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Solar photo-oxidative disinfection of drinking water: preliminary field observations

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R.H. REED, S.K. MANI AND V. MEYER. 2000. The feasibility of using solar photo-oxidation to inactivate faecal bacterial contaminants in drinking water has been evaluated under field conditions in India and South Africa. Freshly drawn samples from all six test water sources were low in dissolved oxygen, at 13–40% of the air saturation value. However, vigorous mixing followed by exposure to full-strength sunlight in transparent plastic containers (1–25 l capacity) caused a rapid decrease in the counts of faecal indicator bacteria, giving complete inactivation within 3–6 h, with no evidence of reactivation. These results demonstrate that solar photo-oxidation may provide a practical, low-cost approach to the improvement of drinking water quality in developing countries with consistently sunny climates.

INTRODUCTION

Water-borne disease is a significant global issue, with approximately one billion people lacking access to a reliable supply of clean drinking water (Black 1999). The consumption of drinking water contaminated with pathogenic microbes of faecal origin is a significant risk to human health in the developing world, especially in remote rural areas and peri-urban 'shanty' communities, with over 3 million deaths per year attributed to water-borne diarrhoeal diseases, especially among infants and young children in poor communities in Africa, Asia and South America (Anon. 1997a). As a result, there is an unmet need for practical systems capable of treating contaminated drinking water in developing countries, thereby reducing the impact of water-borne disease.

In communities with no satisfactory safe drinking water supply, small-scale self-help measures can be used at the household level; these include boiling, filtration and/or chemical treatment (Heber 1985; Anon. 1997b). One small-scale approach that has gained support in recent years makes use of the disinfectant properties of sunlight to treat contaminated water in transparent plastic bottles or plastic bags, in a process termed solar disinfection (Acra *et al.* 1990). Experimental studies have demonstrated that this approach is effective under conditions where (i) the drinking water is subject to contamination with faecal bacteria and (ii) the climate is favourable enough to provide sufficient sunlight (Wegelin and Sommer 1997).

Most of the research into the effectiveness of solar disinfection has focused either on the pasteurizing effects of solar radiation at temperatures above 45–50 °C, in a process termed solar pasteurization (e.g. Ciochetti and Metcalf 1984; Jørgensen *et al.* 1998), or on the synergistic interaction between temperature and solar radiation (e.g. Wegelin *et al.* 1994; McGuigan *et al.* 1998). However, recent laboratory studies have demonstrated that the inactivation of faecal bacteria in sunlight is also strongly dependent upon the oxygen status of the water, due to the formation of free radicals derived from dissolved oxygen via solar photo-oxidation (Reed 1997a). Such observations indicate that solar photo-oxidative disinfection may be a useful approach to water treatment, even in the absence of any thermal effects (Reed 1997b).

The present study was carried out to assess the effectiveness of solar photo-oxidative disinfection under field conditions in India and South Africa, using hand-drawn sources of drinking water. The results show that the contaminant faecal coliform bacteria naturally present in these drinking water sources were inactivated by oxygenation, achieved by vigorous mixing of the water in transparent plastic containers, followed by exposure to full-strength sunlight for up to 6 h.

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MATERIALS AND METHODS

Water sources

All of the water sources tested in the present study were in use by the local communities for drinking and general household purposes. In the Indian field trials (May–June 1997), contaminated water samples were obtained from unprotected dug wells in Jaipur District: sources IN1 and IN2 were wells in the village of Udaipur Gilaria, 10 km north-east of Jaipur, representing heavy contamination and moderate faecal contamination (Feacham 1977), respectively; source IN3 was a moderately contaminated well in Ursewa village, 70 km south-west of Jaipur. The South African field trials (August–October 1998) used sources from Gauteng district: source SA1 was a shallow, unprotected dug well at Mandela village (rural squatter camp), near Mabopane, 38 km north-east of Pretoria; source SA2 was from a site on the Apies river near Hammanskraal, 45 km north of Pretoria; source SA3 was a stream, Soutpan Spruit, Soshanguve, 32 km north-east of Pretoria. All three South African sources were heavily contaminated with faecal bacteria, with over 1000 faecal coliforms per 100 ml (see Table 1).

In all instances, water samples were taken using sterile containers and either tested immediately for physicochemical characteristics (turbidity, temperature and dissolved oxygen) or transported in darkness, within 1 h of sampling, to the Birla Institute of Scientific Research, Jaipur (India) or Technikon Northern Gauteng (South Africa) for analysis of faecal coliforms and solar experimentation.

Physicochemical measurements

Sample turbidity was assayed using either a spectrophotometer (CE1010; Cecil, Cambridge, UK), calibrated in notional turbidity units (NTU) against a formazan standard (sources IN1–IN3), or a turbidity meter (DRT 15CE; Lovibond, Salisbury, UK) (sources SA1–SA3). Dissolved oxygen (mg l^{-1}) and temperature (°C) were measured using either (i) a probe (9010; Jenway, Dunmow, UK) (sources IN1–IN3) or (ii) an M90 system (Mettler Toledo, High Wycombe, UK) (sources SA1–SA3) while solar irradiance was determined using either (i) a pyranometer (SP1100; Syke, Llandrindod Wells, UK) or (ii) a quantum photo/radiometer (Delta Ohm, Hunger, Germany).

