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Energy efficient drinking water purification system using TiO_2 solar reactor with traditional methods ✯

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Abstract

Waterborne diseases are a major health threat in India. The cost of various water purification systems is also high and need a considerable amount of fuel (wood, LPG etc.) or electrical energy to purify them. Keeping this and the rise in conventional energy prices in mind, we designed an experimental drinking water purification system that makes use of solar energy to purify the biological contaminants that are present in the drinking water. For this nano-Titanium Dioxide (TiO_2) coated acrylic tubes are used. By attaching a number of such tubes in parallel connection, a reactor system is constructed. This reactor when exposed to sunlight, with the contaminated water passing through a photocatalytic activity takes place killing the micro-organisms present in the water. Along with this a slow sand filter, a cascaded aeration system and a charcoal filter is introduced to remove turbidity, harmful dissolved gases and heavy metals present in the water. The purification system is used to purify water for drinking purpose and is fixed on rooftops for exposure to sunlight. In this paper, purification of water in the solar reactor for different light intensities and water flow rate is studied. This experimental setup is easily installed in both rural and urban households.

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Keywords: Water Purification; TiO_2; Photocatalyst; Solar Reactor.

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1. Introduction

Here Most of the traditional and modern techniques such as boiling, distillation, reverse osmosis and UV irradiation require a considerable amount of energy input for the purification of drinking water. The rise in fuel prices, both domestic (LPG) as well as commercial fuel (coal, petrol etc.) and their fast depletion with polluting nature (on combustion) are a major concern. Hence an advanced as well as a low-cost water purification system using renewable energy is of at most importance. Titanium dioxide (TiO_2), which is one of the most basic materials in our daily life, has emerged as an excellent photocatalyst material for environmental purification [1]. TiO_2 has properties such as insoluble in water, hydrochloric acid, dilute sulfuric acid and organic solvents eliminating the fear of Titanium dioxide getting dissolved in our drinking water [2]. An addition to the above properties; TiO_2 is used in various confectionaries as white pigment colouring agent, which makes it a food grade material and will not cause any harm if ingested. TiO_2 has the capability of decontaminating bacteria and other organic contamination upon exposure to mild ultraviolet rays [3]. TiO_2 is used as a pigment coating in wrappers of bread and biscuits which helps in preventing the growth of fungus in the products [4]. There are various forms of TiO_2; namely – anatase, rutile and Brookite. Only anatase form displays major photocatalytic properties. The most commonly found anatase form TiO_2 which exhibits photocatalytic properties is Degussa P25 [5].

Various methods have been developed to purify water using the photocatalytic TiO_2. Membranes coated with TiO_2 are used for water purification [6] and TiO_2 infused materials like clay can be used as water filters [7]. Using UV lamps and TiO_2 infused mesh filter can disinfect organically polluted water [8]. In other developments a shell and tube type multiple reactor systems, where TiO_2 coated tubes are placed inside a shell containing water. The inside of the tubes were illuminated with collimated UV light [9]. Most of the above-mentioned systems need a considerable amount of electrical energy for running the system, be it the UV light bulb or the various pumps and actuators. An extensive list of the recently developed techniques in using TiO_2 for purification process is summarized in [10]. Few reactor systems which have used solar radiation as their source of UV light for water purification and also have continuous flow. One such photochemical reactor system was designed and tested where glass plates coated with photocatalytic TiO_2 is used to purify water of its contaminants. [11]. PET bottles with half coated TiO_2 were used to purify the contaminated water by placing the bottle in the open sunlight. [12]. A continuous flow reactor was constructed using a novel glass tube and studied the disintegration organic pollutants using methylene blue. [13].

This paper describes the effect of different intensities of solar irradiation and their photocatalytic bacterial disinfecting for the various flow rates is studied and the optimum flow rate for the water to pass through the reactor is obtained experimentally. The device is designed to be a commercially viable model, which also removes other water contaminants. In addition to the TiO_2 solar reactor, a slow sand filter, aeration system and a charcoal filter are also connected to the purification. The slow sand filter is used to filter the suspended colloidal particles present in the water. This helps in the reduction of the water turbidity and prevents fouling the inner surface of the reactor tubes. The aeration system – a cascade step-drop system, effectively aerates the water, releasing the harmful gases like hydrogen sulfide trapped in the water; into the environment. Charcoal filter helps in the absorption of the heavy metals present in the water. The main advantage of the system is that it uses only the gravity for the water flow and the uses natural sunlight for the water purification.

