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Evaluation of bench-scale solar photocatalytic reactors for degradation of phenolic wastewaters

S. Adishkumar[a,*], S. Kanmani[b], J. Rajesh Banu[a], Ick Tae Yeom[c]

[a]*Department of Civil Engineering, Regional Centre of Anna University, Tirunelveli 627007, Tamil Nadu, India, Tel. +91 9841339016; Fax: +0462 2552877; email: adishk2002@yahoo.co.in (S. Adishkumar), Tel. +91 9444215544; email: rajeshces@gmail.com (J. Rajesh Banu)*
[b]*Department of Civil Engineering, Anna University, Chennai, India, email: skanmani@hotmail.com*
[c]*Department of Civil and Environmental Engineering, Sungkyunkwan University, Seoul, South Korea, email: yeom@skku.edu*

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ABSTRACT

Four bench-scale solar photocatalytic reactors were fabricated viz. solar photocatalytic single-baffle reactor (SPSBR), solar photocatalytic multiple-baffles reactor (SPMBR), solar photocatalytic cascade reactor (SPCR) and solar photocatalytic pond reactor (SPPR) of 5-L capacity. Evaluation of the reactors performance was carried out by varying the volume of wastewaters in the range of 1–5 L and the recycle flow rates in the range of 250–750 mL/min for the degradation of phenolic wastewaters. The single-baffle reactor gives the maximum phenol removal efficiency irrespective of all volume of wastewater. The phenol removal efficiency increases when the recycle flow rate is increased from 250 to 500 mL/min and then decreased for the recycle flow rate of 750 mL/min. The single-baffle reactor showed the maximum phenol removal efficiency with recycle flow rate of 500 mL/min. For untreated pulp and paper mill wastewater of 200 mg/L phenol concentration, the BOD_5/COD ratio is 0.02, while solar photocatalytic treatment of 4 h enhanced the biodegradability values to 0.80.

Keywords: Solar photocatalytic reactors; Titanium dioxide; Phenolic wastewaters; Recycle flow rate; Hydrogen peroxide; Biodegradability

1. Introduction

Photocatalysis, i.e. using semiconductor particles under bandgap irradiation as little microreactors for simultaneous reduction and oxidation of different redox systems has been intensively studied during the last 38 years, since the pioneering work of Carey et al. in 1976. Photocatalysis by titanium dioxide has been demonstrated to be an inexpensive and effective method for treating a variety of organic pollutants in water [1,2]. The UV radiation required for photocatalytic processes may come from an artificial source or the sun. The artificial generation of UV radiation contributes to a large portion of the operating, capital and maintenance costs of a photocatalytic reaction system because of the utility consumption and periodic replacement of the UV lamps. This suggests using the sun as an economically and ecologically sensible light source with a typical UV flux near the surface of the earth of 20–30 W/m^2 the sun puts 0.2–0.3 mol photons/m^2/h in the 300–400 nm range at the process disposal [3]. Principally, these photons are suitable for

*Corresponding author.

destroying water pollutants in photocatalytic reactors. There is, therefore, a significant economic incentive to develop solar powered photocatalytic reactors. In addition, the environmental impact induced by the use of solar energy is minimal and this renders the photocatalytic process environmentally attractive [4]. The application of solar-powered photocatalytic reactors to treat water contaminated with organic pollutants holds promise for regions receiving strong sunlight throughout the year, like India.

To ensure efficient conversion of incident photons to charge carriers, the appropriate design of solar photocatalytic reactor is most important. Over the last two decades, several reactors for the solar photocatalytic water treatment have been developed and tested. The first engineering scale outdoor reactor developed was a simple conversion of a parabolic trough solar thermal collector. The conversion replaced absorber/glazing tube combination of the thermal collector with simple pyrex glass tube through which contaminated water can flow. Since that time, a number of reactor concepts and designs have been advanced by researchers all over the world [5,6]. Based on the method of collecting sunlight, two reactors systems are designed viz. concentrating and non-concentrating reactor systems. Based on the condition of the catalyst, two reactor systems are designed and they are suspended and fixed catalyst systems. Some laboratory and pilot plant photoreactor configurations have been proposed for photocatalysis. The most typical laboratory-scale configurations include vigorously stirred batch photochemical reactor, cylindrical flasks, glass dishes and annular differential photoreactors. Matthews reported the use of suspended TiO_2 in a solar illuminated tubular reactor equipped with a parabolic trough concentrator to degrade a variety of organic pollutants [7]. The light concentrating reactor requires reflectors, which are expensive and only able to concentrate the direct component of the solar irradiation for reaction. This leads to the conclusion that scaling up such a design may be difficult.

