PILOT STUDY OF WATER DISINFECTION USING SOLAR CONCENTRATORS IN RURAL COMMUNITIES

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Abstract The efficiency of solar disinfection for the inactivation of Total Coliforms (TC) and *Escherichia coli* (EC) in drinking water was tested in two pilot studies performed in rural communities of the States of Chihuahua and Oaxaca, Mexico. The solar disinfection of drinking water (or photodisinfection) is an inexpensive alternative of easy application in rural communities. The study zones were selected mainly because they lack formal water supply systems and the population is forced to consume untreated water directly from rivers and shallow or artesian wells. The efficiency of the water disinfection process based on solar energy was determined in the dry and rainy seasons with water from the most contaminated sources in the study zones. The performed tests consisted in studying the effect of disinfecting water by direct exposure to sunlight during the whole day, with and without solar concentrators, in plastic bottles of commercial beverages. The three types of bottles used were transparent, partially painted black (one half of the bottle, along the longitudinal axis), and totally black. The study shows that, in these geographic zones, the available water must be disinfected before consumption, and disinfection efficiency can reach 100 % through the use of solar radiation.

Keywords: Rural communities, solar energy, water disinfection, solar concentrators

1. INTRODUCTION

In Mexico, the National System of Epidemiological Surveillance (SNVE, 2002) reports that diseases caused by potentially hydrotransmissible infectious agents affected 6’319,795 people from January to December of the year 2000. This represented 6.4% of the total population of the country. The population sector most affected by this type of diseases is the rural, formed by those communities with less than 2,500 inhabitants. In this sector lives approximately 25.3% of the national population (26'348,150 people), of which only about 65% has access to a piped water supply (CNA, 2000). Solving the problem of water quality in rural communities is not easy due to the great dispersion of the population and the fact that many of these settlements are inhabited by native people, who very often reject widespread modern water treatment and disinfection methods.

The use of solar radiation for water disinfection has proven to be an efficient technique for the inactivation and destruction of pathogenic bacteria (Reed, 1997; Márquez, 1993; Sommer, 1995, McGuigan, 1998; Conroy, 1999; SODIS, 1998, Wegelin, 1999). This technology is very well suited for rural communities of low income which do not have access to standard modern water purification systems, do not boil or chlorinate the water, and are willing to treat only the water required for their daily consumption.

In previous studies (González-Herrera *et al*., 2000 and 2002; Martín-Domínguez *et al*., 2000), the feasibility of using flat-wall solar concentrators manufactured with materials that are cheap and readily available in rural communities was analyzed. The objective of these studies was to improve the efficiency of this solar disinfection process for its use in areas with low solar radiation levels. The studies consisted in exposing water contained in transparent plastic bottles to solar radiation inside a flat-wall solar concentrator. The disposable bottles used for commercial beverages were the most suitable for this use, since they allow an adequate control of the treated water and reduce the risk of recontamination. The results showed that, with this setup, it is possible to eliminate 10^5 total coliforms (measured as the most probable number MNP/100 mL) and 10^6 viral plaque forming units with four hours of solar exposure during the time of highest radiation in sunny days.

The objectives of the present study were to field-test the results obtained at laboratory level in rural communities, to determine and test the materials for the construction of solar concentrators, to test the efficiency of two new concentrator designs, to understand the habits and beliefs of the population regarding water management, and to determine the efficiency of this disinfection method in real conditions.

2. METHODOLOGY

Materials used for solar disinfection

- Totally transparent bottles, bottles with a black stripe painted lengthwise and bottles painted totally black, all of which were of commercial soft drinks readily available in the study zones.
- Flat-wall solar concentrators lined with either commercial aluminum foil or aluminized duct tape, both of which can be easily obtained in the nearby communities where the rural population periodically makes their shopping.
- Solar concentrators of different design (square with capacity for 3 two-liter bottles, rectangular with capacity for 4 two-liter bottles, and compound parabolic (CPC) with capacity for 2 two-liter bottles). Two-liter bottles were chosen because larger bottles exceed the 10-cm maximum water depth recommended by SODIS (1998) for proper solar disinfection.
- The square flat-wall concentrators were lined with aluminum wrapping foil. The rectangular flat-wall and compound parabola concentrators were lined with self-adhesive aluminized duct tape.