2. Methodology and Materials

The construction method and target contaminants of the water purification system consist of the following steps:

- The construction of slow sand filter.
- The construction of the cascaded step-drop aeration system.
- Charcoal bed filters construction.
- Construction of TiO_2 solar reactor
  a) Preparation of the photocatalytic TiO_2 solution.
  b) Deposition of TiO_2 layer across the inner bottom surface of acrylic tubes.
  c) The construction of the solar reactor tubes by connecting several TiO_2 coated tubes.

2.1. Construction of slow sand filters for turbidity removal

Turbidity is an aesthetic problem as well as a health issue. Water turbidity also causes fouling inside the tube's surface of the solar reactor. Hence it is best to remove the suspended particles in the water before it enters the reactor tubes. The turbidity of water can easily be dealt with using traditional slow sand filtering method. The slow sand filter as shown in Fig.1 is made up of three layers, namely a layer of small pebbles or rocks, followed by an intermediate layer of small gravel and the top most layers consisting of the fine sand particles. The gravel and pebbles prevent the fine sand particles from escaping through the filter outlet. In addition to this, a cloth filter is used at the outlet to further stop the sand particles. When water is poured into the slow sand filter, filtration takes place due to the slow flow velocity of the water through the fine sand and gravel layer, trapping the infinitesimal particles between them and thus removing the turbidity of the water.

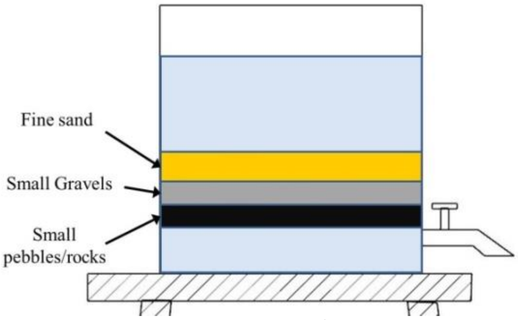

Fig. 1. Slow sand filter

If there is a constant supply of the contaminated water, there would be a thin layer of microbial layer called the Schmutz decked over the top surface of the sand layer. This layer will give a better filtration. The main disadvantage of this layer is that after a period of time, the thickness of the Schmutz decked layer increases preventing the active filtration. Hence the periodic removal of this layer is recommended.

2.2. Cascade Step-Drop Aeration System

Aeration is a process of involving air to mix with the water in a chemical reaction where the toxic chemicals are precipitated out easily. By bringing the trapped gases up close with the atmospheric air it also helps in liberating the VOC gases into the air. From the various types of the aeration system, the cascaded step-drop aeration system is selected due to the factor that it occupies less space and it creates a number of miniature waterfalls, which allows adequate aeration and the water tumble falls by gravity alone and no external energy input is needed. The pipes are stacked on top of each of to form the waterfalls. Here the water moves diagonally in a zigzag manner with a 15 cm drop and changes direction for better efficiency as the water flows from side to side which is shown in Fig.2.

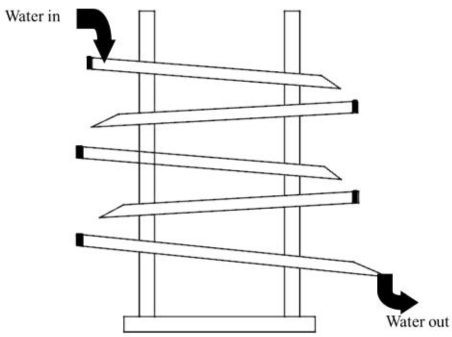

Fig. 2. Cascade step-drop aeration system

During this process, the oxygen from the air comes in contact with the water contaminated with gases like sulphur to produce hydrogen sulphide, which is released into the environment. The infusion of more oxygen molecules into the water also takes place due to this cascaded step drop arrangement. This process is called ionization process and is easily done without any energy input.

2.3. Charcoal Bed Filter

A Charcoal bed filter is used to remove the heavy metals if present in the water. As depicted in Fig.3 charcoal is placed in the bottom of the filter tank, above which a layer of gravel is placed to prevent the charcoal from floating in the water. Heavy metals like aluminium, arsenic, copper, iron, lead and zinc are absorbed by the charcoal. The charcoal should be prewashed to reduce its pH value. Charcoal bed filter is a very cost-effective cleanup procedure with multiple applications. On the downside of using the charcoal is that it will eventually reach its lifetime as a filter. When the charcoal gets saturated with the absorbed metals on its surface, no further purification will take place. This is called breakthrough and now the filtered water will have more contaminates than that of the untreated water. Hence the charcoal has to be replaced in the filter every month as there are no ways or any indications to show that the charcoal has reached its breakthrough. Only through physically smelling or tasting the water this can be found out.