The first engineering scale solar photochemical facility for water detoxification in Europe was developed by CIEMAT using 12 two-axis PTC. But the main disadvantages are that collectors use only direct radiation, expensive and have low optical and quantum efficiencies. Several different substances have been successfully degraded with these collectors viz. dichloroacetic acid, phenol, 4-chlorophenol, dichlorophenol and atrazine. In contrast, non-light concentrating reactors utilizing both the direct and diffuse components have greater potential for process development. Non-concentrating collectors are cheaper than PTC as they have no moving parts or solar tracking devices. Wyness developed flat-plate reactor and tested the reactor in an outdoor solar photocatalytic oxidation facility [8]. Goswami reported that all the three non-concentrating reactors viz. flat-plate, shallow pond and tubular reactors demonstrated satisfactory performance in solar photocatalytic oxidation facilities when tested over a wide range of operating conditions [9]. Goslich et al. developed double-skin sheet reactor (DSSR) and thin film fixed bed reactor (TFFBR) [10]. But it requires large catalyst area for purification of wastewater and also constrained by mass transfer limitations due to laminar flow conditions. Feitz et al. developed fixed catalyst reactors viz. coated mesh and packed bed reactor and its efficiency was very less compared to suspended catalyst [11].

Kanmani et al. developed two water fountain solar photocatalytic reactors of suspended catalyst system for treating textile dyeing wastewaters [12]. Chan et al. constructed a solar photocatalytic cascade reactor (SPCR) to study the photocatalytic oxidation of benzoic acid [13]. Rao et al. presented a novel, low cost, pebble bed photocatalytic reactor (PBPR) having a horizontal or inclined solar trough collector for the treatment of textile wastewater. The photo reactor comprised an inclined trough with the pebbles fixed on its surface. The trough (inner length, 52 cm; inner width, 45 cm; height, 0.8 cm) was fabricated using a transparent Perspex sheet. The metal frame had provisions for tilting the trough at predefined angles between 0˚ and 60˚. The volume of liquid contained in the PBPR when positioned in the horizontal position was 0.66 L with all the pebbles just submerged under the water [14]. Perez et al. studied the removal of micropollutants in the raceway pond reactor (RPR). The fibreglass-RPR has a maximum capacity of 360 L, a length of 3.85 m and width of 0.64 m. It is separated by a central wall, forming two canals. The RPR includes a paddle wheel connected to an engine to obtain a mixed and homogeneous system. The engine was linked to a variable frequency drive to control the paddles' speed [15]. Though a lot of studies have been reported so far, still the efficient use of reactors at large scale are lacking due to opacity, light scattering and depth of radiation penetration. Engineering design and operation strategies are lacking for efficient use of reactors at large scale. Moreover, the requirement of at least one side to be transparent to UV light significantly poses size limitations along with breakage risk. Hence, the objective of this study is to explore the feasibility of using simple, low cost non-concentrating reactors, for treating phenolic wastewater in solar photocatalytic oxidation facilities.

2. Materials and methods

2.1. Wastewater source and characterization

Pulp and paper mill wastewater was obtained from an industry near Chennai, Tamil Nadu, India. The treatment system consisting of a plain sedimentation tank as primary treatment extended activated sludge process as secondary treatment, sand filter beds and carbon filter as tertiary treatment has a capacity of 700 m^3/d. The wastewater used for the experiment was collected at the outlet of the plain sedimentation tank. The sample was collected continuously for 5 d at regular times due to large variations in concentration. The sample was collected in plastic cans that were transported to laboratory and stored at 4˚C. The physicochemical characteristics of the primary treated wastewater determined using standard methods are listed in Table 1. After the primary treatment, the ratio of BOD_5 to COD ratio was 0.02, indicating the non-biodegradable character of the wastewater and the possible presence of minimally biodegradable chemical substances, which decrease the effectiveness of biological treatment.

