Disinfection of drinking water using photocatalytic technique

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High surface-area TiO_2 photocatalysts supported on a glass tube and a stainless steel plate were prepared and evaluated for their bactericidal effect using water primed with *Escherichia coli*, in a quartz reactor using 350 nm light and solar light. *E. coli* concentration decreased to a safe level from initial concentration of 500–100,000 bacteria/ml during 4 h of photolysis using 350 nm light and solar light. Time required for disinfection of water was found to increase with increase in the concentration of bacteria. Dissolved inorganic impurity (1 wt% NaCl) did not have any adverse effect on bactericidal activity. However, small amount of dissolved organic impurity (10 ppm nutrient agar) decreased bactericidal activity by ~40%. The technique was found to be effective when 1 l of water was photolysed by solar light in a plastic tray containing TiO_2 photocatalyst coated on a stainless plate. Our study indicates that the technique can be used for disinfection of ~20 l water daily using solar light. Based on the photocatalytic technique using solar light, a viable, simple and easy-to-use device for disinfection of drinking water on litre scale is reported.

Keywords: Photocatalytic technique, supported TiO_2 photocatalyst, sunlight, water disinfection.

IN a large number of underdeveloped and developing countries, there is scarcity of safe drinking water, particularly in summer when there is plenty of sunlight. People are forced to drink contaminated water infested with disease-causing bacteria. Various methods like chlorination[1], ozonation[2], boiling[3] and irradiation by UV light[4] are used to purify water. However, these methods require chemicals, fuel and electricity, which are not available in remote, undeveloped areas. Hence there is need for a simple method which can work without electricity, chemicals or fuel. Under this condition photocatalytic deactivation of bacteria by non-toxic, reusable photocatalyst using solar light may prove to be an ideal technique for water disinfection. However, not much work has been done to develop a viable, simple and easy-to-use device which can disinfect drinking water on litre scale using the photocatalytic technique. Hence the aim of this work was to design such a device and evaluate it for photocatalytic water disinfection using solar light.

TiO_2 is known to be an effective photocatalyst[5–9]. It is also physiologically inert[10]. Holes (h^+) and electrons (e^-) are generated on the TiO_2 surface[11] when it is exposed to ultraviolet light. Holes (h^+) can oxidize and kill bacteria. Extensive work had been carried out to evaluate bactericidal effect of TiO_2 in powder form using UV light[12–16]. Photocatalytic activity of TiO_2 powder had been used for remediation of wastewater[17,18]. However, separation and reuse of TiO_2 powder is difficult. Such photocatalyst in the powder form cannot be used, particularly for application in purification of drinking water. So it is desirable to use supported TiO_2 photocatalyst which can be separated easily and used repeatedly. Hence supported TiO_2 photocatalyst under solar light may be ideal for disinfection of drinking water. However, the intensity of UV fraction in solar light is small. Hence to utilize solar light effectively, high surface area TiO_2 was prepared by hydrothermal technique and coated on a glass tube and stainless steel plate and used as photocatalyst. These supported photocatalysts were evaluated for their bactericidal activity for disinfection of drinking water using solar light and 350 nm light. To simulate the conditions during actual use, bactericidal effect was evaluated in a closed reactor without any stirring, gas flow or application of electric field[19]. The effect of *Escherichia coli* concentration on organic and inorganic impurities dissolved in water was evaluated on the bactericidal activity of photocatalysts. To study the viability of this technique for disinfection of water on litre scale, a simple and easy-to-scale-up device was designed and evaluated for disinfection of water using solar light and the results are reported here.

High surface area TiO_2 was prepared by hydrothermal method using titanium isopropoxide[20] and was characterized by XRD, UV–visible spectroscopy and N_2 sorption technique. TiO_2 was coated on a glass tube (1.6 cm OD, 35 cm length) by the dip-coating method, calcined at 425°C and evaluated for photocatalytic bactericidal activity by keeping it in a closed quartz cell having 2.5 cm internal diameter and 35 cm length. The glass tube coated with TiO_2 had 12 holes (5 mm diameter) on its wall for better mass transfer (Figure 1). Water samples containing various concentrations of *E. coli* were prepared using sterilized distilled water. About 100 ml water was photolysed in the tubular quartz cell using sunlight or 350 nm light (photon flux of 4×10^{14} photons/s cm^2, Rayonet photo-reactor). Bacterial concentration in water was evaluated as a function of photolysis time by pour plate technique after serial dilution. The plates were incubated at 32°C for 24 h and the number of colony forming units (CFUs) was visually identified, counted, normalized to per ml water and reported. When counts are >300 CFUs/plate due to inappropriate dilution, data are not reliable according to microbiology practices[21] and hence such data were not reported.

