mix approach and first-order kinetics, together with a temperature correction term (Thomann & Mueller 1987; Chapra 2008; Cea *et al.* 2011; Bravo *et al.* 2017; Fraga *et al.* 2020). Nevertheless, the modeling of bacterial decay can also be described as a function of other factors such as water depth, pH, salinity, turbidity and/or solar radiation, as suggested by many authors such as Mancini (1978), Auer & Niehaus (1993), McCorquodale *et al.* (2004), Kashefipour *et al.* (2006), Manache *et al.* (2007), Cho *et al.* (2012) and Whitehead *et al.* (2018). On the other hand, the literature accounts for little research on modeling solar water disinfection (Dessie *et al.* 2014; Haider *et al.* 2014; Carvajal 2015), all studies based on the complete-mix approach and first-order kinetics and considering conventional SODIS devices. Only a few studies proposed new mathematical models for solar water disinfection, such as those of Castro-Alférez *et al.* (2017, 2018), Haider *et al.* (2014), Wegelin *et al.* (1994), in order to account for solar radiation–water temperature synergy and different conditions of turbidity, cloud cover, among other factors. However, no general model that covers all the system designs and operational conditions has been proposed in the literature.

In the present paper, we carried out field, laboratory and modeling studies to test the hypotheses that Aqualuz has EC removal efficiencies higher than those of conventional SODIS devices and that the process of inactivation of coliforms can be described by assuming complete mixing and first-order kinetics, considering three different models: a constant decay rate, a decay rate constant as a function of water temperature and a new formulation for the decay rate as a function of both solar radiation and water temperature. The models were evaluated for different solar exposure–water temperature conditions. Hence, the best-fitting model together with a new relationship between solar radiation and water temperature were used to compare the EC removal efficiencies obtained with Aqualuz and other SODIS devices. It was also possible to predict scenarios of required exposure times to achieve different levels of removal efficiency for several locations in the Brazilian semiarid region. The results from this study will potentially improve water quality management in rural cisterns and can also be extended to other regions by using the proposed model and fitted relationships.

2. MATERIALS AND METHODS

2.1. Study area

The field surveys were conducted in the district of Croatá in the municipality of São Gonçalo do Amarante (latitude −5 °47′36″ and longitude −35 °19′44″), State of Ceará, Brazilian semiarid region, as shown schematically in Figure 1. The municipality has a population of ~49 k inhabitants and is characterized by low-sanitation coverage (26.3%) and recurrent hospitalizations due to diarrhea (0.4‰) (IBGE 2020). Since São Gonçalo do Amarante is inserted in the Brazilian semiarid, it is a beneficiary of the already mentioned P1MC.

2.2. Experimental procedure

Aqualuz is a SODIS device developed by the company Safe Drinking Water for All – SDW (Beserra 2017). As shown in Figure 2, the equipment consists of a stainless-steel box with external dimensions of 57 cm × 57 cm × 8 cm (water depth

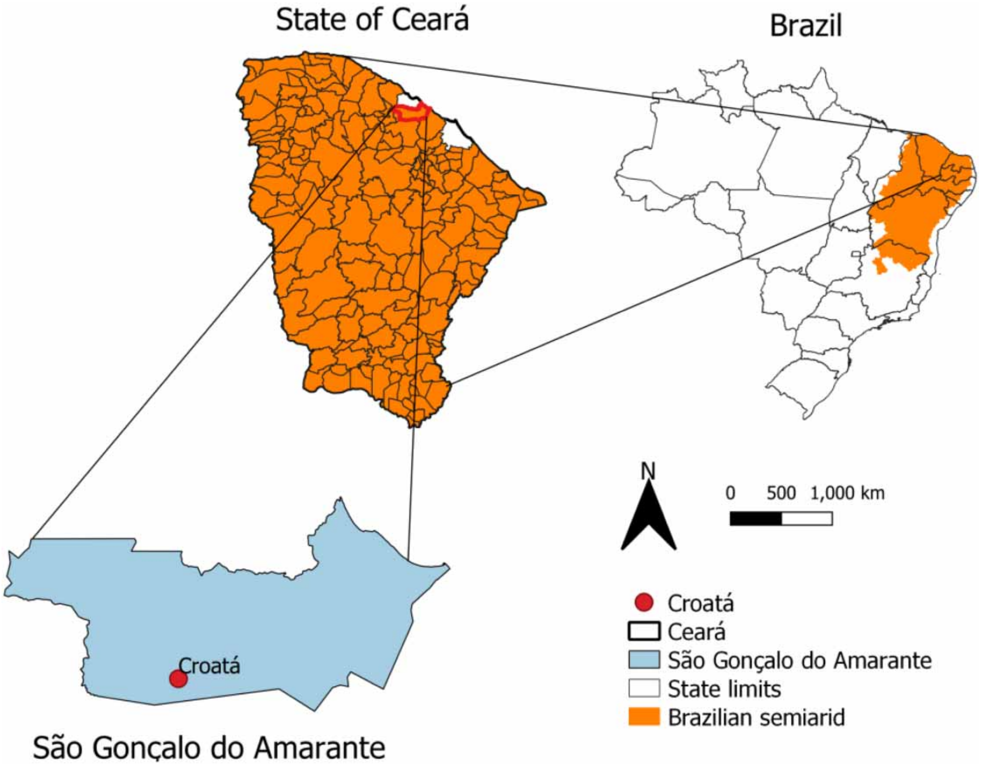


Figure 1 | Location of the district of Croatá in the municipality of São Gonçalo do Amarante (latitude −5 °47′36″ and longitude −35 °19′44″), in the state of Ceará, Brazilian semiarid region.