2.2. Chemicals

All reagents used in this experiment were of analytical grade and used as received without further purification. The chemicals used in this study are phenol crystals (C_6H_5OH), hydrogen peroxide (H_2O_2 30% w/w), sodium thiosulphate ($Na_2O_3S_2$), sulphuric acid (H_2SO_4), potassium dichromate ($Cr_2K_2O_7$), mercuric sulphate ($HgSO_4$), ferrous ammonium sulphate ($Fe(NH_4)_2(SO_4)_2{\cdot}6H_2O$), sodium hydroxide (NaOH), sodium sulphite (Na_2SO_3) were purchased from Merck (India). TiO_2 (Degussa P-25, Germany) was used as photocatalyst without pretreatment. This solid is mainly presented in the anatase form (80% anatase & 20% rutile in weight), has BET surface area of 50 m^2/g and average particle size of 20 nm according to the manufacturer's specifications.

Table 1
Initial characteristics of phenolic wastewater

Parameter	Mean value ± standard deviations
pH	8.0 ± 0.3
Total suspended solids (TSS) mg/L	300 ± 50
Phenol (mg/L)	200 ± 54
Biochemical oxygen demand (BOD) mg/L	10 ± 5
Chemical oxygen demand (COD) mg/L	450 ± 100
BOD_5/COD	0.020 ± 0.005

2.3. Solar photocatalytic reactors

Four bench-scale solar photocatalytic reactors were fabricated viz., solar photocatalytic single-baffle reactor (SPSBR), solar photocatalytic multiple-baffles reactor (SPMBR), cascade reactor and solar pond reactors of 5-L capacity with non-concentrating suspended catalyst system without any UV transparent walls and solar tracking system. The reactors were constructed for conducting bench-scale experiments. The irradiated surface area and volume of reactor was 0.08 m^2 and 5 L, respectively. The set-up consisted of a flow-through reactor placed on a platform under solar irradiation. The wastewater was continuously recycled with the help of circulating pump.

SPSBR was made from an extruded double-skinned acrylic panel with built in flow channels of cross section of 0.4 m × 0.1 m. The size of reactor was 0.4 m × 0.2 m × 0.1 m. Fig. 1a depicts the photographic view of single-baffle reactor. SPMBR was built of acrylic in the form of pond divided with baffle plates of about 0.1 m in height at specific intervals. The size of reactor was 0.4 m × 0.2 m × 0.1 m. Fig. 1b depicts the photographic view of multiple-baffles reactor. SPCR was composed of 6 Nos. of acrylic stairs with stair size of 0.16 m × 0.08 m × 0.1 m. The wastewater flowed over the steps before being collected in a tank, from which it was elevated with a pump to top of the steps for recirculation. Fig. 1c depicts the photographic view of cascade reactor. Solar photocatalytic pond reactor (SPPR) consisted of shallow pond of size 0.4 m × 0.2 m × 0.1 m open to atmosphere. The pond was equipped with a mixing facility. Fig. 1d depicts the photographic view of solar pond reactor.

2.4. Experimental methods

All photocatalytic experiments were carried out at Anna University campus in Chennai, (13˚00. 57´´N; 80˚14.12´´E), Tamil Nadu. The simulated wastewater was prepared in the laboratory with a concentration of the phenol of 50 mg/L. The solutions were prepared by dissolving the compound using double-distilled water. The main characteristics were pH 7 ± 0.5, phenol concentration = 50 mg/L, COD = 150 mg/L, BOD = 0 mg/L. Evaluation of the solar photocatalytic reactors performance for degradation of simulated phenolic wastewaters was carried out by solar/TiO_2 system by varying the volume of wastewaters in the

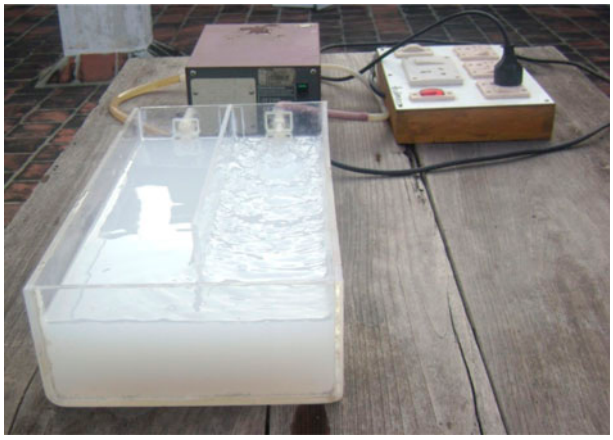

Fig. 1a. Photographic view of SPSBR.