Concentrators used

The theoretical solar concentration, C, of a flat-wall concentrator depends on the effective concentrator openness area, A_e, and its base reception area, A_c, (Merchant, 1966) (Figure 2.1 and Figure 2.2).

$$C = \frac{A_e}{A_c} \qquad \text{(A1)}$$

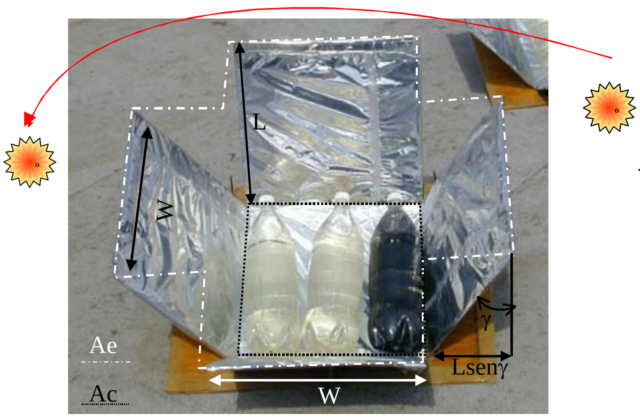

Figure 2.1 Bottle arrangement in the square concentrator

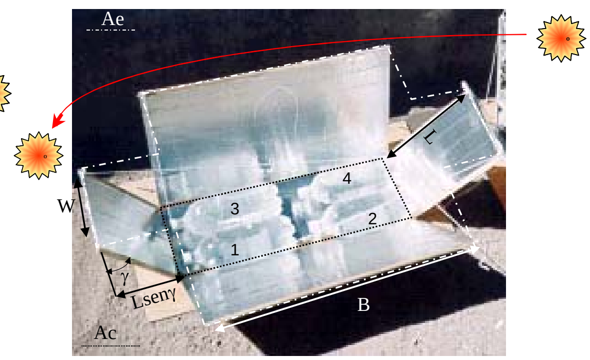

Figure 2.2 Bottle arrangement in the rectangular concentrator

In the case of square concentrators (Figure 2.1):

$$A_e = W^2 + 4 W L\, sen(\gamma) \qquad \text{(A2)}$$

Where W is the length and width of the concentrator, L is the length of the flat walls, and γ is the opening angle of the flaps, with respect to the base-plane perpendicular (A_c).

The square concentrator was sized with a radiation-receiving area of 35 cm x 35 cm, able to contain 3 two-liter bottles. This makes the concentrator relatively small and easy to handle.

The flaps were 35 cm x 35 cm wooden squares that provided a maximum theoretical concentration ratio of 3 when the concentrator was directly oriented to the sun. The devices were oriented to the sun's position at noon and left fixed in that direction. This concentrator was to be aligned once every season to keep the process efficient. The concentrator opening angle allows an unrestricted and shadowless irradiation of the receiving area during 4 hours a day. For a 3X solar concentration ratio, combining equations A1 and A2, the angle required for the flaps is calculated as:

$$\gamma = \sin^{-1}\left(\frac{W}{2\,L}\right) = 30^{o} \qquad \text{(A3)}$$

In the case of rectangular concentrators (Figure 2.2):

$$A_e = B\,W + \left[\,2\,L \sin(\gamma)\,\right](W + B) \qquad \text{(A4)}$$

Where B is the length and W is the width of the collector's base.

For the rectangular concentrator, the same angle and flap length as in the square concentrator were used. It was built to fit 2 rows of 2 bottles each. This resulted in a rectangular receiving area of 75 cm x 22 cm and a maximum theoretical solar concentration ratio of 3. Both concentrators were oriented to the midday sun and fixed in place.

Design equations for the compound parabolic concentrator were taken from the literature (Tripanagnostopoulos, 2002), where a metallic black cylinder was used as a receiver. In this work, however, commercial plastic beverage bottles were used instead of the cylinder (Figure 2.3). As in the case of the flat-wall concentrators, the CPC concentrators were oriented to the midday sun and fixed in position.

