

An Efficient Reactor for Purification of Domestic Water Using Solar Energy

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Abstract-Contamination of water due to various organic substances such as bacteria, pesticides causes serious health issues. A reactor system was fabricated utilizing renewable solar energy for purification of pollutants dissolved in drinking water. A novel glass tube based prototype reactor was constructed by coating *nano*-titanium dioxide (TiO₂) inside the glass tubes. The Nano-TiO₂ was deposited on the bottom surface of the clear glass tubes and is connected in parallel increasing the surface area. For highly contaminated water, increased number of connected tubes and/or several reactors and/or slow flow rate of water are possible. In the present study single reactor module was used for convenience. The reactor was exposed to sunlight and the contaminated water was passed through the reactor. The photocatalytic activity including antibacterial activity was tested using Methylene blue and the bacterial culture, *Escherichia coli*. The reactor system is found to be effective in decontaminating the tested organic entities. The reactor module can be used to purify water for drinking purpose and can be fixed on top of roofs for exposure to sunlight.

Keywords- Solar Energy; Titanium Dioxide; Photocatalyst

I. INTRODUCTION

It is estimated that about 4 billion people worldwide experience lack of clean water supply and millions of people are annually dying from severe waterborne diseases [1]. Therefore, the development of advanced low-cost and high efficient water treatment technologies is stringent. Techniques such as boiling, distillation, reverse osmosis and UV irradiation require considerable energy input. In contrast, low cost photocatalytic purification techniques could be utilized in countries that receive sufficient sunlight [2].

TiO₂ is a well known photocatalyst widely used in the energy and environmental technologies such as generation of hydrogen from water, decomposition of hazardous chemical compounds, odor control, anti-fog window glass, anti-fog mirror, self-cleaning building materials, etc.[1-6]. Recently, it has been shown that TiO₂ is effective in treating even the sea water [7]. They have developed photo electrochemical reactor modules for the decontamination process which need however, electrical energy. It is important to note that some technologies such as air purification, anti-fog mirror, self-cleaning lump, anti-bacterial tiles have already been commercialized while the application of TiO₂ for water treatment utilizing the sunlight is very limited.

Such water treatment technologies are important for countries receiving an adequate sunlight throughout the year. However, the majority of such technologies are in the stage of pilot scale or laboratory research which needs great deal of further work. A continuous flow reactor has been designed to address organic contaminants in water which has not been commercialized yet to the best of our knowledge [8, 9]. The pesticide deactivating ability [10-11] and the anti-bacterial activity of the reactor are to be tested. It is important to investigate the antibacterial activity in real situation as there are factors such as temperature affect the bacterial activity. It is well known that heating of water adversely affects the purity of water as fast microbial growth is possible at certain temperatures. In contrast, sunlight also has the ability to mineralize bacterial activity which is also to be considered. The reported flow reactor systems have limitations in practical application such as infeasibility of scaling up the reactor and possible water leakage of the system. With a view of addressing these issues, an up-scalable novel glass tube based reactor system is developed using the photocatalyst, TiO₂ which is capable of decontaminating bacteria and other organic contamination in water upon exposure to sunlight. The device was designed to be connected to the contaminated water supply and be placed on the top of roofs for exposure to sunlight.

II. METHODOLOGY

The construction of the reactor system for decontamination of organic pollutants in water including bacteria consists of the following steps: (i) the preparation of the dispersion from the photocatalyst, TiO₂; (ii) the deposition of TiO₂ layer across the inner bottom surface of glass tubes Pyrex glass tubes was used which had low absorbance (5%) below 300 nm); (iii) the construction of the reactor; (iv) the connection of several reactors for higher contamination.

A. Preparation of the TiO₂ Suspension

TiO₂ dispersion was prepared by dispersing 1 g of Degussa P25, TiO₂ particles of crystalline size ~25 nm in 100 ml of solution consisting of 90% of water and ethanol and 5% of each acetic acid and polyethylene glycol. The suspension was ultrasonically agitated for 30 minutes.

