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Full Length Research Paper

A study of solar disinfection for rural water supply

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Drinking water available to rural communities in many developing countries contains disease germs. Solar disinfection of water is becoming increasingly appreciated because of the feasibility of its application. This study investigated the level of transmission of ultraviolet light by bottles made of glass, poly vinyl chloride (PVC) and polyethlene terephthalate (PET) in relation to their ability to disinfect water samples in them; two brands of PET bottles, Ragolis and Voltic, were used. Ragolis bottle was the best both in ultraviolet light transmission and microbial inactivation. There was no microbial re-growth during 11 weeks storage of solar–treated water. Rural dwellers in Nigeria have easy access to large quantities of used PET bottles and can use the 1.5 L size to produce solar-disinfected water for drinking.

Key words: Rural water, solar disinfection, exposure time, turbidity, bacterial re-growth.

INTRODUCTION

It is well established that contaminated drinking water poses a major health threat to human beings worldwide and that the problem is particularly significant in rural communities of the developing countries. Waterborne diseases in developing countries lead to millions of deaths and billions of illnesses annually (Burch and Thomas, 1998). The World Health Organization (WHO), the United Nations Children's Educational Fund (UNICEF) and the Water Supply and Sanitation Collaborations Council (WSSCC) prepared a global water supply and sanitation assessment report (WHO, 2000). It states that at the beginning of the year 2000, one sixth of the world population (about 1.1 billion people) was without access to improved water supply.

Many researchers have been stating the problem in graphic terms such as, that waterborne diseases kill more than 400 developing world children every hour (Gadgil and Shown, 1995); that the average child in developing countries has more than two episodes of diarrheoa per year which weaken him and lay him bear to serious forms of illness (Burch and Thomas, 1998); and that the estimated number of children that die each year due to water–related diseases range from 2.5 million to 15 million (Jorgensen et al., 1998). The lack of adequate drinking water in rural areas of developing countries is a continually growing problem due to population increases.

Although there is no universally accepted standard for defining a developing country it can be usefully defined as a country in which ingestion of water–based pathogens is of frequent concern, and in which a significant portion of the population does not have access to water of acceptable drinking water standards. In much of rural and semi–urban areas of Nigeria, waterborne diseases such as cholera, typhoid fever and diarrheoa have continued to afflict the populace (fatally in unbearably large numbers of cases) at a time when these diseases are virtually extinct in the developed world. Almost on daily basis, newspapers report sad cases of cholera epidemics. In 1997, the quantity of water supplied in all 36 states of the federation was less than 25 litres per capita per day (lpcd) on the average (Ogedengbe, 1997) and with population pressure and lack of increasing water supply systems to match, the situation continues to get worse. Polio vaccines have been used to stem the manifestations of poliomyelitis, and oral rehydration therapy (ORT) has been applied in epidemics of cholera. However, the fact remains that people continue to ingest pathogens in waters available to them.

Water disinfection is acknowledged to be one of

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several interventions that can improve public health. Water disinfection methods that are easily employed in rural areas of developing countries are needed. Solar disinfection has been recommended by several researchers for use in countries that receive abundant sunshine, specifically the areas of the globe between latitudes 35°N and 35°S (Acra et al., 1984; IDRC, 1998). The most favourable belt (15°N to 35°N) encompasses many of the developing nations in North Africa and southern part of Asia. It has over 3000 h of sunshine hours per year and limited cloud coverage (Burch and Thomas, 1998; Gadgil and Shown, 1995; IDRC, 1998).

Solar disinfection is a water treatment method where drinking water samples are exposed to solar radiation to inactivate pathogenic organisms. Reportedly, this method has been shown to reduce incidence of diarrheoa in children living in a Massai village in Kenya (Conroy et al., 1996). It is well documented that the combined effects of sunlight–induced DNA alteration, photooxidative destruction and heat are responsible for inactivation of microorganism (Acra et al., 1984; Reed et al., 2000; SANDEC, 2001). The ultraviolet spectrum of light is primarily responsible for bacteria inactivation. Therefore containers, such as bottles, made of different materials can be usefully studied as to their ability to transmit this spectrum of light, with wavelength in the range 200 to 400 nanometers. This is the focus of this study.

