Water Utility Journal 13: 83-90, 2016.

Performance of integrated bio-solar process for domestic wastewater treatment: A sustainable approach to scale-up wastewater management

A. Barwal and R. Chaudhary*
School of Energy and Environmental Studies, Faculty of Engineering Sciences, Devi Ahilya University, Takshashila Campus, Khandwa Road, Indore, Madhya Pradesh, 452001, India
* *e-mail: rubina_chaudhary@yahoo.com*

Abstract: Since water is essential to many aspects of life, and to the surrounding natural environment, there is a need not only for innovative, efficient and sustainable technologies, but also to identify future challenges to its successful implementation. This paper describes an integrated bio-solar process (moving bed biofilm reactor coupled with solar parabolic structured system) which has been designed and developed to get the maximum organic load removal and microbial disinfection from the municipal wastewater. The effluent was first subjected to organic degradation in moving bed biofilm reactor using a low cost plastic media (with optimized carrier filling rate of 50%) followed by the bacterial degradation using solar energy in parabolic trough reactor (PTR) and the changes in values of parameters like pH, turbidity, chemical oxygen demand (COD), bio-chemical oxygen demand (BOD_{5d}) and microbial count were monitored. In PTR, the titanium dioxide (TiO_2) was used as a photocatalyst for the removal of organic load from the wastewater but in optimized conditions. At an optimum dose of 750 mg/L of TiO_2, maximum COD removal of 73.4% and 41.5% was achieved at sunny days and cloudy days respectively within 4 h solar irradiation time. The results obtained showed that it is possible to decrease in six logarithms (log) the concentration of total coliform and fecal coliform within only 240 minutes of solar exposure. Overall, this integrated process is able to remove up to 95-97% COD, 95-98% BOD_{5d}, 99.99% total coliform and 100% fecal coliform from the domestic wastewater during sunny as well as cloudy cover conditions. Therefore, this process can offer economically reasonable, low power requirement, chemical free and practical solution to the processing of domestic wastewater and can be scaled up for small communities, towns and rural areas in the developing countries.

Key words: Municipal wastewater; organic removal; solar disinfection; moving bed biofilm reactor; parabolic trough reactor.

1. INTRODUCTION

Worldwide, one billion people practice open defecation (UN Water, 2015). In rural areas, treatment of domestic wastewater is essential to prevent aquatic environment pollution, which has been of increasing concern (Ichinari et al., 2008). Seven out of ten people without improved sanitation live in rural areas. World Health Organization (WHO) and the Water Supply and Sanitation Collaborative Council indicate that only less than 18% of rural populations have an access to sanitation services in developing countries (Massoud et al., 2009). One third of the world populations (approx. 2.4 billion people) remain without access to improved sanitation in 2015 (UN Water, 2015). In India also efforts are being made to end open defecation under Clean India Mission (Clean India Mission, 2016). Households in rural areas do not have public sewers to manage their wastewater. Many on-site wastewater treatment technologies, such as septic tanks, drain-field systems, aerobic biological treatment systems and membrane bioreactors (MBRs) are available (Nakajima et al., 1999; Abegglen et al., 2008). But the most sustainable technology is the one that is economically viable, socially acceptable, technically and institutionally appropriate, it should also protect the environment and the natural resources. On-site treatment systems often do not meet these requirements. Conventional biological treatment unit and membrane bioreactors (MBRs) effectively remove pollutants, but have high capital, operations and maintenance costs that are not affordable in developing countries (Nakajima et al., 1999; Daude and Stephenson, 2004; Ichinari et al., 2008; Ren et al., 2010). It is therefore an urgent need to conduct research into an alternative disposal system based on local requirements and conditions for the treatment of domestic wastewater.

In the current scenario, renewable energies are rapidly increasing their contribution to the global mix, solar energy being the one with higher potential. The use of solar irradiation for treatment of chemically and biologically contaminated water is not a new phenomenon (Davies-Colley et al., 1994; Conroy et al., 1996; Sinton et al., 1999; 2002; Caslake et al., 2004, Singh et al., 2011). Solar radiation removes a wide range of organic chemicals and pathogenic organisms by direct exposure, is relatively inexpensive, and avoids generation of harmful byproducts of chemically driven technologies (Calkins et al. 1976).