Figure 2 | Aqualuz unit used for removal of EC from cistern water using SODIS. External dimensions of 57 cm × 5 cm × 8 cm^3 (water depth of 5 cm).

of 5 cm), with a glass cover and an inlet pipe containing a control valve and a filter to reduce turbidity from the cistern water, which is pumped manually. The glass cover is 3 mm thick which guarantees protection against the entry of particulate material into the equipment, while ensuring greater resistance and allowing the entry of UV radiation. Aqualuz also has an indicator sticker that displays the water temperature range in different colors.

The field studies were carried out on April 22, 29 and 30, 2019 in an Aqualuz unit installed in a private cistern in the district of Croatá (see Figure 1), which presented different levels of solar exposure: partly cloudy/sunny, sunny and rainy days, respectively. For each day, nine water samples were collected from the Aqualuz unit from 7:00 to 11:00 am with intervals of 30 min. Turbidity was low (<5 NTU) in all the tests, as expected in cistern systems in the Brazilian semiarid (Souza *et al.* 2011). The concentrations of total coliforms (TC) and EC were determined in the Laboratory of Sanitation (LABOSAN) at the Federal University of Ceará – UFC using the Colilert test (IDEXX Laboratories, Portland, ME, USA), as described by Fraga *et al.* (2020). The results are expressed in terms of most probable number (MPN) per 100 mL with a detection limit of one organism per analytical portion of a sample. Initial TC and EC in the tests ranged from 58,000 to 120,000 MPN/100 mL and from 120 to 290 MPN/100 mL, respectively. Since the absence of EC is the mandatory regulation for human consumption according to WHO (2019), the focus of this paper will be on the results for EC removal. The temperature of each water sample was also measured with a regular thermometer with an accuracy of 0.1 °C.

2.3. Calculation of solar radiation

To obtain solar radiation on an hourly scale, we used the formula of Sellers (1974), which has been validated in several studies in Brazil (De Souza *et al.* 2016; da Silva *et al.* 2017) and can be expressed by:

$$I_z = J_o \times \left(\frac{d}{D}\right)^2 \times \cos\left(\sin\phi \sin\delta + \cos\phi \cos\delta \cos h\right) \quad (1)$$

where I_z is the hourly solar radiation (W/m²); J_o is the solar constant of 1,367 W/m²; $(d/D)^2$ relates the earth–sun distance on a given day (d) to the average earth–sun distance (D); ϕ is the latitude in degrees; δ is the solar declination in degrees and h is the hourly angle of sunrise in degrees.

Then, the values of hourly daily solar radiation were corrected for different cloudiness conditions, according to the formula of Angstrom (1924) improved by Prescott (1940), as described by Reddy (1971) and Haider *et al.* (2014):

$$I_g = I_z \times \left[a + \left(b \times \frac{n}{N}\right)\right] \tag{2}$$

where I_g is the hourly corrected solar radiation (W/m²); n is the insolation (h); N is the photoperiod (h) and a and b are coefficients dependent on the latitude and atmospheric conditions. The values of n (1–10 h) and N (about 12 h) were obtained from a meteorological station of the Federal University of Ceará – UFC located approximately 60 km from the study area, while the coefficients of $a = 0.27$ and $b = 0.36$ were assumed the same as previous studies performed in the region (De Souza *et al.* 2016; da Silva *et al.* 2017).

To validate the results, the hourly daily solar radiations were averaged over the days and compared with the monthly solar radiations at the municipality of São Gonçalo do Amarante (Cell ID 57963) obtained from the National Institute for Space Research (INPE 2020).

2.4. Modeling of bacterial decay

Assuming that the water inside the Aqualuz box is well-mixed and that bacterial mortality follows a first-order kinetics (Chapra 2008), the following equation was used to describe the decay rate of EC:

$$EC = EC_o \cdot e^{-kt} \tag{3}$$

where EC is the *E. coli* concentration at time t ($\mathrm{MPN \cdot mL^{-1}}$), EC_o is the initial *E. coli* concentration ($\mathrm{MPN \cdot mL^{-1}}$), t is the elapsed time (h) and k is the decay rate constant ($\mathrm{h^{-1}}$).

Then, the EC decay rate constant (k) was investigated considering three different models: (1) a constant decay rate, (2) a decay rate constant as a function of water temperature and (3) a decay rate constant as a function of both solar radiation and water temperature.

(1) *Constant decay model:*

In this case, a constant k-value was adjusted by fitting Equation (3) to the experimental data of EC, EC_o and t for each field survey: partly cloudy/sunny day (April 22, 2019), sunny day (April 29, 2019) and rainy day (April 30, 2019). The best-fitting model was obtained by minimizing the normalized root mean squared logarithmic error (NRMSLE) between model simulations and experimental results. According to Castro-Alférez *et al.* (2018), a simulation could be considered excellent if NRMSLE $<$ 10%, good if 10 $<$ NRMSLE $<$ 20%, fair if 20 $<$ NRMSLE $<$ 30% and poor if NRMSLE$>$30%. The NRMSLE is commonly used in other studies involving SODIS. Therefore, this statistical analysis was used in the present study in order to compare the results with other articles.

(2) *Temperature model:*

This model considers the classical relationship between decay rate and temperature, as described by Thomann & Mueller (1987) and validated by subsequent studies in rivers and lakes in the Brazilian northeast (Lima *et al.* 2018; Oliveira Filho & Lima Neto 2018; Fraga *et al.* 2020):

$$k = k_{20} \cdot 1.07^{(T-20)} \tag{4}$$

where k_{20} is the decay rate constant at 20 °C ($\mathrm{h^{-1}}$).