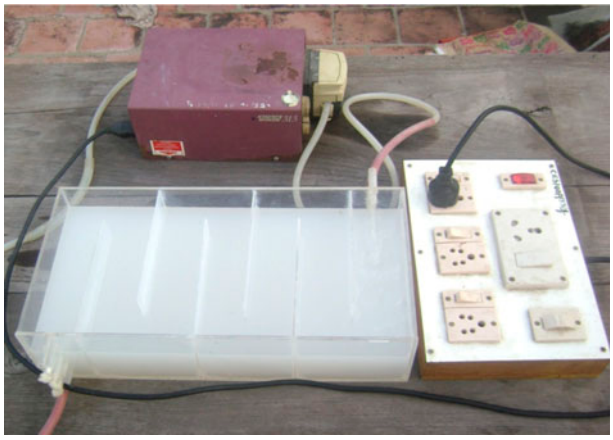

Fig. 1b. Photographic view of SPMBR.

Fig. 1c. Photographic view of SPCR.

Fig. 1d. Photographic view of SPPR.

range of 1–5 L and the recycle flow rates in the range of 250–750 mL/min. The reaction details previously optimized are as follows unless it is mentioned specifically [16,17]. The reaction slurries at pH 6, catalyst amount 0.25 g/L, phenol concentration 50 mg/L and contact time = 6 h.

Treatability studies were carried out in the best reactor for degradation of phenolic wastewaters from the pulp and paper mill industry by solar/TiO_2/H_2O_2 system. Table 1 summarizes its main characteristics. All experiments were conducted using solar light on clear sunny days in the month of April and May (UV intensity 32 ± 2 W/m^2). The tests were started at 10 am and stopped at 4 pm. Experiments were conducted at 27 ± 3°C. At specific time intervals, required amount was withdrawn and filtered to separate the catalyst. The samples were analysed for phenol as per standard methods. Phenol was monitored spectrophotometrically by the aminoantipyrine method using visible spectrophotometer (spectronic) with an optical path length of 1 cm. The method is based on the reaction of phenol with 4-aminoantipyrine in the presence of potassium ferricyanide at pH 7.9 to form a coloured antipyrine complex (AMPH). The COD and BOD_5 of the samples were carried out as per standard methods [18].

3. Results and discussion

3.1. Effect of volume of wastewater and recycle flow rate

In order to study the effect of volume of wastewater and recycle flow rate, the reactors were operated in batch recycle mode with flow rates 250, 500 and 750 mL/min. The volume of wastewaters was varied in the range of 1–5 L. The results of the experimental studies were depicted in Figs. 2a–2d. From the Fig. 2a,

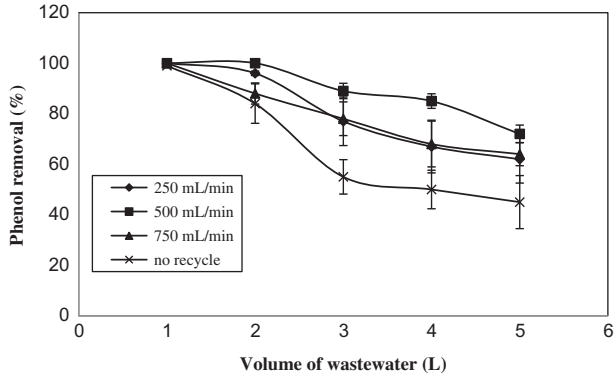

Fig. 2a. Effect of liquid volume and recycle flow rate in single-baffle reactor (pH 6, TiO_2 = 0.25 g/L, phenol = 50 mg/L, time = 6 h).

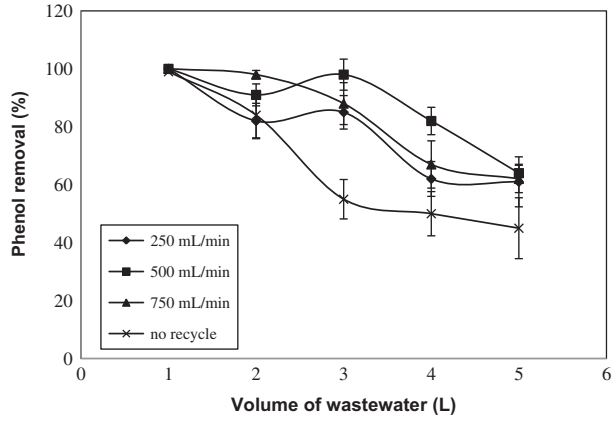

Fig. 2b. Effect of liquid volume and recycle flow rate in multiple-baffle reactor (pH 6, TiO_2 = 0.25 g/L, phenol = 50 mg/L, time = 6 h).