B. Fabrication of the TiO_2 Coated Tubes

TiO_2 layer was deposited on the inner surface of a glass tube by passing the above TiO_2 dispersion through the tubes so that bottom surface is coated and top portion is bare for efficient exposure of the TiO_2 layer to sunlight through the top part of the glass tube. The excess suspension was discarded and heated the TiO_2 coated glass tubes at 450°C for about 30 minutes.

C. Fabrication of the Reactor System

The reactor is constructed by connecting number of TiO_2 coated tubes in parallel using rubber or plastic connectors so that TiO_2 coated surface is oriented in the bottom direction of the reactor as depicted in the Figure 1. The dimension of the glass tubes used to construct the laboratory reactor was $X=30$ cm, $Y=1.0$ cm and $n=10$ for our convenience. The flow rate of water is adjustable so that there is sufficient time for purification of the water passing through the reactor. Multi reactors system for high level contamination also can be constructed by using several reactors as shown in the Figure 1, though it was not investigated in the present study.

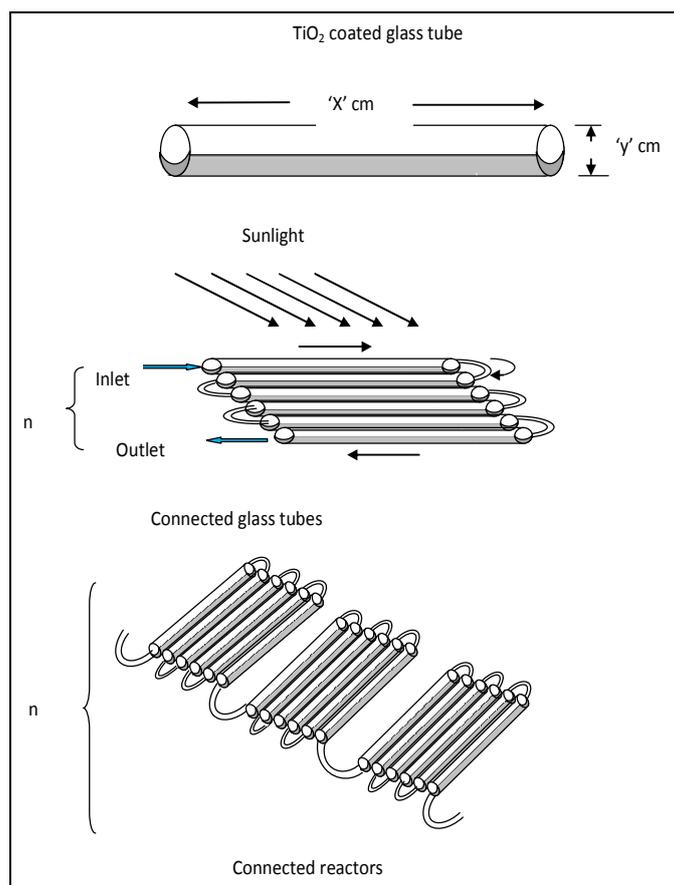


Figure 1 Construction of the reactor system utilizing TiO_2 coated tubes

D. Characterization of TiO_2 Coating

The coating was characterized using X-ray diffractometry (XRD) to identify the presence of photoactive phase of TiO_2 and SIEMENCE, German XRD with $\text{Cu K}\alpha$ radiation was used. The morphology of the TiO_2 coating and the thickness were observed by using a Scanning electron microscope (SEM), LEO-1420VP.

E. Solar/photo-activity

The reactor or multi reactor system is to be set up on the roof, tank or any other place for exposure to sunlight. It should be connected for the domestic water supply or any other water source to be purified. In the real situation the impure water should pass through a filter to avoid mud and other particles that may destroy the photocatalytic properties of TiO_2 in long term. In the present study, the photoactivity of the laboratory scale reactors was tested by keeping it outside the laboratory for exposure to sunlight. The contaminated water was passed through the reactor. The reactor composed of 10 tubes was assembled and a slow flow rate was adjusted so that there is a sufficient time for contaminated water to undergo for photocatalytic reaction. Outlet water was collected for analysis.