Thus, a constant value of k_{20} was adjusted by minimizing the NRMSLE between model simulations using Equations (3) and (4) and experimental data for each field survey, resulting in different decay rate constants k for each experimental condition of EC, EC_o, t and T.

(3) *Radiation–temperature model:*

In this model, we adapted the equations proposed by Kashefipour *et al.* (2006) and Cho *et al.* (2012) for natural water bodies to describe the value of k_{20} as a function of solar radiation:

$$k_{20} = k_{20,d} + \alpha(I_g)^{\beta} \tag{5}$$

where $k_{20,d}$ is the dark or night-time decay rate constant (h^{-1}) and α and β are factors that govern the day-time decay caused by solar radiation.

Hence, constant values of $k_{20,d}$, α and β were adjusted by minimizing the NRMSLE between model simulations using Equations (1)–(5) and experimental data for each field survey, resulting in different decay rate constants k for each condition of EC, EC_o, t, T and I_g.

2.5. Comparison of decay rates and exposure periods

A relationship between solar radiation and water temperature inside the Aqualuz was fitted. This relationship together with the best-fitting model, as described in the previous section, allowed the comparison of the EC decay rates among Aqualuz and other SODIS devices for similar solar exposure–temperature conditions. In addition, different scenarios of exposure periods for achieving 2-, 3- and 4-log reductions of EC were simulated for 34 municipalities in the Brazilian semiarid region using the data of Tiba (2001) and INPE (2020), in order to investigate the variability of required exposure time for EC inactivation among different areas. To illustrate this variability, a color map for the region depicting the exposure periods for 3-log reduction was also created by using the model results and a Geographic Information System – QGIS (https://qgis.org/en/site/). The exposure time was calculated by solving Equation (3) for t:

$$t = \ln \frac{(EC_o/EC)}{k} \tag{6}$$

where the ratio of EC_o/EC can be expressed as a function of the removal efficiency $R[=(EC_o - EC)/EC_o]$: $EC_o/EC = 1/(1-R)$.

3. RESULTS AND DISCUSSION

3.1. Solar radiation

Figure 3 shows a comparison between the monthly solar radiations (I_g) calculated for 2019 by using Equations (1) and (2) and those provided by the National Institute for Space Research (INPE 2020) for the municipality of São Gonçalo do Amarante (see Figure 1). A good agreement between calculated and observed values of I_g was obtained, resulting in a standard deviation of 4% and a coefficient of determination (R^2) of 0.72, which can be considered as a 'good performance', according to Moriasi *et al.* (2007). This corroborates the previous studies of da Silva *et al.* (2017), De Souza *et al.* (2016), Haider *et al.* (2014), Tripathy *et al.* (2008) and Wu *et al.* (2012), in which the Angstrom–Prescott method (Angstrom 1924; Prescott 1940) was

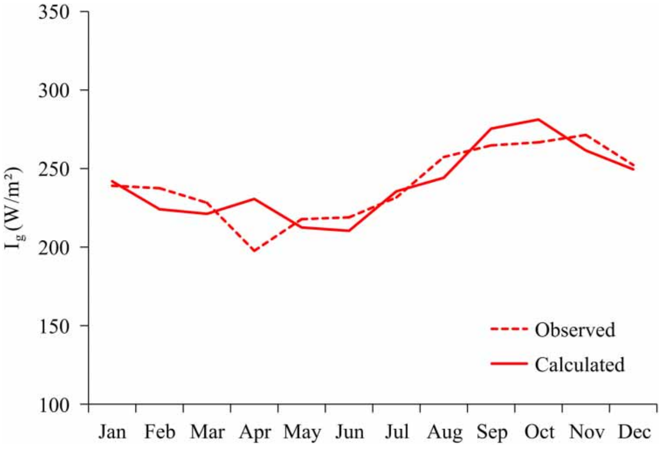


Figure 3 | Comparison of monthly solar radiations in the municipality of São Gonçalo do Amarante calculated for 2019 by using the Angstrom–Prescott method with those observed by the National Institute for Space Research (INPE 2020).

used to estimate I_g on an hourly scale with similar standard deviations and coefficients of determination as the ones obtained in the present study. Therefore, the above-mentioned method was considered sufficiently accurate to estimate hourly solar radiations in the study area for the periods of the field surveys: April 22, 29 and 30, 2019.

3.2. Time-profiles and removal efficiency

The calculated solar radiations (I_g), measured water temperatures (T) and *E. coli* concentrations (EC) for the samples collected during the field surveys are plotted together in Figure 4. The initial EC concentrations ranged from 120 to 290 MPN/100 mL, while the TC concentrations ranged from 0.6 to 1.2×10^5 MPN/100 mL. The decay of TC was very similar to that of EC, as already verified in other SODIS devices (Paterniani 2005) and natural water bodies (Fraga *et al.* 2020). However, the focus of the discussion will be on EC, since its absence is required for safe water consumption according to WHO (2019). The measured values of EC are very similar to the ones observed in other rural cisterns in the Brazilian semiarid (Souza *et al.* 2011). This confirms the recurrent EC contamination in cistern waters and their inadequacy for human consumption, as also verified in other regions of the globe (Crabtree *et al.* 1996; Jordan *et al.* 2008; Abbasi & Abbasi 2011; Ahmed *et al.* 2011; Al-Salaymeh *et al.* 2011; Ayed *et al.* 2018). However, in some of the cases reported in the literature, even higher EC initial concentrations (about 1.0×10^3 MPN/100 mL) were found, which reinforces the need for SODIS and/or other treatment systems for cistern waters, in addition to hygiene education (Luzi *et al.* 2016).