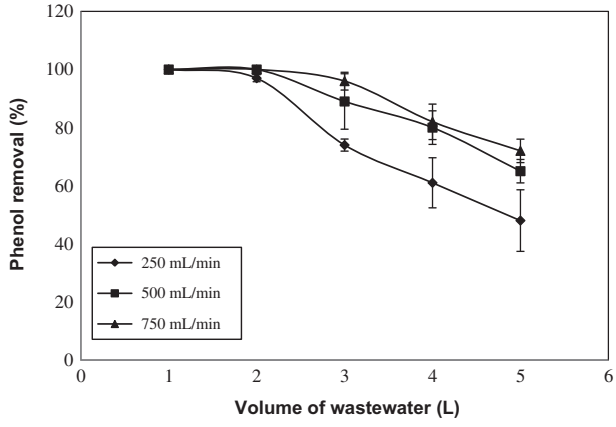

Fig. 2c. Effect of liquid volume and recycle flow rate in cascade reactor (pH 6, TiO_2 = 0.25 g/L, phenol = 50 mg/L, time = 6 h).

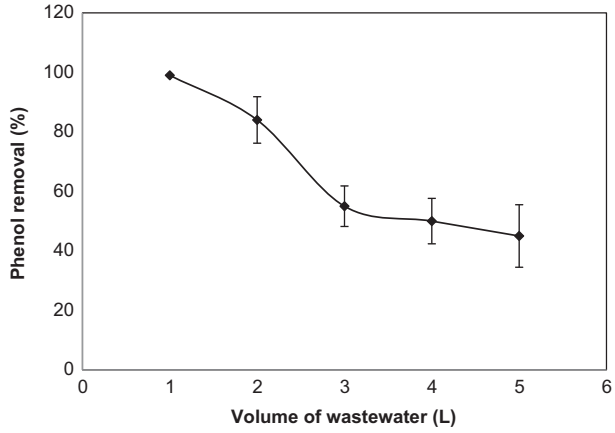

Fig. 2d. Effect of liquid volume in solar pond reactor (pH 6, TiO_2 = 0.25 g/L, phenol = 50 mg/L, time = 6 h).

it was observed that when the volume of wastewater increased from 1 to 5 L in SPSBR, if the wastewater is recycled with a flow rate of 250 mL/min, the phenol removal efficiency decreased from 100 to 62%. For the recycle flow rate of 500 mL/min, the phenol removal efficiency decreased from 100 to 80%. Similarly, for the recycle flow rate of 750 mL/min, the phenol removal efficiency decreased from 100 to 64%. Also it was observed that if no recycle the phenol removal decreased from 100 to 46%. In single-baffle reactor with 5 L volume of wastewater, the percentage removal of phenol for 250, 500 and 750 mL/min flow rate was 62, 80 and 64%, respectively. From Fig. 2b, it was observed that when the volume of wastewater increases from 1 to 5 L in SPMBR, if the wastewater is recycled with a flow rate of 250 mL/min, the phenol removal efficiency decreased from 100 to 62% .For the recycle flow rate of 500 mL/min, the phenol removal efficiency decreased from 100 to 64%. Similarly, for the recycle flow rate of 750 mL/min, the phenol removal efficiency decreased from 100 to 64%. If no recycle the phenol removal decreased from 99 to 40%. In multiple-baffles reactor with 5 L volume of wastewater, the percentage removal of phenol for 250, 500 and 750 mL/min flow rate was 61, 64 and 62%, respectively.

In the SPCR, from Fig. 2c, for the recycle flow rate of 250 mL/min, the phenol removal efficiency decreased from 100 to 48% when the volume of wastewater increased from 1 to 5 L. For the recycle flow rate of 500 mL/min, the phenol removal efficiency decreased from 100 to 65%. Similarly, for the recycle flow rate of 750 mL/min, the phenol removal efficiency decreased from 100 to 72%. In SPCR with 5-L volume of wastewater, the percentage removal of phenol for 250, 500 and 750 mL/min flow rate was 48,

65 and 72%, respectively, In the solar pond reactor, from Fig. 2d, it is observed that if the volume of wastewater increases from 1 to 5 L, the phenol removal decreased from 98 to 45%.