The photoactivity of the reactor was tested by passing methylene blue solution on exposure to sunlight and analyzing the outlet solution. The color degradation of the dye solution was measured in the wavelength, λ , range of 200 nm to 700 nm using a

'Jasco-V-570' double beam UV-visible spectrophotometer.

The antibacterial activity of the reactor was studied by using the bacterial culture, *Escherichia coli* which was maintained on EMB Agar (Himedia –India). Bacterial cell suspension was prepared by sub culturing a loop full of bacterium in to a conical flask containing 250ml sterile nutrient broth and grown overnight at 35°C. The microbe at initial concentration of 10^4 CFU/ml in nutrient broth was transferred individually to the TiO₂ coated reactor (test) and uncoated reactor (control) and exposed to sunlight while the solution was passing through the reactor.

An aliquots from reactor outlet were inoculated in to tubes containing 10 ml sterilized distilled water and the contents of the tubes were mixed by vortex mixer for 10 seconds. Subsequently serial dilutions were prepared from 10^{-1} to 10^{-5} . From each dilution tube 10 and 100 μ L were pipetted to sterile Petri plates and pour plate technique was followed with selective media (Nutrient Agar, Himedia- India). Plates were incubated at 35°C for 19 hours. Colonies were counted using a colony counter and the antibacterial assessment was repeated three times. Experiments were carried out in parallel by making the serial dilutions followed by pour plate technique to detect the count in control to compare the antibacterial activity.

III. RESULTS AND DISCUSSION

A. Photoactivity of TiO₂ Coating

The bottom surface of the clear tube is coated with the photocatalyst, whereas the top surface is kept uncoated so that sunlight is irradiated on the photocatalyst through the bare top portion of the glass tube. Degradation of organic compounds in water is caused by hydroxyl free radicals (OH \cdot) [12]. The photocatalyst (TiO₂) generates electron-hole pairs upon absorption of light and rapidly tunnel into the solution. Holes are accepted by OH \cdot ions in the solution to generate highly oxidative OH \cdot which degrade the organic molecules including bacteria. Electrons are consumed by dissolved oxygen to yield superoxide ion O₂ $^{\cdot-}$ and the charge transfer cycle is completed by reaction of O₂ $^{\cdot-}$ with H $^+$ ions. The length of the reactor is designed so that the complete mineralization of organic pollutants occurs on exposure to sunlight.

Generally TiO₂ is photoactive or it has the ability to destroy pollutants only if it is in anatase form and the other phases such as rutile and brookite are not photoactive [13]. Therefore attempts were made to identify whether the anatase phase of TiO₂ retains after depositing on glass tubes at high temperature since anatase form is unstable at elevated temperatures. For the present study, heating at higher temperature is necessary for preparation of stable TiO₂ layer on top of the glass and also to decompose the other organic matters present in the TiO₂ suspension. Figure 2 shows the XRD spectra of TiO₂ at room temperature and at different temperatures. It is clear that peaks corresponding to photoactive anatase form of TiO₂ decreases with increasing temperature and peaks corresponds to rutile phase is more intense at higher temperatures. The anatase phase retained up to 500°C although fare amount of rutile phase is also present. Although anatase form of TiO₂ is stable at temperatures below 500°C, it is desired to test the photocatalytic activity of the TiO₂ coating in tubes at these temperatures. Therefore, photodecomposition of Methyl violet solution was studied for the TiO₂ coating fired at different temperatures. The Table 1 shows the initial and final concentration of Methyl violet before and after exposure to sunlight. It was observed that the optimum temperature that the photoactivity of TiO₂ is high in tubes fired at 400°C-500°C which is in consistence with the XRD analysis. The low photoactivity at 300°C is obviously due to the presence of other organic materials in the coating such as polyethylene glycol which adversely affect the photocatalytic activity of TiO₂. The colour of the coating is also brown at that temperature suggesting that some materials are still present in the coating. Therefore the coating temperature was selected as 450°C.