The specific objectives are to investigate the level of transmission of ultraviolet spectrum of light by various bottles made of different materials; to determine the effects of exposure time, volume of water and its turbidity on microbial inactivation in samples of water in the various bottles; and to investigate the possibility of bacteria re-growth during storage of solar–disinfected water, thus establishing its shelf life.

The scope of the work is limited to inactivation of total coliform bacteria, other microorganisms such as viruses, fungi and algae were not monitored. Solar disinfection efficacy is usually established through inactivation of indicator organisms. The main characteristics of an ideal indicator organism are that: they are used for all types of water; they are present when enteric pathogens are present; they have a reasonably longer survival rate than most pathogens; testing methods for them are easy to perform; their density in water alludes to the extent of fecal pollution; and they are a member of the microflora of warm–blooded animals (Burch and Thomas, 1998; Jorgensen et al., 1998; IDRC, 1998; SANDEC, 2001). Thus, a disinfection method that kills indicator organisms-the coliforms–would have killed bacteria including the causative organisms of cholera, typhoid fever, etc, and protozoa, including the causative organism of amoebic dysentery.

METHODOLOGY

The items of work involved in conducting this study consisted of the following, in the main: determination of the extent of ultraviolet-visible light transmission through samples from bottles made of different materials; investigation of the effects of relevant parameters and their interactions on the efficacy of bacteria inactivation by UV radiation; determination of optimal wavelength of light spectrum for bacteria inactivation and the extent of the inactivation, using synthetic water samples; application of the results to real water samples from a stream and from a well; and determination of shelf life for the disinfected water samples (Ajayi, 2010).

Bottles made of polyethylene terephthalate (PET), from used Ragolis and Voltic water bottles, glass, and poly vinyl chloride (PVC) were collected. Small pieces from them (1 cm by 3 cm) were tested, using a Cary 100 ultraviolet–visible spectrometer[1] as to ability to transmit UV light. Six types of bottles were used, namely: PET (Ragolis and Voltic), PVC (plain and coloured) and glass (plain and coloured). In each case, when the 'run' button was pressed the wavelength and the percentage transmittance results were displayed on the screen in graphical mode which was sent to the printer.

The bottles, labels removed, were washed carefully with non-disinfectant soap. Using distilled water dosed with quantities of kaoline clay to produce turbidity values ranging from zero to 60 NTU, a 2^3 factorial experiment was set up. The parameters were turbidity (T) with a low of 0 NTU and a high of 60 NTU; exposure period (E) with a low of 30 minutes and a high of 300 min; and water volume in litres (V) with low and high set at 0.5 L and 1.5 L respectively. This was to determine the significance, if any, of the factors T, E and V and their interactions in the solar disinfection process. At each withdrawal of samples for microbial analysis, ambient temperature and water sample temperature were recorded. The weather condition was also noted. Analytical procedure for coliform count in the water samples was by pour plate technique, using standard methods (APHA, 1985). This involved serial dilution in a set of test tubes, transfer into sterile Petri Dishes, addition of sterile molten MacConkey agar and incubation at 35°C for 48 h. The optimal wavelengths for bacterial inactivation were determined.

Real (natural) water samples taken from a stream, representing a surface water source, and a well (a groundwater source) were subjected to the solar disinfection procedures. In all the solar disinfection experiments the samples were laid out in the open, away from shadows. Figure 1 shows a typical layout of bottles containing water samples.

Finally, bottles containing disinfected water were stored, some in normal room light and others in the dark, to investigate the possibility of bacterial re-growth in order to establish shelf life of the disinfected water.