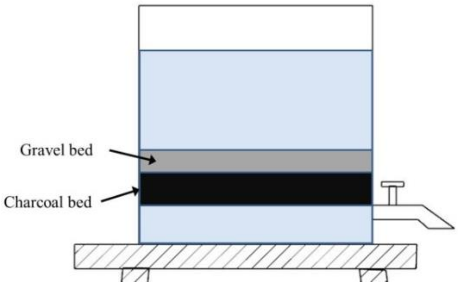

Fig. 3. Charcoal bed filter

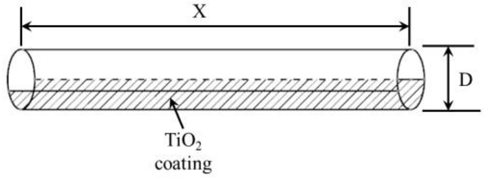

Fig. 4. TiO_2 coated tubes

2.4. Construction of TiO_2 Solar Reactor

Photocatalytic TiO_2 is present in commercially available Degussa P25 which has 3/4 of anatase/rutile proportion. Hence Degussa P25 is used for the removal of organic contaminants such as bacteria and virus in the presence of the UV light. Here the UV light from the sun is used as the source to promote the photocatalytic destruction of biological contaminants present in the water.

2.4.1. Preparation of the TiO_2 Suspension

The TiO_2 suspension is prepared by slowly mixing 10g of Degussa P25 (contains TiO_2), in 100 ml of a solution consisting of 90 ml of water and ethanol, 5 ml of acetic acid and 5 ml of polyethylene glycol. The suspension is continuously stirred for 30 minutes.

2.4.2. Preparation of the TiO_2 Coated Tubes

Acrylic is chosen over the glass as the material for the solar reactor construction due to its following advantages over glass. Acrylic tubes are as transparent as glass tubes and it is easy to handle, i.e., will not break easily when compared to the brittle glass tubes. Fig.4 shows the dimension of the acrylic tubes used to construct the reactor is taken as length X=1000 mm, D=10 mm outer diameter and the number of tubes n=10 for our experimental purpose.

The bottom surface of the tube is alone coated with TiO_2 such that the top portion of the tube is left transparent for the UV radiation to pass through them and fall on the TiO_2 layer on the bottom surface. TiO_2 layer is left to dry and is later soaked in $HClO_4$ for about 3 hours to acidify the coating and help it adhere to the acrylic wall.

2.4.3. The construction of the solar reactor tubes by connecting several TiO_2 coated tubes

The reactor is constructed by connecting a number of TiO_2 coated tubes in parallel connection using plastic tubes so that TiO_2 coated surface is oriented in the bottom direction of the reactor as depicted in Fig.5 (a).

These tubes are clamped to the wooden frame. The Fig.5 (b) shows the cross-section view of the solar reactor. The solar reactor is tilted at an angle of 20 degrees from the ground surface, facing the north- south direction.

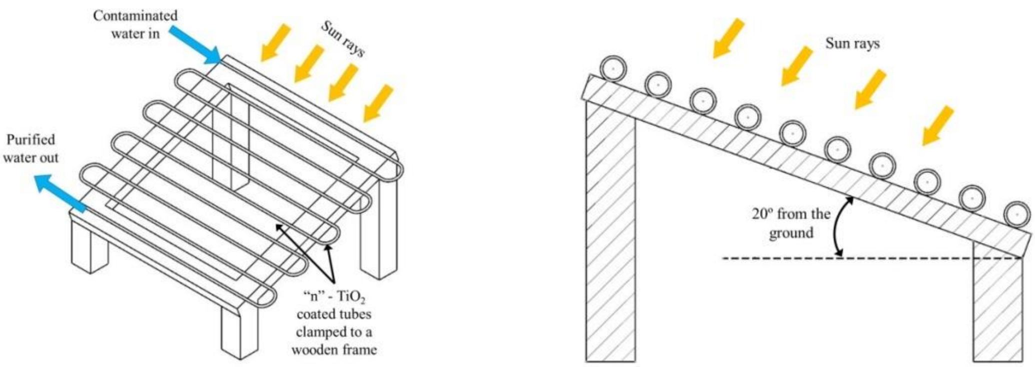

Fig. 5. (a) Solar Reactor; (b) Cross section view of the Solar Reactor

2.4.4. Solar Reactor - Photocatalytic Reactions of TiO_2

When a photon (hv) from the ultraviolet spectrum of the sun's rays falls on the TiO_2 it produces an electron - hole pair as shown in the following reaction.