The time-profiles and removal efficiencies of EC varied according to the initial concentration, water temperature and solar radiation. Figure 4(a) shows the decay of EC from 7:00 to 11:00 am in a cloudy–sunny day, where I_g and T increased from about 160 to 670 W/m² and 27 to 45 °C, respectively, while EC decreased from 290 to 7 MPN/100 mL. Despite not having reached the standard of potability of water, this resulted in a removal efficiency of 98% for a total exposure of 4.0 h under the average solar radiation of about 460 W/m². On the other hand, Figure 4(b) shows EC decay in a sunny day, with I_g and T increasing from about 190 to 750 W/m² and 26 to 48 °C, respectively, and EC decreasing from 122 MPN/100 mL to below the detection limit. Note that in this case, 100% removal efficiency was reached within 2.5 h with an average solar radiation of about 410 W/m², which is below the minimum of 500 W/m² recommended in the literature for bacterial inactivation (Sommer *et al.* 1997; Oates *et al.* 2003; Haider *et al.* 2014). Finally, Figure 4(c) shows EC decay in a rainy day, where I_g and T increased from about 90 to 370 W/m² and 27 to 32 °C, respectively, while EC decreased from 120 MPN/100 mL to below the detection limit. In this case, 100% removal efficiency was reached within 4.0 h with an average solar radiation of about 250 W/m², which corresponds to half of the aforementioned limit (500 W/m²) for bacterial inactivation. It is important to mention that the relatively low rate of EC removal on the cloudy–sunny day may partially be due to the high initial EC concentrations obtained for the day in question when compared to the sunny and the rainy days. Also, these results suggest that Aqualuz has a higher efficiency than conventional SODIS devices, which may be attributed to the rectangular and slim shape of its box (see Figure 2), that potentially contributed to a more uniform and efficient distribution of solar radiation and temperature in the water volume. The rectangular shape may favor a more perpendicular incidence of solar radiation over the glass sheet surface, while the small water depth (5 cm) may contribute to a more efficient heat transfer from top to bottom. Observe that conventional SODIS devices such as PET bottles or plastic bags usually present a curvilinear surface and water depths larger than 5 cm (Sommer *et al.* 1997; Oates *et al.* 2003; Dessie *et al.* 2014; Loeb *et al.* 2015).

3.3. Model calibration

The model calibration process consisted in minimizing the NRMSLE between simulations and experimental results. Figure 5 shows the fitting of the three models to the experimental data of EC for each field survey. Considering the constant decay model (Equation (3)), the calibration process resulted in a fixed value of $k = 0.60\ \mathrm{h}^{-1}$ for all the experimental conditions, with NRMSLEs of 13.1, 17.1 and 8.3% for the cloudy–sunny, sunny and rainy days, respectively. Considering the temperature model (Equations (3) and (4)), a constant value of $k_{20} = 0.32\ \mathrm{h}^{-1}$ was obtained, while the temperature-corrected values of k ranged from 0.51 to 1.74 (0.98), 0.48 to 2.13 (1.13) and 0.51 to 0.72 (0.59) h^{-1}. In this case, the values of NRMSLE for the cloudy–sunny, sunny and rainy days were 9.0, 15.6 and 6.4%, respectively. Finally, considering the radiation–temperature model (Equations (3)–(5)), constant values of $k_{20,d} = 0.21\ \mathrm{h}^{-1}$, $\alpha = 0.05$ and $b = 0.15$ were obtained, while the values of k corrected for radiation and temperature ranged from 0.51 to 1.86 (1.03), 0.48 to 2.29 (1.20) and 0.50 to 0.75 (0.60) h^{-1}. Here, the values of NRMSLE for the cloudy–sunny, sunny and rainy days were 8.6, 15.1 and 6.3%, respectively. The above results indicate that the three models performed well with NRMSLE $< 20\%$, similar to Castro-Alférez *et al.* (2018). However, the radiation–temperature model provided the best fitting to the experimental data, followed by the temperature model.