RESULTS AND DISCUSSION

The percentage values of transmission for light wavelengths varying from 200 to 600 nm are as shown in Figure 2 for material samples from the six types of bottles. The graphs were re-plotted from the Cary 100 spectrophotometer printer graphs. It can be seen from these graphs that for wavelengths of light 300 to 600 nm (covering ultraviolet and visible light spectrums) the material of which PET Ragolis bottle is made is the highest transmitter, followed by PET Voltic and plain glass materials respectively. Those of white and coloured PVC and of coloured glass materials are poor

[1] The UV–visible spectrometer available at the Central Science Laboratory of Obafemi Awolowo University, Ile-Ife, was used.

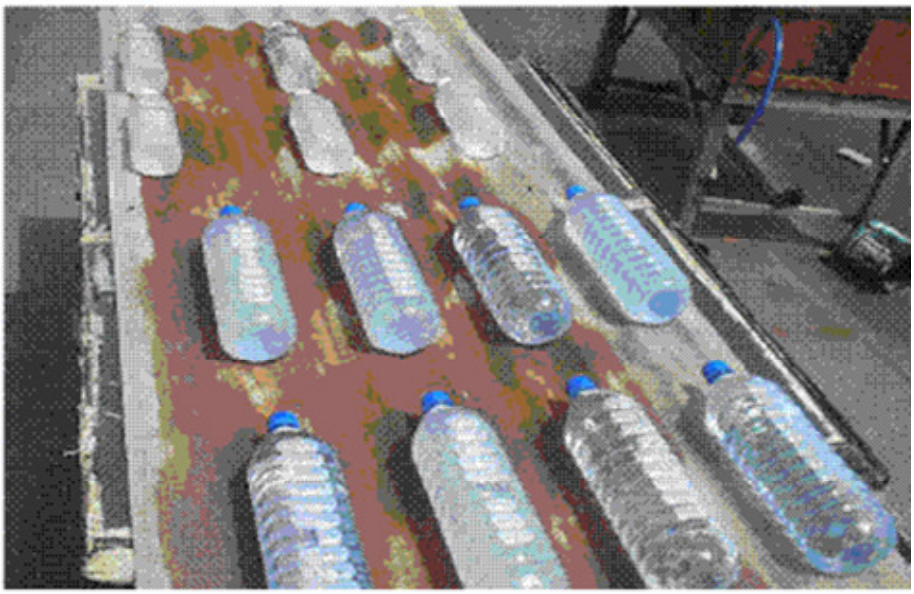

Figure 1. Water samples in PET (Ragolis and Voltic) laid out for solar disinfection.