$$TiO_2 + hv \rightarrow TiO_2 .(e^- + hole^+) \quad (1)$$

The recombination reaction is

$$TiO_2 .(e^- + hole^+) \rightarrow TiO_2 + Heat \quad (2)$$

The overall reaction of the photocatalytic reaction when water flows through it is

$$TiO_2 + hv + H_2O \rightarrow TiO_2 .(e^- + hole^+) + OH^- + H^+ \quad (3)$$

$$hole^+ + OH^- \rightarrow OH^0 \quad (4)$$

This highly oxidative OH° degrades the organic molecules like bacteria, thereby killing the bacteria present in the water.
After this OH^0 reacts with H^+ and the electron to reform H_2O water back.

$$OH^0 + e^- \rightarrow OH^- \quad (5)$$

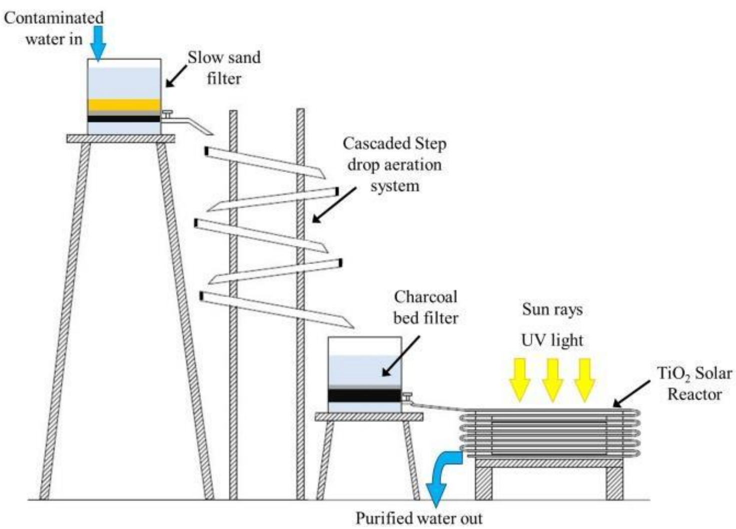

Fig. 6. Experimental set up.

3. Experimental procedure

The experimental set up is constructed as shown in the Fig.6. The water is first poured into the slow sand filter, where the suspended colloidal particles present in the water are removed. Once the turbidity of the water is removed, the water then flows through the cascaded step drop aeration system; here the dissolved hydrogen sulphide and other VOC gases escape from the water. Furthermore ionization of the water, i.e. there is the addition of extra oxygen molecules in the water. The water which is free of turbidity and dissolved gases now is made flow through the charcoal bed filter to remove the heavy metals present in the water. This semi-treated water is now passed into the TiO_2 photocatalytic solar reactor system. The flow rate is adjusted so that there is a sufficient time for contaminated water to undergo photocatalytic reaction. The photocatalytic reaction takes place by destroying the biological contaminants, due to the oxidation of the contaminant's cell surface by the OH^o ions. The photocatalytic sterilization property of TiO_2 was studied by testing the solar reactor during the morning, afternoon and evening for various water flow rates. Time taken for 1 liter of water to flow through the reactor was taken at 5 min, 7.5 min, 10 min, 12.5 min and 15 min for experimental purpose. A reference sample (R) was taken before the water passes through the reactor, where the reactor was not exposed to sunlight. Bacterial culture for these samples was done and the results are shown in the graph. An average value of the readings in the various flow rates for a particular time frame such as morning, afternoon and evening is taken and tabulated.

4. Results

The photocatalytic sterilization property of TiO_2 of the solar reactor was tested during the morning, afternoon and evening for various water flow rates. The experiment was done throughout the week to take seven samples each of the various flow rates for filling one liter of water as mentioned previously. Bacterial culture was done for all the samples and results for these samples are shown in the following graphs.

The average bacterial colony per plate is plotted against time taken for the water to flow through the reactor tubes in the morning session. It can be seen that around 12.5 to 15 min all the contaminants are destroyed. Average values for the cluster in each flow rate are taken as M1, M2, M3, M4 and M5 respectively [Fig.7 (a)].