Illumination in sunlight

Water samples were incubated in locally obtained, clear plastic containers of either 1- or 22-l capacity (IN1–IN3) or 2- or 25-l capacity (SA1–SA3). Containers were first aerated by vigorous mixing for at least 2 min, to ensure oxygen saturation (Reed 1997b) and then exposed to full-strength sunlight, measured at > 500 W m^{-2} for the duration of the experiment, as required for effective solar inactivation (Acra *et al.* 1990; Wegelin 1999). All containers were shaken (mixed) at hourly intervals, to maintain oxygen equilibration between the water samples and the atmosphere, with sampling every hour from 10 a.m. until 4 p.m. Control samples for all water sources were incubated indoors in darkness.

Enumeration of faecal bacteria

Aliquots of water were processed by standard bacteriological membrane filtration (MF) procedures, using 1·0–100·0 ml water filtered through either GN-6 (Gelman; Michigan, USA) or HC membranes (Millipore, Bedford, MA, USA) and enumerated either on Membrane Lauryl Sulphate medium (Merck, Poole, UK) (Anon. 1994; sources IN1–IN3) or on M-FC agar (Merck) (Anon 1992; sources SA1–SA3). Media were incubated at 44·5 ± 0·5 °C for 24 h prior to counting. The number of presumptive faecal (thermotolerant) coliforms (FC) in each sample is expressed per 100

Table 1 Representative physicochemical and microbiological data for water sources used in field trials of solar photo-oxidation (India and South Africa)

Source	Turbidity (NTU)	Temperature (°C)	O_2 (mg l^{-1})	O_2 saturation (%)	Initial FC (cfu 100 ml^{-1})	FC $T_{99·9}$ (min)
IN1	2·4	27·5	3·1	39	5500	125
IN2	4·0	28·0	2·7	35	900	150
IN3	7·9	23·3	1·1	13	660	220
SA1	2·1	18·8	3·7	40	1450	245
SA2	3·7	19·0	3·2	34	2900	255
SA3	1·5	15·0	4·0	39	6750	280

FC, Faecal (thermotolerant) coliforms; cfu, colony-forming units; FC $T_{99·9}$, 99·9% inactivation time for FC (oxygenated, full sunlight) in plastic bottles of either 1 l (IN1–IN3) or 2 l (SA1–SA3) capacity; NTU, notional turbidity units.

ml, based on the formula: FC per 100 ml = (MF colony count × 100) / (sample volume in ml). For counts of presumptive faecal streptococci (FS), MF samples were enumerated using Slanetz and Bartley medium (Merck) (Anon. 1994) incubated at 44·5 ± 0·5 °C for 48 h prior to counting. All counts were performed in duplicate. Samples were always shielded from direct sunlight during transport to the laboratory and throughout processing to avoid photoinactivation.

RESULTS AND DISCUSSION

Table 1 shows typical data for the physicochemical characteristics of water samples from each source. All were of low turbidity, at under 10 NTU, ensuring the effective penetration of sunlight during solar photo-oxidation experiments, in contrast to other field studies which have investigated the effects of solar treatment on highly turbid water sources where optical inactivation is minimal and thermal inactivation enhanced (Joyce *et al.* 1996; McGuigan *et al.* 1999). The level of dissolved oxygen in freshly drawn water samples was low, at 1·1–4·0 mg l^{-1} O_2, representing 13–40% of the oxygen saturation value at the corresponding water temperature (Green and Carritt 1967). A low dissolved oxygen status is a common feature of many surface and ground waters, due to the limited solubility and low diffusion coefficient of oxygen in water, the consumption of oxygen in redox reactions with inorganic compounds and the respiratory activity of aquatic microorganisms (Malard and Hervant 1999). Previous experiments have shown that failure to increase the oxygen content of water to its air-equilibrated value can substantially reduce the rate of solar inactivation of faecal bacteria (Reed 1997a; Meyer 1999).

Table 1 also shows that all sources were contaminated with FC, ranging from 660 FC 100 ml^{-1} (IN3) to 6750 FC 100 ml^{-1} (SA3). At such levels, the untreated water sources can be regarded as unsatisfactory for human consumption, representing a high risk of transmission of water-borne disease, since they all indicate substantial faecal contamination, of either human or animal origin, failing to meet international guidelines for drinking water quality (e.g. Lewis 1991; Anon. 1997b).