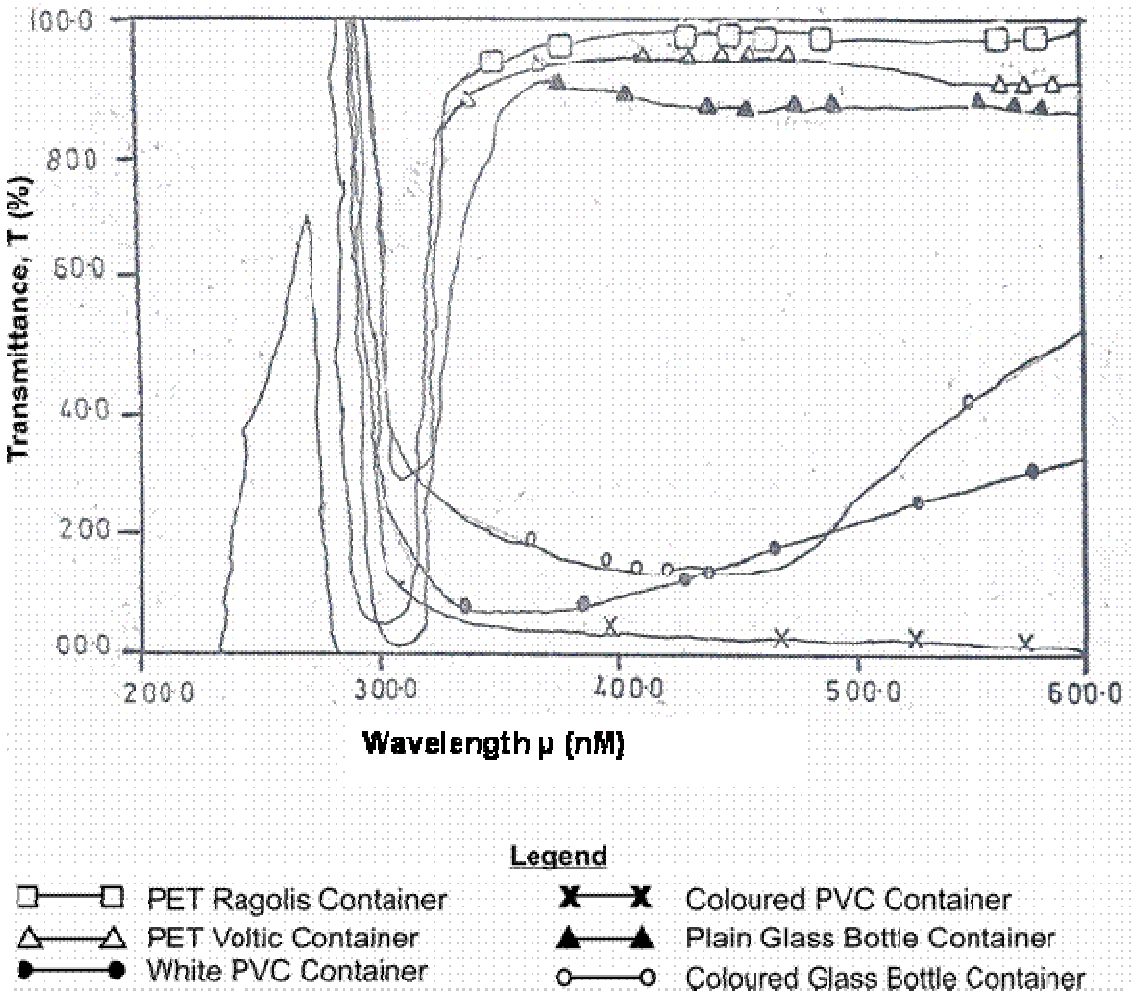

Figure 2. Cary 100 UV-visible spectrometer readings for the containers.

Table 1. Complete factorial experiment with analysis of variance.

Run	Factors			Variables and interactions	Average percentage microbial removal (%)	Standard deviation	Yates' algorithm			Divisor	Effects	Sum of squares	Degree of freedom	Mean sum of squares	F-values
	Turbidity (NTU)	Exposure (Hour)	Volume (L)				1	2	3						
1	0.00	0.50	0.50	1	98.70	0.00	191.30	389.95	765.45	8	95.68	18309.80	-		
2	60.00	0.50	0.50	T	92.60	0.99	198.65	375.50	-13.05	4	-3.26	21.29	1	37.41	1.18
3	0.00	5.00	0.50	E	99.75	0.07	178.50	-6.95	25.85	4	6.46	83.53	1	253.13	7.95**
4	60.00	5.00	0.50	TE	98.90	0.14	197.00	-6.10	11.35	4	2.84	16.10	1	30.42	0.96
5	0.00	0.50	1.50	V	92.30	0.42	-6.10	7.35	-14.45	4	-3.61	26.10	1	129.61	4.07
6	60.00	0.50	1.50	TV	86.20	1.27	-0.85	18.50	0.85	4	0.21	0.09	1	1.45	0.05
7	0.00	5.00	1.50	EV	98.50	0.07	-6.10	5.25	11.15	4	2.79	15.54	1	114.76	3.61
8	60.00	5.00	1.50	TEV	98.50	0.07	0.00	6.10	0.85	4	0.21	0.09	1	3.25	0.10
					Error							31.82	4	7.96	
					Total sum of squares							162.74	7	23.25	