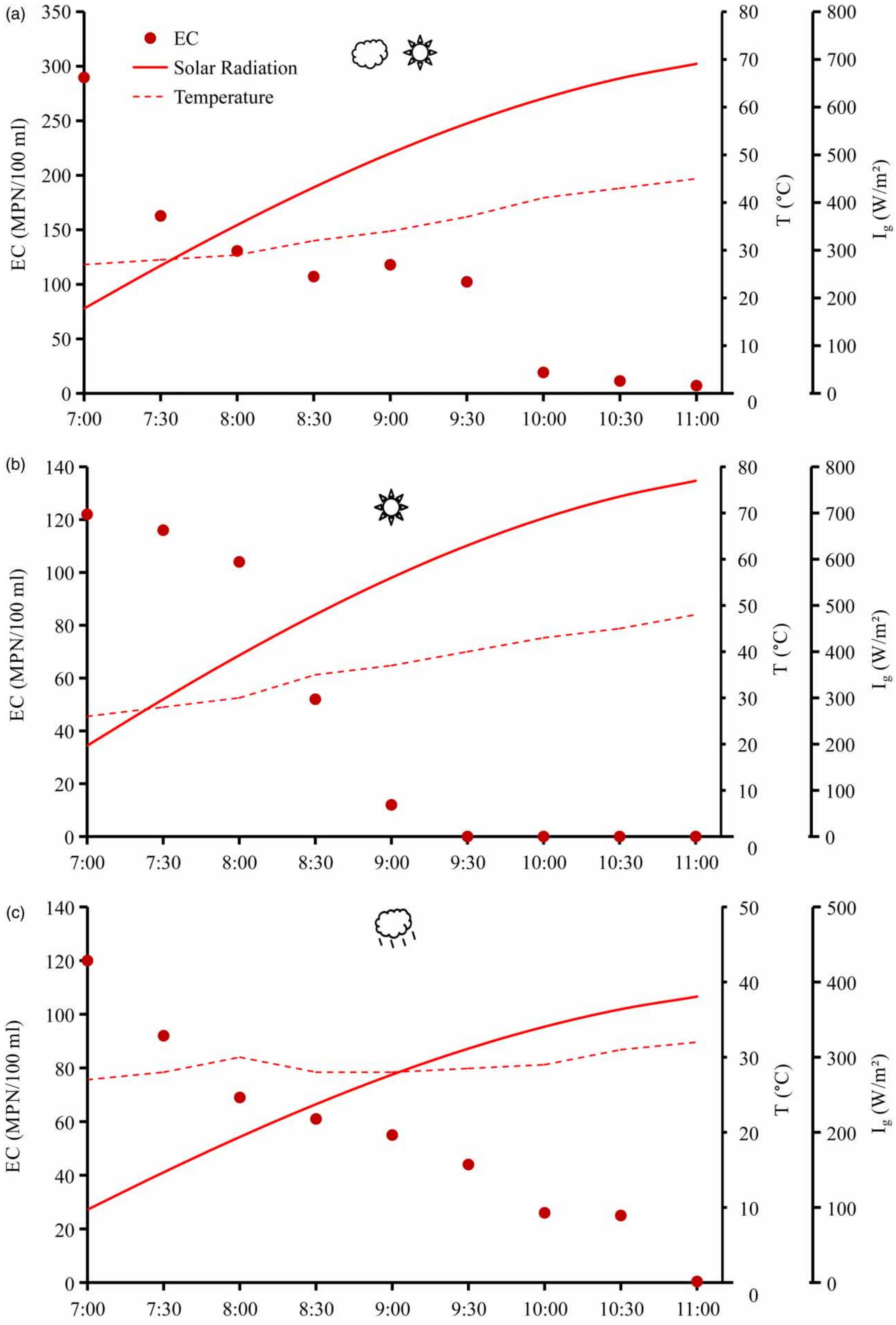


Figure 4 | Solar radiation, water temperature and EC concentration for samples collected on April 22, 29 and 30, 2019: (a) cloudy–sunny day, (b) sunny day and (c) rainy day.