Bio-solar process, a combination of biological secondary treatment (MBBR) and tertiary treatment (solar PTR), is an interesting and novel alternative for wastewater treatment as it is an efficient low cost integrated on-site treatment technology to make domestic wastewater ready to recycle and reuse for different applications. It is reliable and compact systems due to development in their designs and operation which has resulted in decreased water footprints, significantly lower suspended solid production, consistent production of high quality and reusable water and minimal waste disposal (Barwal and Chaudhary, 2014). However, in MBBR, the choice of support carrier (media) is a crucial step for the efficient operation of reactor to maintain a high amount of biomass. The bio-carrier used in MBBR for wastewater treatment should have low cost, high effective surface area, good mechanical strength and be suitable for microbial aggregation. Therefore, in this study, a scope of using low cost plastic carrier was also evaluated as an alternative for conventional high density polyethylene bio-carriers (Barwal and Chaudhary, 2014) used in biofilm reactors.

This study was focused on performance evaluation of the bio-solar process (during sunny and cloudy conditions) for treating the high concentrations of organic load to achieve very low COD and BOD_5 values and disinfection of municipal wastewater using solar irradiation in an economical manner. Due to its low capital and operating costs, low power requirement and chemical-free solution, this technology can be scaled up for small communities, townships and rural areas in the developing countries.

2. MATERIAL AND METHODOLOGY

2.1 Treatment system description

An integrated bio-solar reactor was designed and fabricated for the treatment of domestic wastewater to achieve very less COD, BOD and no fecal Coliform presence. The schematic of the experimental set-up is shown in Figure 1.

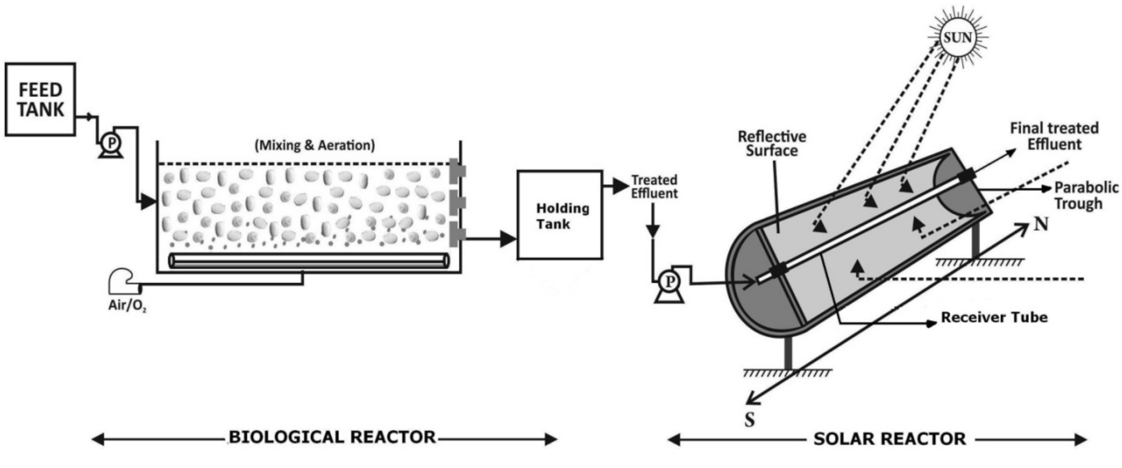

Figure 1. Schematic diagram of the experimental set-up of integrated reactor

2.1.1 Biological reactor

A laboratory scale rectangular reactor with a volume of 30 L made up of acrylic sheet was used in this study. The effective working volume was 20 L. The reactor was filled with low-cost biofilm carriers, which have small protuberant over its ellipsoid surface (Figure 2, density < 0.98 g cm^{-3}, height 11.55 mm, specific gravity 0.97 g cm^{-3} and specific surface area 380 m^2 m^{-3}). The reactor was continuously fed with synthetic municipal wastewater. The composition of the synthetic nutrient solution (Barwal and Chaudhary, 2015) used in this study is given in Table 1. Characteristics of influent wastewater were- pH: 7.2, COD: 440 mg L^{-1}, BOD_5: 380 mg L^{-1}, turbidity: 73 NTU and Fecal Coliform: 20×10^6 MPN/100 mL respectively. An aeration pump was used for air supply and for keeping the sludge in suspension.

Figure 2. Photo of plastic biofilm support carriers used in biological reactor

Table 1. Composition of prepared synthetic wastewater

Chemical Compound	Unit (in mg L^{-1})	Food Ingredients	Unit (in mg L^{-1})	Trace Metals	Unit (in mg L^{-1})
Urea	91.74	Starch	122.00	$Cr(NO_3)_3.9H_2O$	0.770
NH_4Cl	12.75	Milk Powder	116.19	$CuCl_2.2H_2O$	0.536
Na-Acetate	79.37	Yeast	52.24	$MnSO_4.H_2O$	0.108
Peptone	17.41	Soya Oil	29.02	$NiSO_4.6H_2O$	0.336
$MgHPO_4.3H_2O$	29.02			$PbCl_2$	0.100
KH_2PO_4	23.40			$ZnCl_2$	0.2080
$FeSO_4.7H_2O$	5.80				

2.1.2 Parabolic trough reactor

In continuation with the biological reactor, a parabolic trough reactor (PTR) was designed in the shape of a parabolic cylinder which reflects and concentrates sun radiations towards a receiver tube located at the focus line of the parabolic cylinder (Figure 1).