It was observed that for all reactors, the phenol removal efficiency increases when the recycle flow rate is increased from 250 to 500 mL/min. It might be due to the fact that higher recycle flow rate provides much more dissolved oxygen molecules, which play a roll of scavengers of excited electrons, which results in prohibiting holes. The dissolved oxygen attached by electron, the super oxide ion O^{2-}, reacts with hydrogen ion to reduce radicals $OH^{\cdot}$ and $OOH^{\cdot}$. Whereas the positive holes oxidize the hydroxide ions to yield $OH^{\cdot}$ radicals. Recycle flow rate also make these radicals come together with much more chemical compounds to be oxidized [19]. Similar results were also observed for the degradation of benzoic acid and the percentage removal of TOC increased from 7 to 8% when the flow rate increased from 2 to 5 L/min. And also reported that the turbulence created by recycle flow rate promoting effective mass transfer during photocatalytic process [4]. And also, the recycling ensures homogenous mixing of catalyst in the wastewater without setting. When the flow rate is further increased from 500 to 750 mL/min, the phenol removal efficiency decreased. It might be due to the fact that the turbulence is more in this case, catalyst particles not able to absorb the photons effectively. From the performance studies of the reactors, it was observed that for 5-L volume of wastewater, the single-baffle reactor shows the maximum phenol removal of 80% with recycle flow rate of 500 mL/min. In order to ensure proper mixing of catalyst, the SPMBR was developed, but due to the shading effect of the baffles, the absorption of photon by catalyst from the solar light is reduced. It causes the reduction in the phenol removal efficiency. When compared the performance of the cascade reactor, the phenol removal efficiency was better but it requires large area and also the evaporation losses may be more due to thin film formation of wastewater. In solar pond, it was observed that due to decrease in the penetration of light, the phenol removal efficiency is reduced.

From the studies, it was observed that in all reactors without recycle, the phenol removal efficiency decreased with an increase in the volume of wastewater. A possible explanation to this behaviour is that the reactor can be divided in two theoretical zones, where the reaction can proceed in different manner. The two zones were the illuminated zone (equal for all reactors) where radiation is absorbed by the catalyst and a dark zone (larger as the volume increases) where radiation cannot penetrate. In this case, the reactions assume to occur only in the illuminated zone [20]. Hence, the penetration depth of light decreases causing reduction in phenol removal efficiency. If it is assumed that the luminic step is the controlling one, that is, the reaction occurs only in the illuminated zone, the equation of the mass balance for phenol is change. Thus, the volume considered for the rate of phenol removal ($V_T.dc/dt$) is the total volume, because the measured concentration of phenol is referred to the total volume. However, if reaction only occurs in the illuminated zone, the reaction rate is referred only to the volume of this zone (V_i). Thus, the mass balance for phenol removal $dc/dt = -k.c$ can be rewritten in the following manner $V_T.dc/dt = -k'c\ V_i$ where V_T is the total volume of the reactor and V_i is the volume of the illuminated zone. Integrating the equation becomes $V_T.\ln(C_0/C) = -k'.V_i$. From the Fig. 3a, it was observed that the product $V_T.\ln(C_0/C)$

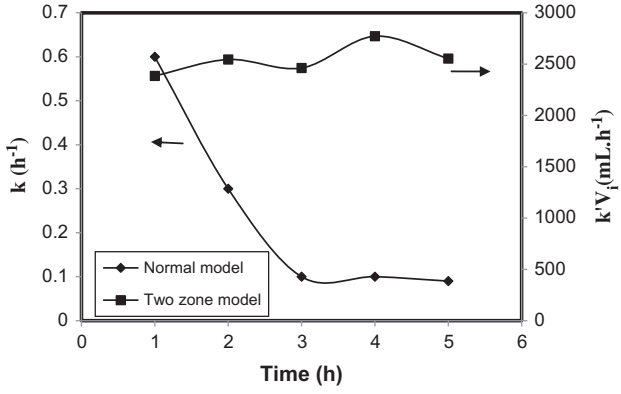

Fig. 3a. Effect of without recycle in single-baffle reactor (pH 6, TiO_2 = 0.25 g/L, phenol = 50 mg/L).