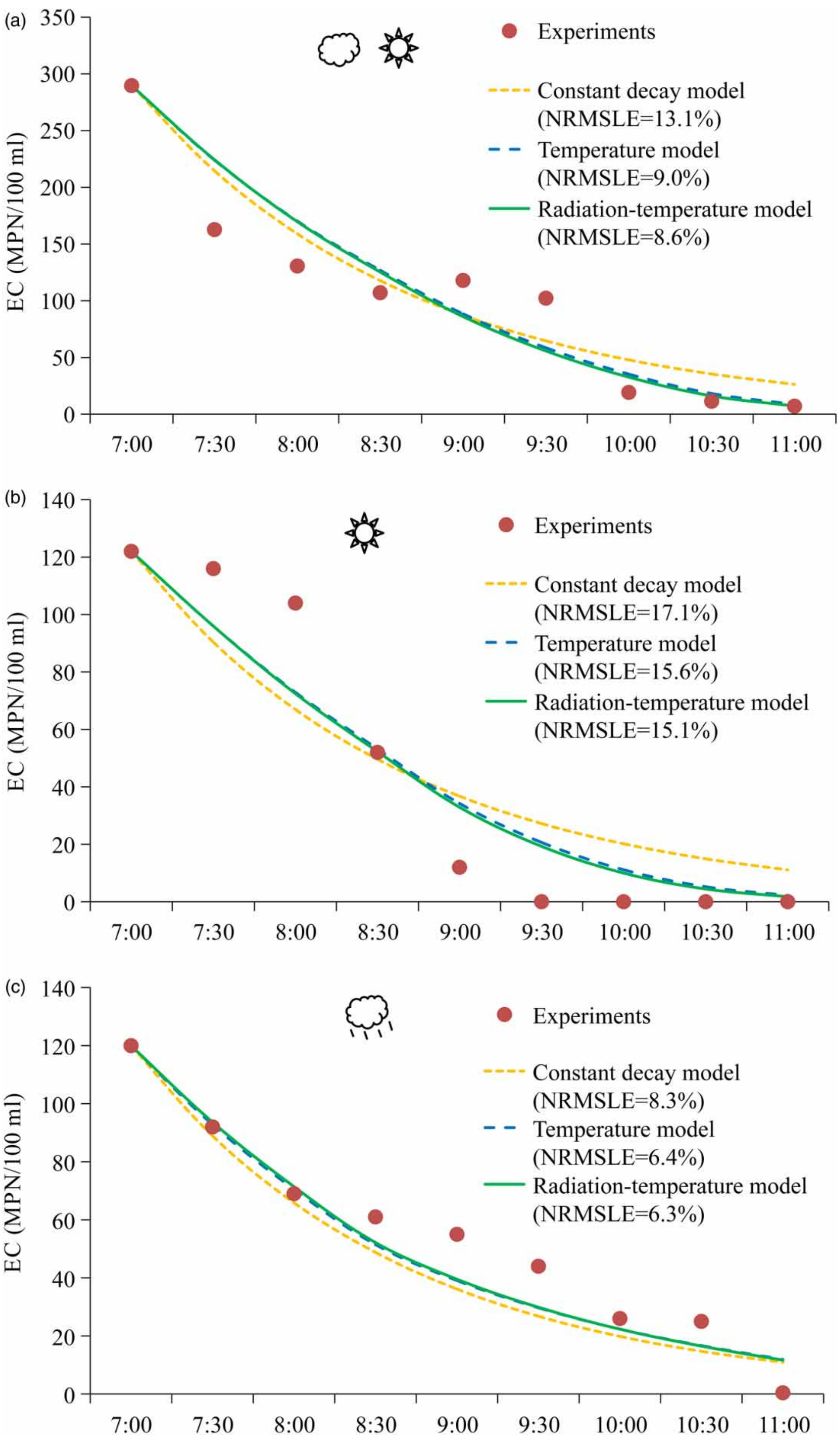


Figure 5 | Fitting of the three models to the experimental data of EC for the field surveys conducted on April 22, 29 and 30, 2019: (a) cloudy–sunny day, (b) sunny day and (c) rainy day.

Conducting a simple sensitivity analysis, by varying the values of the calibrated coefficients within a typical range of $\pm 20\%$, it is noticed that $k_{20,d}$, α and β exert an important influence on the inactivation time (12, 8 and 7%, respectively), indicating that model results are sensitive to both temperature and radiation. Therefore, the radiation–temperature model with the fitted parameters is proposed here to predict the EC decay rates using Aqualuz for different solar exposure–water temperature conditions:

$$k = [0.21 + 0.05(I_g)^{0.15}] \cdot 1.07^{(\mathrm{T}-20)} \tag{7}$$

where k is the EC decay rate constant (h^{-1}), I_g is the solar radiation (W/m²) and T is the water temperature (°C).

It is also important to stress that the above-mentioned k-values for both the temperature and radiation–temperature models increased consistently from the rainy ($k = 0.59$ and $0.60\ \mathrm{h}^{-1}$) to the cloudy–sunny ($k = 0.98$ and $1.03\ \mathrm{h}^{-1}$) and to the sunny ($k = 1.13$ and $1.20\ \mathrm{h}^{-1}$) days, respectively, which gives credence to the model calibration process. This was attributed to the effect of cloud cover on reducing solar radiation, as pointed out by Haider *et al.* (2014).

Figure 6 shows a relationship fitted between solar radiation obtained from INPE (2020) and water temperature measured inside the Aqualuz (Equation (8)), resulting in $R^2 = 0.9781$, which can be considered as a 'very good performance', according to Moriasi *et al.* (2007). Combined with Equations (3) and (7), this relationship will be used in the next section to compare the EC decay rates among Aqualuz and different SODIS devices, as well as to predict the required exposure periods for achieving different levels of EC removal at different locations in the Brazilian semiarid.

$$T = 5\mathrm{E} - 05(I_g)^2 - 0.0106(I_g) + 27.673 \tag{8}$$

3.4. Decay rates

Figure 7(a) shows the EC decay rate constant k obtained by considering dark thermal inactivation of EC at different temperatures, where the results for Aqualuz are compared with those of Castro-Alférez *et al.* (2017) from laboratory experiments in an open-stirred vessel under controlled conditions of solar radiation and water temperature. The dark thermal inactivation represents the natural bacterial die-off rate, taking into account factors other than radiation, such as temperature, turbidity and pH of the water (Kashefipour *et al.* 2006; Cho *et al.* 2012). In our case, we assumed that solar radiation is null ($I_g = 0$) in Equation (7), so that only the effect of the temperature on the decay rate could be considered. The idea of setting $I_g = 0$ was to make the results directly comparable with the well-controlled laboratory conditions of Castro-Alférez *et al.* (2017), where the effect of solar radiation was eliminated. It is clearly seen that Aqualuz promoted higher values of k, probably because in the field surveys we were not able to completely isolate the effect of solar radiation, differently from the laboratory study of Castro-Alférez *et al.* (2017). Note that early in the morning (7:00 am), we already had values of $I_g > 90$ W/m² (see Figure 4). However, interestingly, for $T = 45$ °C, the k-values were very similar (about $1.0\ \mathrm{h}^{-1}$). This probably occurred because for higher water temperatures, heat transfer becomes more intense and the geometry of the SODIS device becomes less important. Figure 7(b) shows a comparison of the k-values obtained with Aqualuz [Equations (7) and

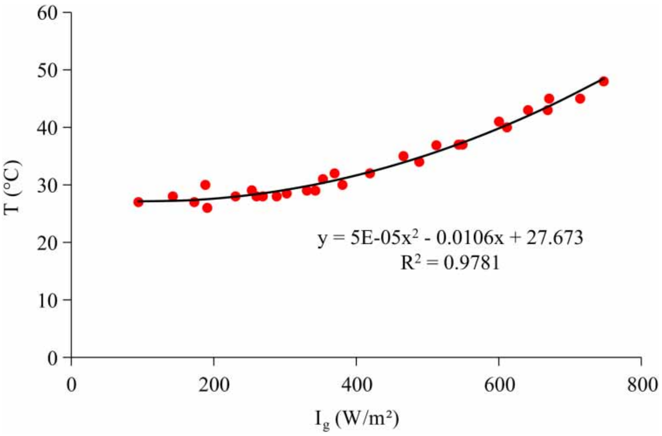


Figure 6 | Fitted relationship between solar radiation and water temperature inside the Aqualuz.