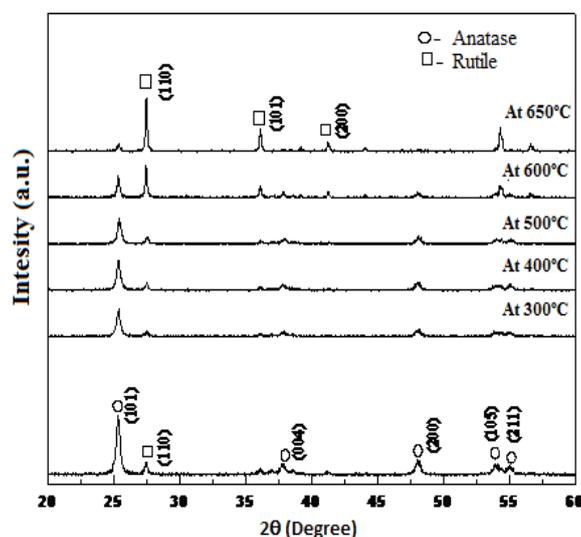


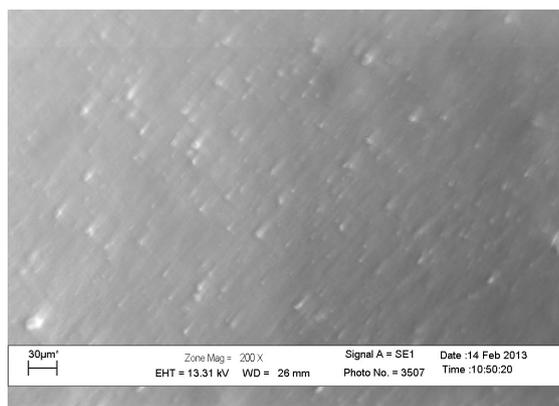
Figure 2 XRD spectra of TiO₂ coated at different temperatures.

TABLE I PHOTOACTIVITY OF TiO₂ AT DIFFERENT TEMPERATURES

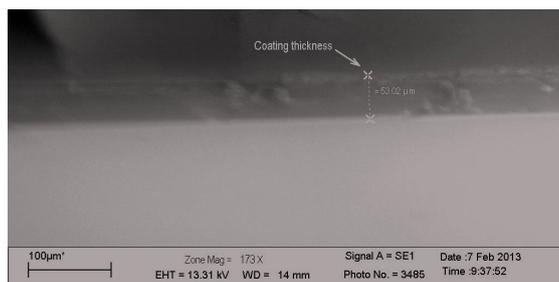
Firing temperature	Photoactivity
350°C	low
400°C	high
500°C	high

B. Morphology of TiO₂ Coating

Scanning electron microscope images of the TiO₂ surface coating is shown in Figure 3. Uniform dispersion of *nano*- TiO₂ is observed throughout the film except some agregations in certain areas. The thickness of the TiO₂ layer is about ~52 μm as observed through the image.



(a)



(b)

Figure 3 (a) SEM image of the surface of TiO₂ coating, (b) SEM image of the cross section of TiO₂ coated glass

C. Photocatalytic Activity

The photocatalytic activity of the reactor was investigated by observing decomposition of Methylene blue solution on exposure to sunlight. The outdoor experiments were carried out in bright sunlight between 9.00 am and 1.00 p.m. The environmental temperature was about 28°C and the humidity was about 70%. The absorbance and concentration of the Methylene blue solution with the exposure time to sunlight as measured using the UV-Visible spectrophotometer were shown in Figure 4 and Table 2.

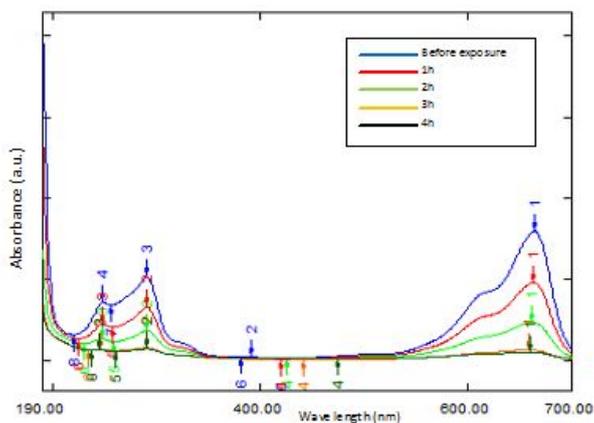


Figure 4 Mineralization of Methylene blue by the TiO₂ coated reactor

TABLE II PHOTODECOMPOSITION OF METHYLENE BLUE SOLUTION

Time / h	Absorbance	C / ppm	PCA / %
0	1.097	5	0
1	0.780	3.6	28
2	0.420	1.9	62
3	0.260	1.2	76
4	0.100	0.4	92