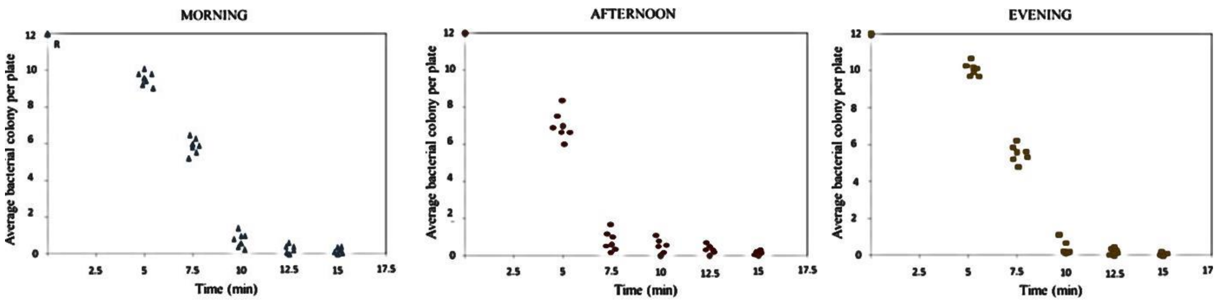

Fig. 7. Destruction of bacteria in the (a) morning; (b) afternoon; (c) evening

Table 1. Summary of the TiO_2 bacterial disinfection

Average value of each sample set	Time to fill 1 litre (min)	Average bacterial colony per plate
R (reference)	-	12.2
	Morning 10 am	
M1	5	9.8
M2	7.5	5
M3	10	0.3
M4	12.5	0
M5	15	0
	Afternoon 12 noon	
A1	5	6.5
A2	7.5	0.4
A3	10	0
A4	12.5	0
A5	15	0
	Evening 3pm	
E1	5	10.1
E2	7.5	4.8
E3	10	0.15
E4	12.5	0
E5	15	0

From the Fig.7 (b), it can be seen that during the afternoon when the solar radiation levels are high, the total destruction of the bacteria takes place relatively in the low time period, around 10 min. It takes less time for the destruction when compared to the morning session owing to the high level of radiations received from the sun during the peak afternoon hours. Similar to the morning readings, average values for the afternoon section is also taken A1, A2, A3, A4 and A5.

From Fig.7 (c), the test results in the evening session show a similar time taken by the solar reactor to decontaminate the bacteria when compared to the morning section. There is the complete destruction of bacteria around 12.5 min. The average values are taken as E1, E2, E3, E4 and E5 likewise. These are then compared with the bacterial culture of the sample test water taken before. The results of the bacterial count are tabulated in Table.1

5. Conclusion

From the correlation of the three graphs [Fig.8 (a)], we can conclude that the appropriate time frame for 1 liter of water to flow through the reactor can be selected as 12.5 to 15 min. Thus 15 min can be taken as the safe duration for the water to flow through the reactor for the complete destruction of the contaminants during day time.

The Fig.8 (b) shows the comparison of the bacterial degradation of the solar reactor for various flow rates and their corresponding time periods to that of the reference sample.

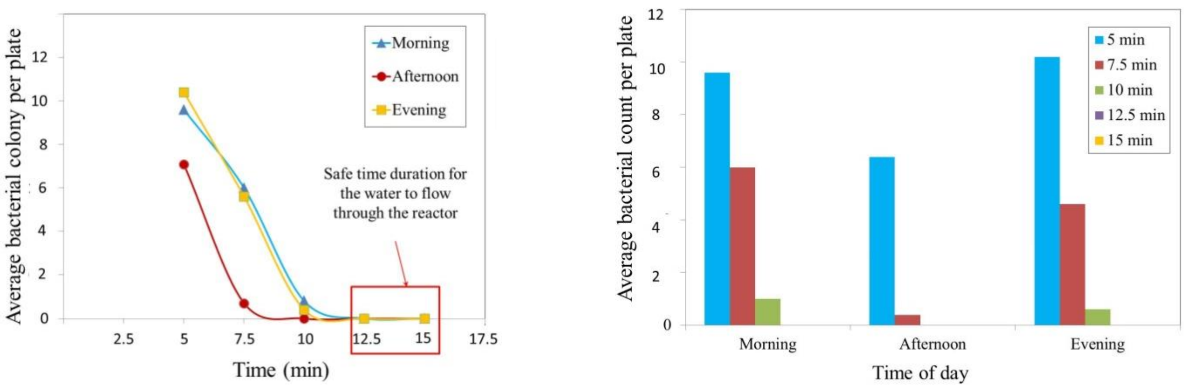

Fig. 8. (a) Safe time duration for the water to flow through the reactor; (b) Comparison of Bacterial Degradation

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