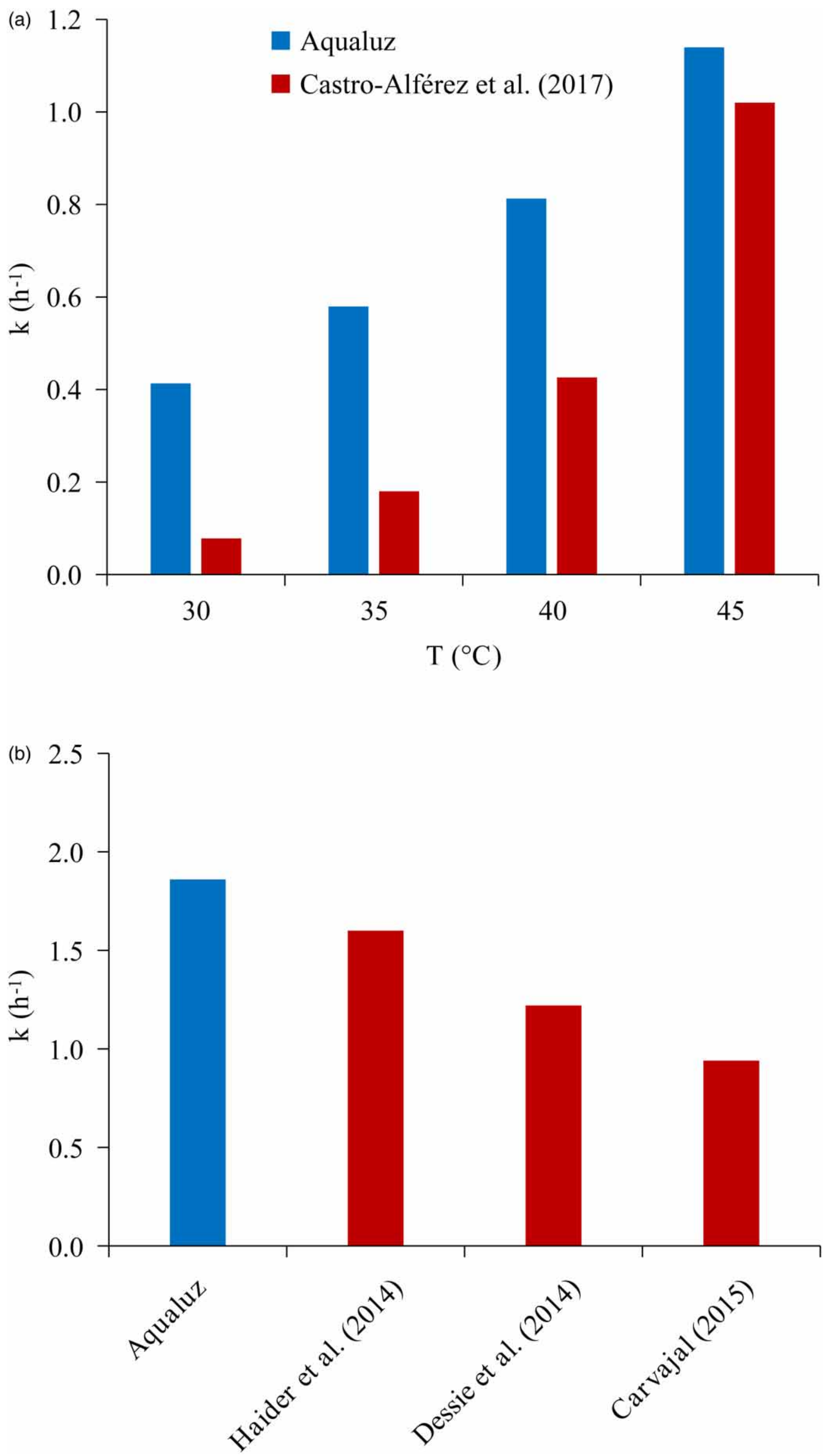


Figure 7 | Comparison of EC decay rates obtained with Aqualuz and other SODIS devices operating at low turbidity conditions ($<$5 NTU): (a) dark decay rates for different water temperatures and (b) decay rates for $I_g \approx 700$ W/m².

(8)] and conventional PET bottles (Dessie *et al.* 2014; Haider *et al.* 2014; Carvajal 2015), all operating at low turbidity (<5 NTU) and similar solar radiation conditions ($I_g \approx 700\ \mathrm{W/m^2}$). Again, our *k*-values were higher than the ones reported in the literature. As already mentioned in section 3.2, this higher efficiency is attributed to the rectangular and slim shape of the Aqualuz device (see Figure 2), which potentially contributed to a more uniform and efficient distribution of solar radiation and water temperature in the box. In fact, the PET bottles evaluated in the above-mentioned studies had circular cross-section, which may cause a less perpendicular incidence of solar radiation over their surfaces, as compared to Aqualuz. On the other hand, all the bottles had diameters larger than the water depth in Aqualuz (5 cm), probably reducing the efficiency of heat transfer from top to bottom. The impact of water depth on reducing EC removal efficiency has already been reported by Dessie *et al.* (2014) and Wegelin *et al.* (1994).