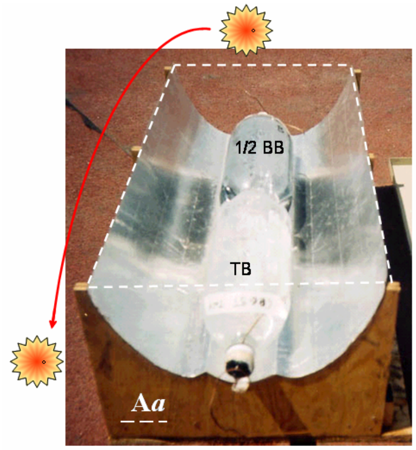

Figure 2.3 Bottle arrangement in the compound parabolic concentrator

The solar concentration ratio achieved with this setup is calculated as:

$$C = \frac{Aa}{Ar} \qquad \text{(A5)}$$

Aa is this model's opening area of 31 cm x 60 cm.
Ar is the exposed surface of 2 two-liter bottles, calculated as if each bottle were a perfect cylinder of 11 cm in diameter and 30 cm in length, and 3/4 of the bottles' surface were exposed to solar radiation.
Considering this:

$$Ar = ¾\ (3.1416 \text{ x } 11 \text{ cm}) \text{ x } 60 \text{ cm} = 1{,}555 \text{ cm}^2.$$

Consequently:

$$C = \frac{1{,}860}{1{,}554.6} = 1.2$$

Following the author's recommendations, an opening angle, α, of 90º was used in order to have a longer operation time without requiring modifications in the equipment's alignment during the day.
For these tests, compound parabolic concentrators were built from thin metal sheets lined with aluminized duct tape on a wooden base. The results obtained with all three concentrator types were compared against each other, based on their best individual operating conditions, regardless if they were different for each concentrator.

Measuring procedures

The incident solar radiation was measured using an Eppley Black & White pyranometer, model 8-48, with a detection spectrum of 285-2800 nm. It was positioned horizontally near the concentrators and connected to a data acquisition system that made it possible to take readings every ten minutes. Water temperature was measured every 10 minutes inside the bottles using Fluke data logging digital thermometers, but only in the Norogachi tests.

Bacteriological Analysis Methods

The bacteriological quality of water was determined based on the amount of TC and EC as the most probable number for every 100 milliliters (NMP/100 mL) using the Colilert specific substrate method. This method was approved by the US EPA, is considered a standard method for water quality determination, and is very well suited for field use in rural areas. In the result graphs, values marked as "0" actually indicate "<1", which is the method's determination limit.

Selection of the pilot community and the water quality monitoring zone

The communities selected for this study were Santa Lucía, in the Ocotlán municipality, State of Oaxaca, located in the south of México and with a humid climate (4,000 inhabitants); and Norogachi, in Guachochi county, State of Chihuahua, located in the north of the country and with a dry climate (672 inhabitants). The main selection criterion was that the only water quality problem should be bacteriological and there should be a rejection by the local population of the use of chlorine as a disinfection medium. These communities have different average solar radiation levels during the year (Figure 2.4).

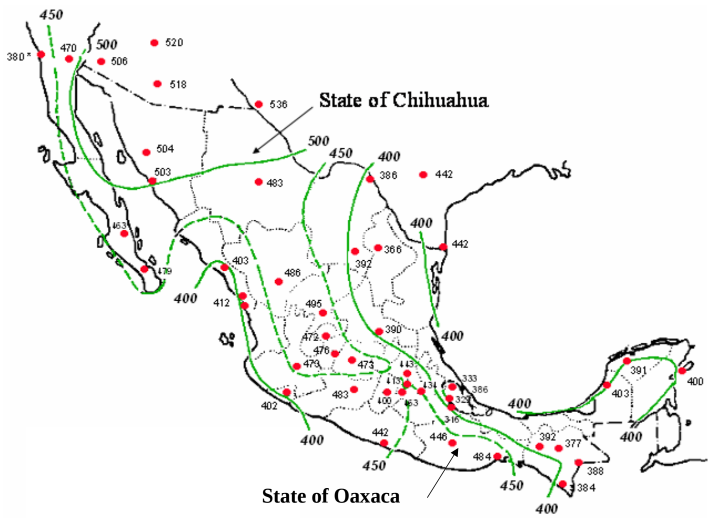

Figure 2.4 Average total daily radiation in México, in Langley (Langley=0.484 W/m^2) (Almanza-Salgado, 1994).