Since natural water contains dissolved inorganic and organic impurities, their effect on the bactericidal activity was studied using 1% NaCl and 10 ppm nutrient agar respectively. The bactericidal effect of photolysis alone was

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*For correspondence. (e-mail: arvindb@apsara.barc.ernet.in) evaluated keeping uncoated support in the photo-reactor to maintain the geometry. A simple device was designed to evaluate the photocatalytic technique (using solar light) for disinfecion of water on litre scale. It consists of highly porous TiO_2 coated on a stainless steel plate (23 cm × 28 cm) placed in a plastic tray (23 cm × 28 cm), which was covered with 5 mm thick glass plate (Figure 1) to avoid contamination by dust particles. This device was evaluated for disinfection of water using 1 l water primed with *E. coli* and using sunlight.

XRD spectrum of hydrothermally prepared TiO_2 indicated formation of TiO_2 in anatase phase[22]. N_2 sorption studies indicated formation of highly porous TiO_2 having high surface area of 125 m^2/g compared to the surface area of commercial TiO_2 (Aldrich, anatase, 10.2 m^2/g). UV–visible spectra indicated that the TiO_2 prepared by hydrothermal technique absorbs light at <380 nm.

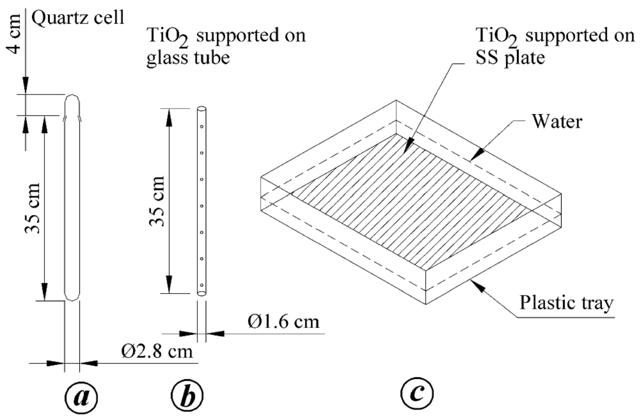

Figure 1. Schematic diagram of quartz cell (*a*), TiO_2 photocatalyst supported on a glass tube (*b*) and TiO_2 photocatalyst supported on a stainless steel plate kept in a plastic tray (*c*).

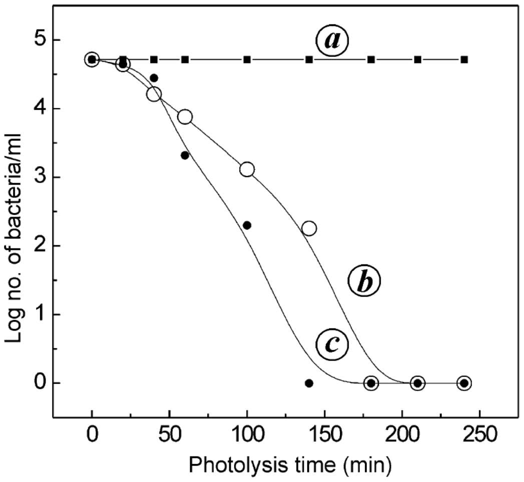

Figure 2. Logarithm of bacterial concentration as a function of photolysis time without photolysis (*a*), without photocatalyst (*b*) and with TiO_2 photocatalyst supported on a glass tube using sunlight (*c*).

Figure 2 shows the plot of logarithm of bacterial concentration as a function of exposure time over TiO_2 photocatalyst coated on a glass tube using solar light. Figure 2 *c* shows that in the presence of photcatalyst, *E. coli* concentration decreased from 52,000 bacteria/ml to zero during ~170 min of photoirradiation under solar light. It is seen from Figure 2 *b* that photolysis alone can kill bacteria. However, in the absence of photocatalyst, the time required to kill all bacteria was ~25% higher (~210 min; Figure 2 *b*). This is an important observation because even if the catalyst does not work efficiently, photolysis alone (using solar light) can disinfect water, though slowly (by ~25%). However, in the presence of photcatalyst organic impurities in water[17] get degraded. Figure 2 *a* shows that without photolysis, bacterial concentration remains unchanged during 4 h with and without photocatalyst. Similar results were obtained with other concentrations of *E. coli*.

Table 1 shows the effect of *E. coli* concentration on photocatalytic/photolytic deactivation of bacteria with and without TiO_2 photocatalyst supported on a glass tube under 350 nm light. It is seen from Table 1 that *E. coli* concentration decreases from 402 CFUs/ml to zero during ~160 min of exposure time. It was observed that time required for killing all bacteria increased with increase in bacterial concentration, e.g. for water containing 100,000 bacteria/ml, similar decrease in bacterial concentration was observed in 220 min. This disinfected water remained bacteria-free up to two days, when kept in a closed cell under ambient condition. It was observed that in the absence of photocatalyst, the time required for killing all bacteria was ~25% higher.