Confidence level at: a) 90%, $F_{0.10}$ (1,4) = 4.54 b) 95%, $F_{0.05}$ (1,4) = 7.71 c) 97.5%, $F_{0.025}$ (1,4) =12.22 d) 99%, $F_{0.001}$ (1,4) = 21.20; ** Significant at 95% confidence level ($F_{4,1}$).
F-values = Mean sum of squares / Mean sources error;
r = number of replication = 2;
k = number of variables = 3;
n = number of observations = 8;
T = Sum of all data;
Estimate = final Yates value/divisor;
Sum of squares = $r2^{(k-2)}$ $(estimate)^2$;
Correction term, C = T^2/rn;
Mean sum of squares = Sum of squares divided by the Degree of freedom;
Error of squares = Total sum of squares – Treatment sum of squares – Replication sum of squares.
Total degree of freedom = $2^n - 1$
$= 2^3 - 1$
$= 7$

transmitters. For the three highest transmitters of light the value for the wavelength corresponding to the highest level of transmittance was 371 nm. This value is within the ultraviolet spectrum. At this wavelength, the percentage transmission through the six bottle types were 100 for PET Ragolis, 96.6 for PET Voltic, 92.8 for plain glass, 18.5 for coloured glass, 12.6 for white PVC and 7.8 for coloured PVC.

The results of the factorial experiment using the Yate's Algorithm (Johnson, 2003), and analysis of variance (ANOVA) are summarized in Table 1. From this table it can be seen that exposure time is significant at 95% confidence level, with an F–value of 7.95 compared to $F_{0.05}$ (1, 4) of 7.71. The parameter V and the interaction of exposure time (E) and volume (V) are not significant even at 90% confidence level ($F_{0.10}$ (1, 4) =4.54). However, with F-values respectively at 4.07 and 3.61, they can be considered important. The effects of turbidity (T), turbidity–volume interaction (TV) and turbidity–exposure time–volume interaction (TEV) are very low. It was fortunate that the weather condition with respect to cloud cover, ambient temperatures was reasonably stable during the study.

Table 2 summarizes the results of microbial removal for all the six types of bottles, for the various exposure periods from two minutes to 300 min. The other variables were kept constant: turbidity zero, volume of water sample 1.5 L. The results show 100% microbial inactivation at 5 h in the three samples contained in PET Ragolis, PET Voltic and Plain glass and 99.62% in white PVC. The levels of removal in coloured glass (75.56%) and coloured PVC bottle (14.36%) were very

Table 2. Summary of results of microbial removal for all types of bottles.

S/N	Exposure period (minutes)	Ragolis PET bottles average microbial removal (%)	Voltic PET bottles average microbial removal (%)	White PVC bottles average microbial removal (%)	Coloured PVC bottles average microbial removal (%)	Plain glass bottles average microbial removal (%)	Coloured glass bottles average microbial removal (%)
1	2	0.00	0.00	0.00	0.00	0.00	0.00
2	5	0.89	0.85	0.36	0.31	0.89	0.89
3	10	9.79	8.45	2.22	1.87	2.67	2.67
4	15	26.23	22.23	9.56	2.65	20.89	3.56
5	20	34.67	33.79	17.74	3.78	34.23	16.45
6	30	50.90	50.02	23.78	6.89	44.46	19.11
7	40	63.96	63.94	41.23	7.78	64.01	28.45
8	60	91.06	90.24	41.12	7.78	74.89	30.45
9	90	93.38	93.36	61.28	8.58	94.36	41.02
10	120	99.64	99.65	74.05	9.34	99.64	45.78
11	150	99.87	99.86	91.40	9.96	99.82	50.23
12	180	99.98	99.99	96.83	10.31	99.96	56.89
13	210	99.99	99.99	99.11	11.56	99.99	63.12
14	240	99.99	99.99	99.29	12.23	99.99	65.34
15	270	99.99	99.99	99.51	13.56	100.00	68.89
16	300	100.00	100.00	99.62	14.36	100.00	75.56

poor. These results show that the bottles that transmitted UV light the most (Figure1) were the ones in which highest levels of microbial inactivation occurred.