2.2 Operating conditions

To initiate biological growth and development of the biofilm, the reactor was inoculated with mixed culture of biomass. Whole study was performed under ambient conditions. The experimental work was carried out with optimized carrier filling ratio of 50%. The duration of experimental run was 15-days with 10-days microbial acclimatization time. The effluent from biological reactor goes to the PTR with the help of peristaltic pump. The duration of the solar experiments was fixed from 11:00 to 15:00 h, when maximum solar irradiation was available.

2.3 Experiment and analysis

All physico-chemical parameters and bacterial enumeration (in terms of MPN/100ml) in the inlet and outlet were determined in accordance with the *Standard Methods* (APHA, 2012). Pyranometer (Make SM 201 solar, Central Electronics Ltd, India) was used to measure the direct solar radiation on the horizontal surface and the irradiation data was collected in Wm^{-2}. Turbidity and temperature was measured by using digital nephelo-turbidity meter (Make 132, Systronics) and digital thermometer.

Calculation of removal efficiency (RE%): In order to quantify the whole treatment performance of the reactors, removal efficiencies (RE) were calculated for the chemical parameters (COD and BOD_5,) using the following equation:

$$RE\ (\%) = \left(\frac{C_{in}-C_{eff}}{C_{in}}\right) \times 100 \quad (1)$$

where C_{in} and C_{eff} are the concentrations in the influent and in the effluent, respectively.

Titanium dioxide (TiO_2) was used in solar PTR as a catalyst and was used in mobilized form. The experiment was done under continuous process conditions. A two hourly reading of temperature (ambient and wastewater), pH, turbidity, COD and fecal coliform values were monitored as a function of exposure time for the sunny and cloudy conditions. Experiments were performed at an optimum catalyst dose of 750 mg L^{-1} which gives the maximum reduction.

3. RESULTS AND DISCUSSION

The effectiveness and performance of an integrated bio-solar process was evaluated in two phases, secondary treatment and tertiary treatment options. The secondary phase treatment option describes the use of biological process (MBBR with low cost polystyrene media) for organic load degradation from municipal wastewater based on an optimal biocarrier filling ratio of 50%, while the tertiary treatment phase explains the efficiency of the simultaneous disinfection and further organic load reduction by using the direct solar irradiation in presence of photocatalyst.

3.1 Performance of the MBBR system: a secondary treatment

3.1.1 COD and BOD removal

The bio-reactor performance in terms of temperature, turbidity, COD and BOD_5 removal was studied for the duration of 15 days using 50% of low cost biocarrier filling ratio. Figure 3 shows the trend of COD, BOD_5 and turbidity removal in MBBR for the duration of 15 days. Temperature of the wastewater in the reactor was ranging from 23.5 – 30.5^{o}C. The organic matter concentration in the biofilm reactor were observed to decline from an initial concentration of 440.0 to 41.4 mg L^{-1} of COD (91% removal) and 380.0 to 24.7 mg L^{-1} of BOD (93.5% removal) respectively. The COD and BOD_{5d} concentration leaving the biological reactor were found to be 41.4 mg L^{-1} and 24.7 mg L^{-1}, respectively. Turbidity was also observed to decrease from 73.0 to 39.4 NTU (approx. 46%) in the bioreactor.

3.2 Performance of the solar PTR: a tertiary treatment

The effluent from the biological secondary treatment was fed to the solar parabolic trough reactor to achieve the disinfection and removal of remaining organics. The effect of solar intensity, photocatalyst dosing on COD and coliform bacterial removal efficiency was assessed.