The percentage photo-catalytic activity (PCA%) was calculated using the following equation.

$$\text{PCA\%} = [(C_B - C_S) / C_B] \times 100 \quad (1)$$

C_B : Initial concentration of Methylene blue solution

C_S : Concentration of methylene blue after exposed to sunlight for a known time period. The flow rate was adjusted so that outlet solution can be collected by 1h, 2h, etc.

$(C_B - C_S)$: Concentration of methylene blue degraded

The percentage photocatalytic activity of the reactor (PCA) was 92% after 4 hour exposure to sunlight. Uncoated reactor was also tested for comparison and the Methylene blue decay was found to be negligible in that case.

D. Antibacterial Activity

The photocatalytic sterilization property of TiO_2 has been studied extensively which was initially studied against *E coli* [14]. Wide spectrum organisms including viruses, bacteria, algae [15] and cancer cells [16] have been disrupted effectively utilizing the photocatalytic effect. Further, TiO_2 has been used as self sterilizing material for coating clinical; tools including sanitary wear and items for use in hospitals [17].

TiO_2 exhibit antimicrobial activity in the presence of sunlight or UV light due to its strong oxidizing property. Efforts have been made to understand the mechanism of destruction of microbial action and it has been found that when the irradiated TiO_2 particles come in to contact with microorganisms, the microbial surface was the primary target of the initial oxidative attack [18]. Reactive oxygen species such as hydroxyl radical, super oxide anion and hydrogen peroxide generated as explained previously, promote peroxidation of the polysaturated phospholipids components of the lipid of the microorganisms. The observations obtained from light and scanning electron microscope reveals that the microbial destruction activities take place through direct damage to cell walls caused by hydroxyl radicals [19]. Among the human pathogens *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus* and *Enterobacter faecium* has been shown the disinfection of photo catalytic oxidation with TiO_2 in the presence of UV radiation [19]. There are interesting findings regarding the antibacterial performances of TiO_2 against *E coli* and it could reach even 99.99% bacterial reduction under activation by even visible light [20].

In the present study only *Escherichia coli* was investigated as the bacterial culture. As described in the experimental section, the colony count before and after exposure to sunlight was measured. The colony count in a unit volume was drastically reduced in the outlet solution of the reactor on exposure to sunlight and it is less in non-coated glass tube reactor as shown in the Table 3, even though the illumination of the light itself could destroy some organism to certain extent. The process was replicated several times. The microbial activity can be further destroyed by continuing exposure to sunlight.

TABLE III MICROBIAL COLONY COUNT IN WATER OF TiO_2 COATED AND BARE REACTOR OUTLET

On exposure to sunlight	E-coli Count/ml	
	TiO_2 coated reactor	Bare reactor
Before exposure	5.9 x 10 ²	
After exposure	1.4 x 10 ²	5.4 x 10 ²

The ability of TiO_2 to decompose the other pesticides such as paraquat and carbofuran is well documented [9-10]. The present study is mainly limited to investigation of anti-bacterial and the organic compounds decompose ability of the novel reactor module.

IV. CONCLUSIONS

Low cost domestic reactor was fabricated for water purification using non toxic materials and the solar energy, the renewable energy source. Hence the reactor doesn't need additional energy cost for electricity, etc. Microbial and organic pollutants free water can be obtained for drinking purpose. The effective surface area of the coated films is high since *nano* particles of the photocatalyst have been used. Hence high surface to the reactor volume is available for photocatalytic water purification process. The device can be connected to the domestic water supply and be placed on the top of a roof. The device satisfactory operates in diffuse daylight when the sky is cloudy. The length of the tubes or the number of the tubes can be increased de-

pending on the level of contamination.

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