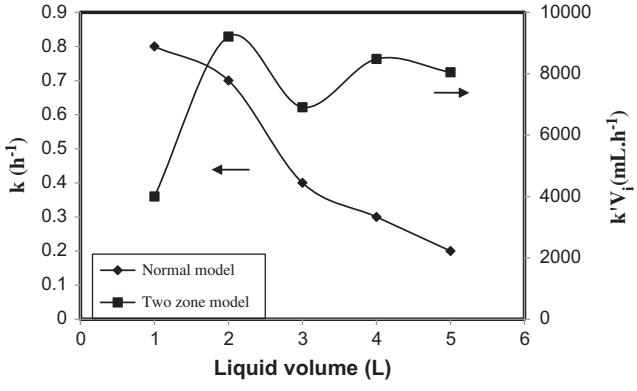

Fig. 3b. Effect of recycle in single-baffle reactor (pH 6, TiO_2 = 0.25 g/L, phenol = 50 mg/L).

remains practically constant and does not depend on the volume. This implies that the product $k'.V_i$ is constant. In addition, it can be said that V_i also constant, because the catalyst concentration and reactor surface area are constant. This means that k' will be really constant. Hence, the reaction occurs only in the illuminated zone. This problem was prevented by continuously recycling the wastewater, in order to eliminate the zone formation and to ensure every drop of wastewater come contact to solar light. From the Fig. 3b, it was observed that after recycling the wastewater, the phenol removal efficiency was increased and also $k'.V_i$ is varying, it indicates that the reaction occur thorough out the depth, i.e. no zone formation. In general, when compared the performance of solar photocatalytic reactors with respect to volume of wastewater, it was observed that the SPSBR gives the maximum phenol removal efficiency irrespective of all volume of wastewater.

The reusability of catalyst was investigated for the removal of phenol. The results of the experimental studies are depicted in Fig. 4. It was observed that 70% phenol removal after 10 trails. Hence, it could be stated that the catalyst is reusable at least for 10 times. It was also observed that about 7–10% of catalyst was lost in every cycle of separation through settling. This suggests that fresh catalyst loading would be required to compensate the loss after few runs. And also, it was observed that the phenol removal efficiency reduced from 95 to 48% after 15 trials of reuse. It might be due to the adsorbed species on the active sites of the catalyst surface and on the change of the dimension of the catalyst particles. Both of the above factors account for the reduction of number of available photoactive sites [12].

Fig. 4. Effect of catalyst reuse (pH 6, TiO_2 = 0.25 g/L, phenol = 50 mg/L, contact time = 6 h).

3.2. Treatment of phenolic wastewaters by solar/TiO_2/H_2O_2 process

The phenolic wastewaters collected from the pulp and paper mill industry are non-biodegradable in nature, the feasibility of enhancement of biodegradability of wastewater was carried out by solar/TiO_2/H_2O_2 system, in a single-baffle reactor with reaction slurries at pH 6, catalyst amount 0.25 g/L, H_2O_2 dosage 0.3 g/L and volume of wastewater 5 L with a recycle flow rate at 500 mL/min [16,21]. The biodegradability of the phenolic wastewaters was tested and assessed as BOD_5/COD ratio. The results of the experimental studies are depicted in Fig. 5. Biodegradability was increased from 0.02 to 0.80 due to the increase in BOD_5 (10–85 mg/L) and the decrease in COD (450–100 mg/L), after 4 h of irradiation. As a reference, this parameter for biodegradable municipal wastewater is of around 0.6. It should be noticed that BOD_5/COD ratio higher than 0.6 indicate a readily and rapidly degradable solution, while ratio below 0.4 involve the presence of slowly biodegradable compounds [22]. The results indicated that the solar photocatalytic process could break down or rearrange molecular structures of organic matters and convert the non-biodegradable organics to more biodegradable forms. This is a fact of remarkable importance for the application of photocatalytic–biological integrated systems to wastewater treatment. Photocatalytic process could transform organic recalcitrant compounds into easily biodegradable products, improving the efficiency and reducing the cost of further biological steps. Around 93% of COD was depleted at 5 h (Fig. 5). By increasing the contact time, the exposure of the reaction mixture to solar light allowed the