In Santa Lucía, the participating organizations summoned potential users to an assembly, from which local participants were selected for training. Several workshops were conducted with the selected group, in which the users were provided with part of the material required for building the concentrators (the rest they brought themselves), and teams were then organized for the construction of the devices (Figure 2.5 a). The material used for the construction of the concentrators was waste wood, obtained from fruit and vegetable crates. In this community, the square type concentrator lined with aluminum foil was used.

Concentrators were placed at ground level in several house yards, where they could receive sunlight all day long. Users were told to leave the bottles in the concentrators from dawn to dusk and, after removing the bottles at sunset, to store them in a cool place. Once cool, water was ready for consumption.

In this community every house has its own water well, from which the test water was taken. The house owners themselves were in charge of taking the water bottles in and out of the concentrators. Test samples of disinfected water were taken the morning after the irradiation day. The results in Table 3.1 show the average water quality of all monitored wells and all disinfected bottles per day.

In the community of Norogachi, Chihuahua, water wells are communal and people carry their own water back to their houses in buckets. In this community, the tests were performed months after the tests in Santa Lucía, by when the two new concentrator designs and reflective materials were available. A single water well, the most contaminated in the community, was used for the tests. In this test, the bottle handling was carried out by the authors. Training lectures were given to the people, and the test results were also shown to them (Figure 2.5).

a)

b)

Figure 2.5 a) Solar concentrator construction workshop in Oaxaca, México, b) Training lectures held in the Tarahumara Sierra with graphic material from SODIS Foundation.

In both communities, water samples were taken before and after the solar irradiation, during a period of three to five consecutive days, at two different seasons of the year. Because of the concentrators' orientation and the angle of the flaps, the most useful irradiation time for the setup used in this work, was between 9:00 and 17:00 hours.

3. RESULTS

Santa Lucía, Oaxaca

In this community, the average measured irradiation varied between 407 and 788 W/m^2 during the test period, and the TC concentration in well water was high in most of the cases. The average disinfection efficiency attained was very high, except for cloudy days, which presented low radiation (Table 3.1).

Completely transparent bottles were used in the dry season, but their fecal coliform elimination efficiency was below 100%. During the rainy season, bottles with a black stripe painted lengthwise were used to increase the disinfection efficiency. During this time, the water quality was very poor in almost all of the analyzed wells, with total coliforms counts ranging from 1,015 to 7,270 MPN/100 mL. A possible reason for this phenomenon was very few wells had adequate protection to avoid rainwater from washing contaminants into them. However, even though the irradiation levels were low, results showed adequate bacteria elimination. The day with the lowest radiation (cloudy and rainy) coincided with the worst water quality (7,270 MPN/100 mL), and under these conditions only 73% disinfection efficiency for total coliforms (TC) was achieved. Nevertheless, a clear improvement was observed in all the performed tests when the resulting water quality was compared with the initial conditions, especially for fecal coliforms (FC).

During the study time, the reflective material (commercial aluminum foil) of some concentrators was damaged and, therefore, had to be changed. This showed that aluminum is too weak, and another reflective material should be considered for this purpose.

Table 3.1 Water sample irradiation doses, and bacteriological water-quality before and after exposure to solar radiation in Santa Lucía, Oaxaca.