Table 1 also shows the results of preliminary experiments where fully mixed (air-equilibrated) water samples in transparent plastic drinks bottles of either 1 l (IN1–IN3) or 2 l (SA1–SA3) capacity were then exposed to sunlight. The effect of this treatment on the contaminant FC is expressed in terms of the time required to reduce the FC count by 99·9% ($T_{99.9}$, based on a plot of log FC 100 ml^{-1} against time and determined as the time required to give a 3-log reduction in FC 100 ml^{-1}; Reed 1996). All six water samples showed a rapid inactivation of FC on exposure to sunlight under oxygen-equilibrated conditions, while no significant change in FC counts was observed for control samples kept in darkness (data not shown). The $T_{99.9}$ values given in Table 1 are sufficient to give a zero count for FC 100 ml^{-1} within approximately 3–6 h, depending upon the intial FC count, and are comparable to those of earlier experimental studies using water deliberately contaminated either with pure cultures of coliform bacteria or with sewage (e.g. Gameson and Saxon 1967; Evison 1988). To test for the reactivation of sublethally injured bacteria following *illumination* (Fujioka and Narikawa 1982), samples were kept in darkness for a further 24 h and then tested for FC; there were no detectable counts, confirming that the inactivation was irreversible.

Figures 1 and 2 show time course data for the solar inactivation of faecal indicator bacteria in larger plastic containers holding either 22 l (IN1) or 25 l (SA1) of fully-mixed (oxygen-equilibrated) water from a single representative source from each country. Both sources showed rapid inactivation of FC on exposure to full-strength sunlight, with FC $T_{99.9}$ values only slightly higher than those obtained for the smaller volumes (cf. Table 1), at 150 min for IN1 (Fig. 1) and 290 min for SA1 (Fig. 2), while control samples maintained in darkness showed no measurable change in FC count. Sample IN1 was also assessed for FS, giving a lower initial FS plate count but a similar rate of inactivation compared with FC (Fig. 1). A sample of SA1 made anaerobic by bubbling with nitrogen prior to exposure to sunlight gave a far slower rate of FC inactivation than under air-equilibrated conditions (Fig. 2), confirming an oxygen requirement for the rapid solar inactivation of FC (Reed 1996).

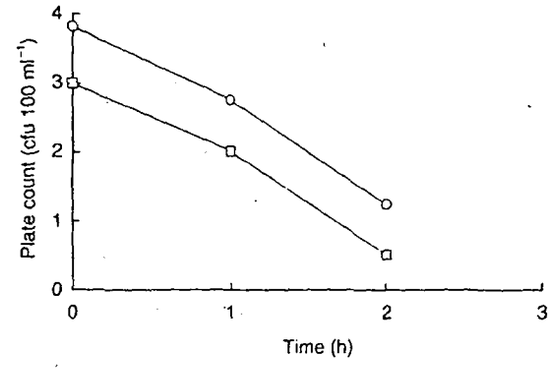

Fig. 1 Inactivation of faecal coliforms (○) and faecal streptococci (□), expressed as colony-forming units (cfu) 100 ml^{-1}, in water samples from source IN1 (22-l plastic container). No counts were detected for either faecal coliforms or faecal streptococci at 3 h

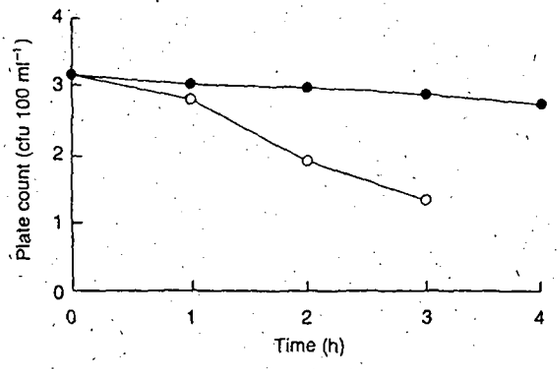

Fig. 2 Inactivation of faecal coliforms (expressed as colony-forming units (cfu) 100 ml^{-1}) in oxygenated (○) and deoxygenated (●) samples from water source SA1 (25-l plastic container). No counts were detected in the oxygenated sample after 3 h

Throughout exposure to sunlight, the temperature of the water samples reached a maximum of 30 °C (SA1–3) and 38 °C (IN1–3). These values are below the lethal temperatures of faecal bacteria (Anon. 1994) and lower than the level required for optimal synergy between optical and thermal inactivation (McGuigan *et al.* 1998; Wegelin *et al.* 1994; Lawand *et al.* 1997). These results clearly demonstrate that solar photo-oxidation is sufficient to inactivate FC bacteria in heavily contaminated water sources under field conditions, supporting the findings of earlier, laboratory-based studies (Reed 1997a). The data obtained using containers of 22 and 25 l capacity are especially promising, since they demonstrate that a volume of water appropriate for the daily drinking requirements of an individual family could be treated using solar photo-oxidation. It is noteworthy that solar photo-oxidation may be particularly relevant in rural India where there are significant problems related to the spread of water-borne disease (e.g. Nigam *et al.* 1997) and where there are records of solar water treatment dating back over 2000 years. As one of the traditional approaches to the provision of 'safe' water in India (Patwardhan 1990) this may assist its implementation, which is influenced strongly by the socio-cultural background of end-users (Wegelin 1999).

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