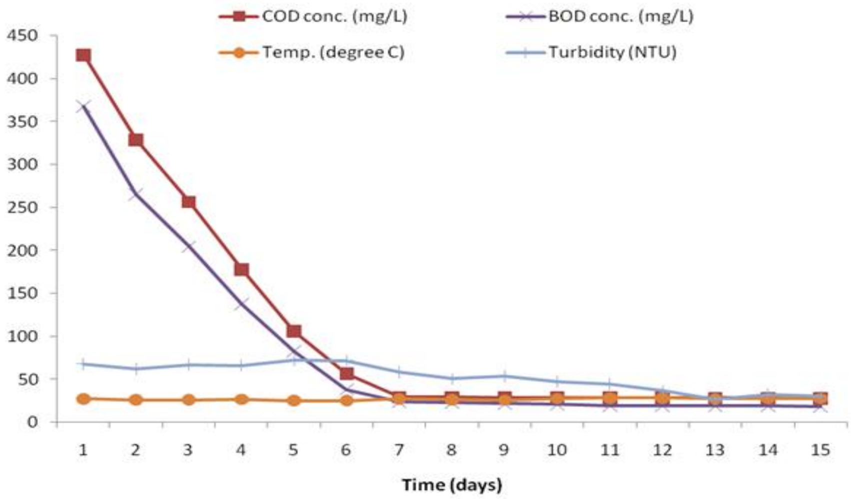

Figure 3. Trend of COD, BOD and turbidity reduction at an optimum carrier filling ratio in a biofilm reactor

3.2.1 Effect of TiO_2 concentration on COD removal

The catalyst concentration was varied from 100 mg L^{-1} to 1000 mg L^{-1} to obtain an optimum concentration. The results are shown in Figure 4. It is clear from the figure that the best COD removal efficiency was obtained at the dosing of 750 mg L^{-1}. At this optimum concentration, the COD value of the wastewater reduced gradually over solar exposure time resulting in 73.4% removal at the end of 4 h photocatalytic treatment which corresponds to less than 15 mg L^{-1} COD concentration in finally treated effluent of this bio-solar process. The higher TiO_2 concentration led to the decreased degradation rate due to the interference of the light by the suspension. The results were found in agreement with Chakrabarti and Dutta, 2004; Ehrampoush et al., 2011; Singh et al., 2013.

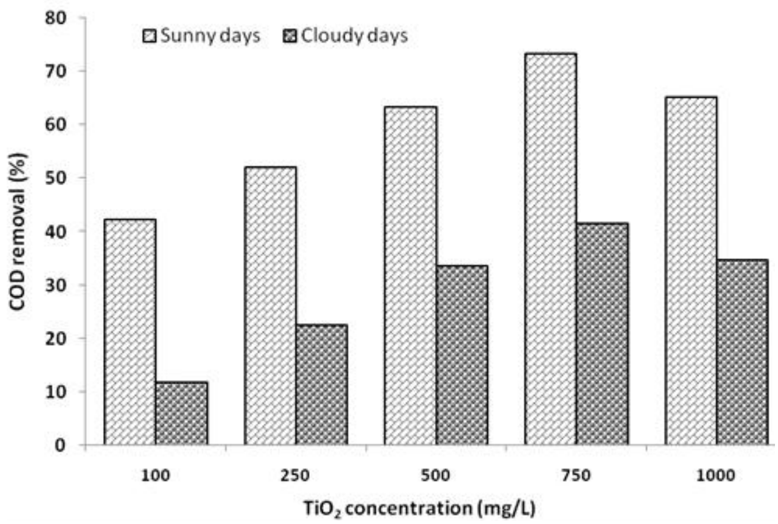

Figure 4. Effect of TiO_2 dosing for COD reduction during sunny and cloudy days

3.2.2 Effect of solar intensity on COD removal

The maximum solar radiation intensity was available in the 4 h (11:00 to 15:00 h) with maximum reduction. It can be presumed from Table 2 that the reaction was performed efficiently at the solar irradiation between 500-700 Wm^{-2}. A reduction in COD level below 15 mg L^{-1} concludes that a process of solar mineralization gives a highly satisfactory performance. Similar, experimental run were also performed on a cloudy cover conditions, (solar irradiation 150-210 Wm^{-2}), showed low significant COD reduction (41.5%) in 4 h at an optimized photocatalytic dosing (Table 2). The COD concentration in effluent was observed to be less than 15 mg L^{-1} in sunny conditions and 25 mg L^{-1} in cloudy conditions, which is very much less than the subjected worldwide stringent environmental regulations.