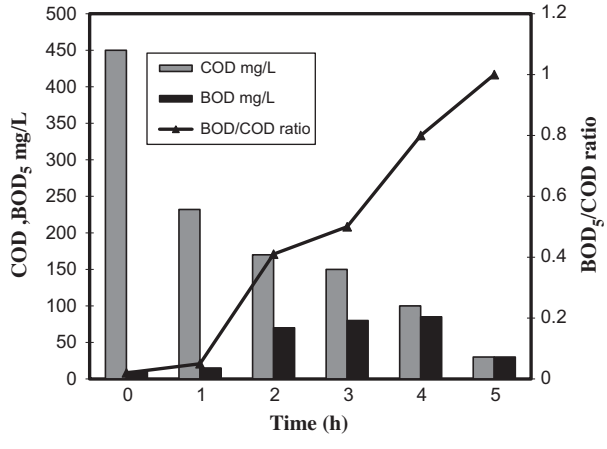

Fig. 5. Biodegradability of phenolic wastewaters from pulp and paper mill industry (pH 6, TiO_2 = 0.25 g/L, H_2O_2 = 0.3 g/L).

Table 2
Characteristics of solar/TiO_2/H_2O_2 treated phenolic wastewater

Parameters	Solar/TiO_2/ H_2O_2	Minimal National Standards (MINAS) for disposal
pH	7	6.5–9.0
TSS (mg/L)	20	100
BOD_5 (mg/L)	30	100
COD(mg/L)	30	250

utilization of more energy to produce more hydroxyl radicals [23]. Table 2 shows the treated characteristics of the phenolic wastewater. The COD and BOD_5 of phenolic wastewater after treatment were reduced to 30 mg/L.

3.3. Design of the field scale reactor

The field scale reactor was designed to treat the phenolic wastewater with a flow rate of 1 m^3/d. The reactor was designed for 93% COD removal. The average yearly solar UV light intensity for the location of study was calculated as 23 ± 2 W/m^2, and the average daily useful solar hour was found to be 6 h. Sagawe et al. [5,6] suggested the equation for the kinetic model, which accounts for the effect of pollutant concentration, volumetric flow rate, light intensity and solar irradiation area; these were used to arrive at a lump parameter (K_3).

$$K_3 = \ln (C_0/C) \times Q/(q_{UV} \times A) \quad (1)$$

where K_3 = lump kinetic parameter representing the efficiency of the photocatalyst (m^3/W min); C_0 = inlet concentration of COD (mg/L); C = outlet concentration of COD (mg/L); Q = volumetric flow rate (m^3/min); q_{UV} = time averaged radiation density flux (W/m^2); and A = effective area of solar irradiation (m^2).

$K_3 = \ln (450/30) \times 1.66 \times 10^{-5}/(23 \times 0.08) = 2.44 \times 10^{-5}$ m^3/W min.

The scaling up of the field scale reactor can be given by the following Eqs. ((2) and (3)):

$$(K_3)_{\text{bench-scale reactor}} = (K_3)_{\text{field-scale reactor}} \quad (2)$$

$$\text{Area of field-scale reactor} = \ln (C_0/C) \times Q_{\text{field-scale reactor}}/(q_{UV}) \times (K_3)_{\text{bench-scale reactor}} \quad (3)$$

$$= \ln (450/30) \times 3.33 \times 10^{-3}/\ 23 \times 2.44 \times 10^{-5}$$

$$= 16.28\ m^2$$

4. Conclusion

Four bench-scale solar photocatalytic reactors were fabricated viz. single-baffle reactor, multiple-baffles reactor, cascade reactor and solar pond reactors of 5-L capacity for treating phenolic wastewaters. It was observed that for all reactors, the phenol removal efficiency increases when the recycle flow rate is increased from 250 to 500 mL/min and the phenol removal efficiency decreased with an increase in the volume of wastewater. From the performance studies of the reactors, it was observed that for 5-L volume of wastewater, the single-baffle reactor shows the maximum phenol removal of 80% with recycle flow rate of 500 mL/min. It was observed that catalyst is reusable at least for 10 times. The results indicated that the solar photocatalytic process could break down or rearrange molecular structures of organic matters and convert the non-biodegradable organics to more biodegradable forms. This is a fact of remarkable importance for the application of photocatalytic–biological integrated systems to wastewater treatment.

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