The temperature of water samples in the bottles corresponding to the microbial removal in Table 2 are shown in Table 3. Plain glass heated up most rapidly. The sample in it had reached 50°C in 2.5 h and reached 58°C in 5 h. The samples in PET Ragolis and PET Voltic bottles reached 50°C at about 3 h and 55°C and 56°C temperature respectively at 5 h. Table 4 places together for each bottle type the percent transmittance at 371 nM wavelength and corresponding microbial removal together with final water temperature after five hours of exposure. It shows the combined effects of UV and water temperature on microbial inactivation. Judging from the combination of 100% removal at 100% UV transmittance and 55°C water temperature for PET Ragolis; 100% removal at 96.6% transmittance and 56°C temperature for PET Voltic; and 100% removal at 92.8% transmittance and 58°C temperature for plain glass, it can be deduced that the effects of % UV transmittance and water sample temperature on microbial inactivation are synergistic. The transmittance capability of the container materials would appear to be more important than the final water temperature, at least at these relatively low water temperatures (between 50 and 60°C). It has been reported that killing or inactivation of bacteria by UV light is by photochemical alteration of cellular DNA; that the DNA must be damaged faster than the microbe can repair it (Acra et al., 1984; Reed et al., 2000) for the process is reversible as the bacteria may again become viable if conditions allow cells to be repaired. It has also been reported, concerning the separate effect of temperature, that micro-organisms can only function within certain temperature ranges because of limitations of their metabolism. When these temperature ranges are exceeded, proteins and other micromolecules are denatured, with the likelihood of killing the microbe (McVeigh, 1977; Wegelin et al., 1994).

Tables 5a and b present the results of solar disinfection of stream water and well water respectively, using Ragolis bottles. The experiment was repeated using Voltic bottles shown in Table 6a and b. The results show, in both bottle types, complete inactivation of coliforms within 5 h for surface water and well water. The results of water samples solar-treated for varying hours and stored in room light for 11 weeks are shown in Table 7. There was no re-growth. The control and the solar-treated samples were tested every week and the testing was stopped after 11 weeks. As can be seen in the table there was reduction in bacterial contamination over time. It can be concluded from this that solar-treated water samples in PET Ragolis bottles remain free of contamination for at least 11 weeks when they had been exposed to good sunshine for about six hours.

The results of this study should be useful in developing countries such as Nigeria where there is much sunshine with moderate cloud cover. Furthermore, used PET

Table 3. Temperature variation with period of exposure.

S/N	Exposure Period (Minute)	Temperature (°C)					
		Ragolis PET	Voltic PET	White PVC	Coloured PVC	Plain Glass	Coloured Glass
0	0	26	26	26	26	26	26
1	2	26	26	26	26	26	26
2	5	26	26	26	26	26	26
3	10	27	27	27	27	28	27
4	15	30	29	28	28	30	28
5	20	34	35	31	29	34	29
6	30	39	39	34	31	39	31
7	40	41	42	37	32	43	32
8	60	43	44	39	34	46	34
9	90	46	46	39	35	48	35
10	120	47	47	41	37	49	37
11	150	49	49	43	39	50	38
12	180	51	51	45	40	52	40
13	210	52	51	47	42	53	41
14	240	52	52	48	43	54	43
15	270	53	54	49	45	56	43
16	300	55	56	49	47	58	45

Table 4. Final microbial removal, water temperature and UV-A transmittance of each type of container.

Container type	Percentage transmittance of UV-A at 371nM (%)	Final microbial removal (%) after 5 h exposure period	Final water temperature after 5 h exposure period (°C)
Ragolis PET	100	100	55
Voltic PET	96.6	100	56
White PVC	12.6	99.62	49
Coloured PVC	7.8	14.36	47
Plain glass	92.79	100	58
Coloured glass	18.5	75.56	45

Table 5a. Solar disinfection of stream water using Ragolis bottle.

S/N	Sample code	Coli MPN presumptive (cell/100 ml)	Water temperature (°C)	Ambient temperature (°C)
1	Control	>1100	25	30
2	S01	>1100	32	31
3	S02	1100	39	33
4	S03	90	44	34
5	S04	0	45	33
6	S05	0	46	32

Table 5b. Solar disinfection of well water using Ragolis bottle.