		Average radiation	Average water quality of all monitored wells before disinfection		Average disinfection efficiency of all water samples	
Monitored wells	Bottle types	9:00-17:00 h	TC	FC	TC	FC
		W/m^2	MPN/100 mL		%	
8	TB	788	1315	269	98.2%	98.9%
6	TB	607	1445	227	99.2%	99.8%
11	TB	594	2023	603	99.9%	100%
9	TB	602	1702	305	97.2%	91.7%
10	TB	433	1783	382	88.6%	98.2%
4	½ BB	-	3719	170	100%	100%
3	½ BB	407	7270	231	73%	99.7%
4	½ BB	543	3373	147	98.9%	100%
3	½ BB	486	1015	222	99.5%	100%
5	½ BB	617	6504	460	100%	100%
TB = transparent bottle; ½ BB half black bottle						

Norogachi, Chihuahua

Tests performed in this community show that, after exposing the bottles to sunlight for the whole day, the total elimination of up to 5×10^3 TC (MPN / 100 mL) was achieved with all the disinfection setups used, except with the bottle painted totally black during cloudy days (Figure 3.1). This clearly shows that temperature alone cannot produce a 100% disinfection efficiency, and that the most important factor for the elimination of bacteria is solar radiation. Results obtained with transparent bottles support this conclusion.

While monitoring the water quality every two hours (Figure 3.2) during a day with an average solar radiation of 701 W/m^2, the best results were observed when using the large concentrator with the half-black bottle (LC - ½ BB), and the compound parabolic concentrator (CPC) with the half black and transparent bottles. After four hours of solar radiation, TC had been eliminated in all the monitored bottles, except in the completely black bottle. This kind of bottles does not ensure disinfection, since the only bactericide effect is temperature.

To disinfect water using this technology, considering the conditions of radiation and water quality found in the monitored zone of the State of Chihuahua, transparent bottles could be used directly on the floor, as long as weather conditions are semi-cloudy or totally sunny and bottles are exposed to this radiation during the whole day. In case these requirements are not met, half black bottles and solar concentrators should be used.

By using solar concentrators and partially blackened bottles, the water temperature reached 65°C, while only 50°C were reached when completely transparent bottles and the same concentrators were used.

Nomenclature used in the graphs:

F - TB	=	Transparent Bottle on the Floor
F - BB	=	Completely Black Bottle on the Floor
F - ½ BB	=	Half-Black Bottle on the Floor
LC - TB	=	Large Concentrator (rectangular), Transparent Bottle
LC - ½ BB	=	Large Concentrator (rectangular), Half-Black Bottle
CPC - ½ BB	=	Compound Parabolic Concentrator, Half-Black Bottle
CPC - TB	=	Compound Parabolic Concentrator, Transparent Bottle

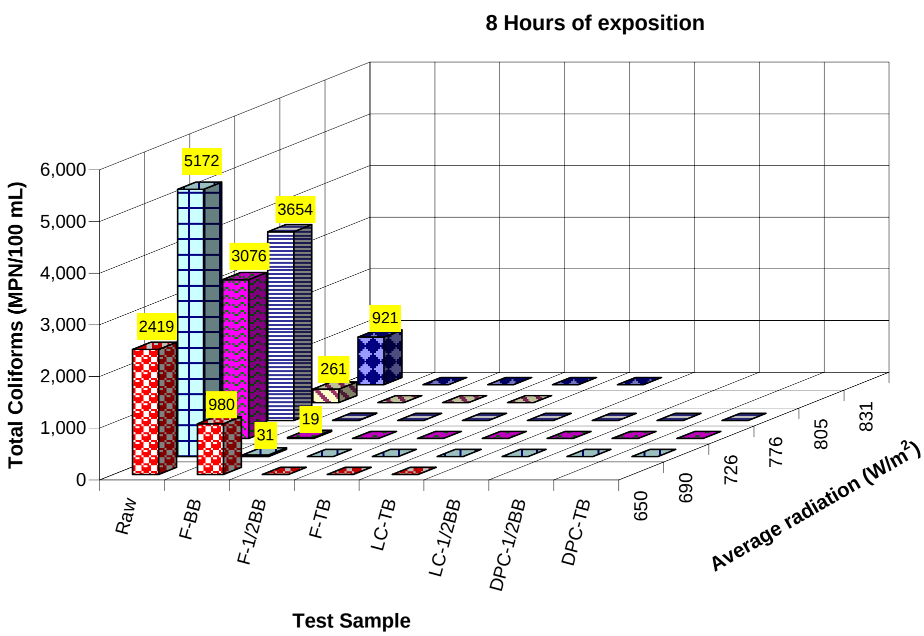

Figure 3.1 Results of water disinfection after 8 hours of exposure with several radiation levels.