Table 2 shows the effect of dissolved impurities on the bactericidal activity of TiO_2 photocatalyst supported on a glass tube. It can be seen from Table 2 that in the absence of impurities, bacterial concentration decreased from 27,700 CFU/ml to zero during 180 min of photolysis. The presence of inorganic impurities (1% NaCl) did not affect bactericidal activity. However, in the presence of 10 ppm organic impurities (nutrient agar), bactericidal activity was decreased by ~40%, indicating adverse effect of organic impurities on bactericidal activity. This may be due to a competition between the bacteria and organic molecules for reaction with the reactive species formed on the TiO_2 surface during photolysis. Under normal conditions, concentration of dissolved organics in water[23] is <6 ppm. However, for polluted water, dissolved organics in water can be monitored by BOD measurements[24] and can be easily removed using activated charcoal[25] before photocatalytic treatment.

Table 3 shows the concentration of bacteria as a function of photolysis time, during studies carried out using the device (Figure 1 *c*) to photolyse water on litre scale. About 1 l water was photolysed by solar light using this set-up. It is evident from Table 3 that in the presence of photocatalyst, bacterial concentration became negligible during

Table 1. Bacterial concentration as a function of photolysis time with and without TiO_2 photocatalyst (supported on a glass tube) using 350 nm light: effect of *Escherichia coli* concentration

	Bacterial concentration (CFU/ml)							
Photolysis time (min)	Catalyst	No catalyst	Catalyst	No catalyst	Catalyst	No catalyst	Catalyst	No catalyst
0	402	402	16660	16660	27700	27700	100000	100000
45	204	280	11580	12920			74800	85400
65					2500	5540	4000	38800
90	26	150	50	930	700	3810	800	2800
135	8	46	7	140	30	410		
167	0	15			2	210	8	180
180			0	30	0	140		
193	0	2			0	90		
209	0	0					4	70
220	0	0	0	0	0	4	0	60

Table 2. Bacterial concentration as a function of photolysis time over TiO_2 photocatalyst supported on a glass tube using 350 nm light: effect of impurities

	Bacterial concentration (CFU/ml)		
Photolysis time (min)	Distilled water	Saline water (1% NaCl)	10 ppm nutrient agar
0	27700	27000	16000
45		24300	
60	2500	1500	560
90	700	600	
120			156
135	30	40	
160	2	4	85
180	0	0	68
240	0	0	24
300	0	0	4

Table 3. Bacterial concentration as a function of time of photolysis (under sunlight) using a device consisting of TiO_2 photocatalyst supported on a stainless steel plate (23 cm × 28 cm) placed in a 23 cm × 28 cm plastic tray covered with a glass plate

	Bacterial concentration (CFU/ml)	
Photolysis time (min)	Without photocatalyst	With photocatalyst
0	259000	240000
35	62000	45000
70	12000	6000
131	3000	2000
224	600	100
270	28	5
300	10	1

~5 h of photolysis. Bactericidal rate was lower than that observed with the quartz reactor. UV–visible spectra of the glass cover used showed that it transmits only ~70% light in the 400–320 nm region and did not transmit below 320 nm, decreasing photon flux at the catalyst surface and hence lower bactericidal activity. Therefore, choosing a suitable tray cover with higher transmittance for UV light, bactericidal rate can be improved. Thus the device based on the photocatalytic technique is effective for disinfection of water on litre scale. Scaling up catalyst and tray size (to 1 m × 1 m) and maintaining the same ratio of water volume/area exposed (flux received), about 15 to 20 l water (which is the normal requirement of drinking and cooking water for a small family) can be disinfected daily by solar light irradiation for ~5 h. During actual use, water filled in such a device may be exposed to sunlight for a full day instead of 5 h, for adequate safety margin. The photocatalyst which was used 30 times, maintained its bactericidal activity at the same level. The photocatalyst which was kept under ambient condition maintained its bactericidal activity after ~1 year, indicating that the catalyst is stable under ambient condition and can be used repeatedly.

Supported TiO_2 photocatalysts showed bactericidal activity under 350 nm light and solar light. Bacterial concentration (500–200,000 CFUs/ml) in drinking water can be brought down to a safe level using supported TiO_2 photocatalyst under 350 nm light and solar light. This disinfected water when kept in a closed vessel, was found to be bacteria-free up to 2 days studied. Time required for disinfecting water increased with increase in bacteria content. Presence of inorganic impurities like NaCl (1 wt%) did not affect bactericidal activity. However, presence of ~10 ppm of organic impurity decreased bactericidal rate by ~40%. Bacteria concentration was found to decrease by photolysis alone. However, the presence of photocatalyst increased the rate of deactivation of bacteria by ~25%. Supported TiO_2 photocatalyst was found to be stable under ambient condition and maintained its bactericidal activity for 1 year. The study indicates that a scaled-up device, consisting of a catalyst and tray of 1 m × 1 m size, can disinfect ~15–20 l of water daily using solar light.

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