S/N	Sample code	Coli MPN presumptive (cell/100 ml	Water temperature (°C)	Ambient temperature (°C)
1	Control	>1100	29	30
2	W01	>1100	31	31
3	W02	>1100	37	33
4	W03	300	41	34
5	W04	100	45	33
6	W05	0	47	32

Table 6a. Solar disinfection of stream water using Voltic bottle.

S/N	Sample code	Coli MPNPresumptive (cell/100 ml)	Water temperature (°C)	Ambient temperature (°C)
1	Control	>1100	25	30
2	S01	>1100	31	31
3	S02	1100	40	33
4	S03	100	44	34
5	S04	0	46	33
6	S05	0	47	32

Table 6b. Solar disinfection of well water using Voltic bottle.

S/N	Sample code	Coli MPN presumptive (cell/100 ml)	Water temperature (°C)	Ambient temperature (°C)
1	Control	>1100	29	30
2	W01	>1100	32	31
3	W02	>1100	36	33
4	W03	280	42	34
5	W04	90	45	33
6	W05	0	46.5	32

bottles are available in large quantities all over the country from social events such as wedding and burial ceremonies. Although this study shows that plain glass bottles are good in terms of their UV light transmission, water temperature and microbial inactivation, they are more fragile and not readily available. Available waters in streams and hand-dug well will usually have turbidity values much below 60 NTU and even much below 30 NTU – a value suggested as maximum for direct solar disinfection (SANDEC, 2001). Nevertheless water with settleable suspended solids can be drawn into a covered bucket from where the supernatant is drawn into 1.5 L PET bottles for the solar disinfection process. Extension workers such as in the Department of Agricultural Extension and Rural Sociology would be useful in carrying the results of this study to rural areas as usual.

To be sure, cysts and worms are resistant to UV light, and even to chlorination. A filtration process would be required to remove these (Burch and Thomas, 1998). In this connection a relationship would need to be

Table 7. Result of bacteria re-growth experiment.

Sample	Period of exposure of water sample to sunlight (hours)	Coli MPN presumptive (cells/100 ml)	Coli MPN presumptive (cells/100 ml)
		Samples immediately after sunlight exposure	Samples stored in room light for 11 weeks
Control	0	640000	480000
SW1	1	57000	2500
SW2	2	11200	240
SW3	3	1500	93
SW4	4	720	10
SW5	5	63	9
SW6	6	0	0

established between use of activated palm kernel shell filters (Ogedengbe et al., 1985), and solar disinfection of water supplies.

CONCLUSION

From the results presented in this paper, the following conclusions can be drawn:

1) PET bottles are the most suitable containers for solar disinfection of water among the materials studied. Where different design shapes are available, the cylindrical and conical shape show more transmittance of UV-A than the square and rectangular shape, therefore, are more appropriate for the use in solar disinfection. Plain glass bottles were also found suitable for solar disinfection. However, the problem of availability and durability make them unsuitable for regular use. Coloured glass and PVC bottles are not suitable for solar disinfection.
2) Samples in 0.5 L, 0.75 L and 1.5 L bottles experienced similar E. coli disinfection rate with exposure period of 5 hours. Water volumes from 0.5 L to 1.5 L can therefore be treated in approximately the same amount of time.
3) Period of exposure of water to sunlight is the most significant factor to achieving complete bacteria inactivation. Exposure of samples to sunlight on a sunny day of average ambient temperature of 32°C for 5 h resulted in total bacteria removal on all water samples using PET container types.
4) The weather condition must be favourable, that is, clear and sunny to ensure availability of solar radiation for total microbial inactivation in water samples. Weather conditions other than sunny (i.e. cloud cover and with low temperature) may require longer exposure period or exposure for two consecutive days, to achieve total inactivation of bacteria.
5) Bacteria re-growth was not recorded from the treated water samples with complete bacteria removal within the 11- week period of testing.
6) Water samples with high turbidity should first be allowed to settle for some period and decanted to remove the settled solid particles before exposure to sunlight to avoid interference of solid particles in UV-A penetration.

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