3.5. Exposure periods

Figure 8 shows a color map of the Brazilian northeast region generated with QGIS, indicating the exposure times *t* for an EC removal efficiency $R = 99.90\%$ (3-log reduction), obtained by using Equations (1), (2), (6), (7) and (8) and the data of n, N, a and b available in Tiba (2001) and INPE (2020) for 34 municipalities in the Brazilian semiarid region. Therefore, this section shows an application of the results obtained in the present study that can be useful in water management. The results indicate exposure times ranging from 1.8 to 5.6 h, which were associated with the variability of solar radiation of 611–876 W/m² over the area. The removal efficiency of $R = 99.90\%$ was chosen because the values of initial concentration (EC_o) ranged from 120 to 290 MPN/100 mL, similarly to other cistern systems in the Brazilian semiarid (Souza *et al.* 2011). Thus, a 3-log reduction would result in final concentrations (EC) of 0.12–0.29 MPN/100 mL, respectively, which are below the detectable limit of one organism per 100 mL. The color map shown in Figure 8 is important to assist the population in managing the Aqualuz system in order to control the time for water treatment according to the location in the Brazilian semiarid. The results can also be replicated to other drylands such as in Africa, Asia and Latin America. Although not plotted here, the exposure times for other removal efficiencies of $R = 99.00$ and 99.99% (2- and 4-log reductions) were also evaluated, resulting in *t*-values of 1.2–3.8 h and 2.4–7.5 h, respectively. These results for 2- and 4-log reductions are also important in case lower or higher

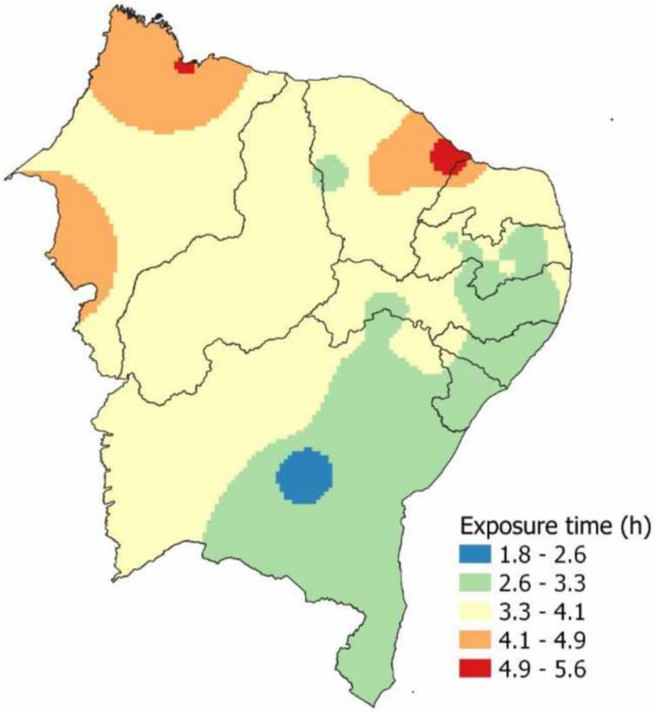


Figure 8 | Color map of the Brazilian northeast region indicating the simulated exposure times for EC removal of 99.9% (3-log reduction). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/aqua.2022.092.

values of initial concentration (EC_o) are observed. Haider *et al.* (2014), for instance, considered 2-, 3- and 4-log reductions for conventional SODIS systems, as the values of EC_o ranged from 8 to 1.6×10^3 MPN/100 mL.

4. CONCLUSIONS

In this paper, we reported field, laboratory and modeling studies to investigate the efficiency of a new SODIS device called Aqualuz for removal of EC from cistern water in the Brazilian semiarid region. The results revealed initial EC concentrations higher than 100 MPN/100 mL, but exposure periods of 2.5–4.0 h under solar radiation of about 250–410 W/m² were sufficient for reducing the concentration to below the detection limit. This suggests that Aqualuz has a higher efficiency than conventional SODIS devices, which usually require a minimum of 500 W/m² for bacterial inactivation. The faster elimination of EC may be attributed to the Aqualuz shape, that potentially contributed to a more uniform and efficient distribution of solar radiation and temperature in the water volume. Its rectangular shape may favor a more perpendicular incidence of solar radiation over the glass cover surface, whereas the small water depth of 5 cm may contribute to a more efficient heat transfer from the top to the bottom of the box. Moreover, first-order decay rate constants of EC (k) were adjusted considering three different models: constant k-value, k as a function of water temperature and a new formulation for k as a function of both solar radiation and water temperature. All models performed well with NRMSLEs ranging from 6.3 to 17.1%. The best fitting was obtained with the new radiation–temperature model. Consistently, the adjusted k-values were higher than observed previously in conventional SODIS studies. A polynomial curve relating water temperature to solar radiation was also fitted. Combining this curve with the radiation–temperature model, it was possible to simulate the EC inactivation for 34 municipalities in the Brazilian northeast, resulting in a color map for the region indicating the exposure periods of 1.8–5.6 h for reaching a 3-log reduction. Exposure periods of 1.2–3.8 h and 2.4–7.5 h were also obtained for 2- and 4-log reductions, respectively. These reference values can be useful to assist the population in managing the Aqualuz system for initial EC concentrations ranging from about 10 to 1,000 MPN/100 mL. Finally, the results from this study will potentially improve water quality management in rural cisterns and can also be extended to other regions by using the proposed model and fitted relationships. However, there are some factors to be considered in future studies to improve the knowledge of EC inactivation mechanisms in the Aqualuz, among them is the performance of more measurements at different sampling points, as well as the evaluation of EC morphology before and after the treatment and the radical quenching experiment.

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DECLARATION OF CONFLICTS OF INTEREST

The authors declare that they do not have a conflict of interest of order: financial, commercial, political, academic and personal.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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