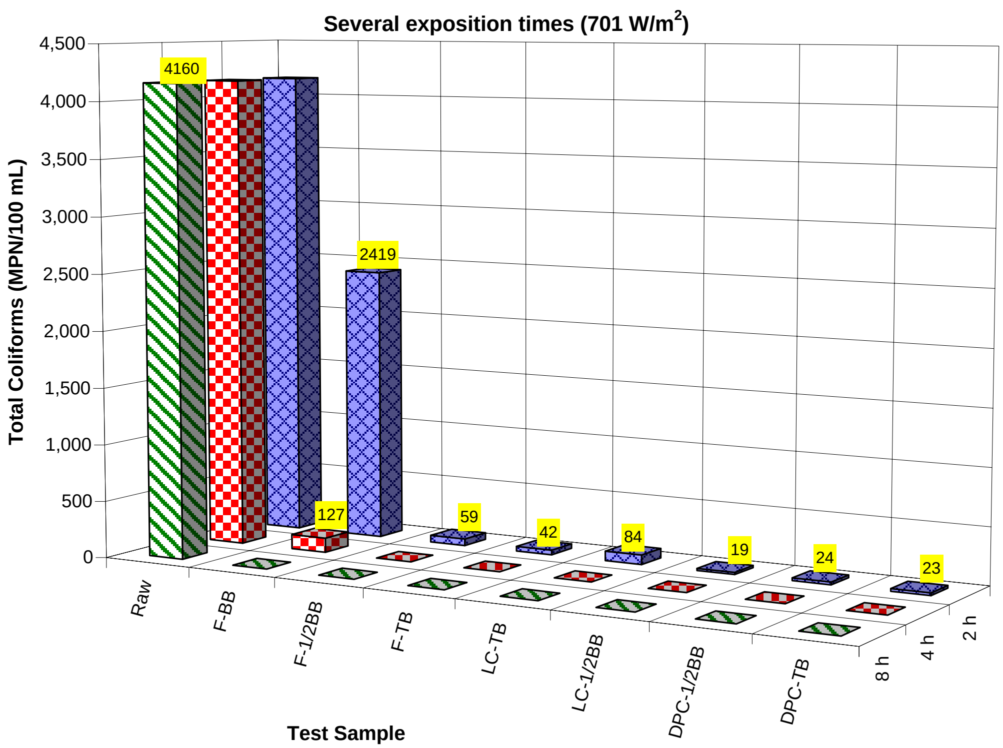

Figure 3.2 Results of water disinfection at several exposure times

4. CONCLUSIONS AND RECOMMENDATIONS

Solar disinfection technology is an option to improve the bacteriological quality of water for human consumption in rural communities; however, it is important to take into consideration two important factors.
The first factor is weather. In rainy days, when it is very cloudy and little solar radiation is received by the water, it is not possible to completely eliminate the total and fecal coliforms. For highly contaminated water, it is necessary to increase the water irradiation time, and the use of half-black bottles and solar concentrators is recommended.

The second factor is the affected people's habits and beliefs. The communities' perception, habits and beliefs regarding water must be taken into consideration. Otherwise, the period of assimilation of this kind of technologies can be very long, or the method can be rejected altogether.

It was found that, since more than 4 hours of daily solar radiation are available during most of the year in Norogachi, no solar concentrators are really necessary to ensure the complete elimination of bacteria. In Santa Lucía, however, the use of concentrators and half-black bottles, as well as more than 8 hours of solar radiation, are required to achieve acceptable disinfection efficiency.

It is essential to continue the search for reflective materials that are more weather-resistant and require less maintenance, which would prevent equipment abandonment due to deterioration.

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