Table 2. Experimental data with different photocatalyst dosing at sunny and cloudy conditions

TiO_2 Conc. (mg L^{-1})	Time (h)	Sunny conditions					Cloudy conditions				
		Solar Irradiance (Wm^{-2})	Ambient Temp. (°C)	Wastewater Temp. (°C)	pH	COD Reduction (%)	Solar Irradiance (Wm^{-2})	Ambient Temp. (°C)	Wastewater Temp. (°C)	pH	COD Reduction (%)
100	11:00	670.00	34.50	44.00	7.30	28.20	185.00	25.00	26.00	7.40	8.30
	13:00	700.00	37.50	54.50	7.70	42.80	195.00	26.00	26.50	7.30	11.50
	15:00	490.00	35.00	49.00	7.70	55.80	185.00	26.00	27.00	7.40	15.40
	Mean	**620.00**	**35.67**	**49.17**	**7.57**	**42.27**	**188.33**	**25.67**	**26.50**	**7.37**	**11.73**
	SD	**113.58**	**1.61**	**5.25**	**0.23**	**13.81**	**5.77**	**0.58**	**0.50**	**0.06**	**3.56**
250	11:00	680.00	36.50	44.50	7.20	43.90	215.00	23.50	23.00	7.30	15.40
	13:00	690.00	38.50	56.00	7.50	52.60	220.00	25.00	25.50	7.30	23.50
	15:00	570.00	39.00	47.50	7.60	59.60	210.00	25.50	26.00	7.50	28.70
	Mean	**646.67**	**38.00**	**49.33**	**7.43**	**52.03**	**215.00**	**24.67**	**24.83**	**7.37**	**22.53**
	SD	**66.58**	**1.32**	**5.97**	**0.21**	**7.87**	**5.00**	**1.04**	**1.61**	**0.12**	**6.70**
500	11:00	660.00	36.00	47.50	7.70	52.50	195.00	24.00	24.50	7.50	28.40
	13:00	690.00	38.50	54.50	7.80	60.20	200.00	23.50	25.50	7.30	32.50
	15:00	600.00	38.00	52.50	7.50	77.50	210.00	24.50	27.00	7.40	39.80
	Mean	**650.00**	**37.50**	**51.50**	**7.67**	**63.40**	**201.67**	**24.00**	**25.67**	**7.40**	**33.57**
	SD	**45.83**	**1.32**	**3.61**	**0.15**	**12.80**	**7.64**	**0.50**	**1.26**	**0.10**	**5.77**
750	11:00	670.00	37.50	49.50	7.40	68.10	180.00	23.00	24.50	7.20	38.80
	13:00	700.00	38.50	55.50	7.40	73.20	195.00	24.50	25.50	7.30	41.90
	15:00	610.00	37.50	53.00	7.20	78.90	190.00	25.00	27.50	7.40	43.70
	Mean	**660.00**	**37.83**	**52.67**	**7.33**	**73.40**	**188.33**	**24.17**	**25.83**	**7.30**	**41.47**
	SD	**45.83**	**0.58**	**3.01**	**0.12**	**5.40**	**7.64**	**1.04**	**1.53**	**0.10**	**2.48**
1000	11:00	690.00	36.00	48.00	7.20	60.50	195.00	24.00	26.00	7.50	30.30
	13:00	710.00	39.50	56.50	7.50	65.80	200.00	24.50	26.50	7.40	35.60
	15:00	670.00	38.00	50.50	7.30	69.50	190.00	25.00	27.50	7.40	38.40
	Mean	**690.00**	**37.83**	**51.67**	**7.33**	**65.27**	**195.00**	**24.50**	**26.67**	**7.43**	**34.77**
	SD	**20.00**	**1.76**	**4.37**	**0.15**	**4.52**	**5.00**	**0.50**	**0.76**	**0.06**	**4.11**

3.2.3 Effect of solar radiation on coliform bacteria removal

A solar disinfection unit has been designed and successfully tested for disinfection of contaminated water under polychromatic solar light. Solar UV disinfection was found effective in reducing mean concentration of indicator microorganisms i.e. total coliform (TC) and fecal coliform (FC) after 4 h of exposure to direct sunlight. During sunny conditions, the treated water was found to have less than 500 total coliform/100 mL and no fecal coliform/100 mL whereas, during cloudy conditions, values were found less than 10^4 total coliform/100 mL and 2500 fecal coliform/100 mL, respectively. It was observed that around 400-700 Wm^{-2} was required to reduce the bacterial population by six log cycles. Similar results were also obtained by Qualls et al. (1983), Dababneh et al. (2012) and Queluz and Sánchez-Román (2014).

Overall, a tremendous reduction was observed with respect to the permissible limits (CPCB standards, 2016). The wastewater parameters of MBBR effluent and finally treated wastewater are mentioned in Table 3. This treated wastewater has multiple applicability and can deliver positive benefits to the irrigation, industrial sector, recharge of ground water and for municipal supply. With careful planning various industrial and agricultural demands may be met by purified sewage water thereby freeing fresh water only for domestic use.

Table 3. Characteristics and comparison of treated wastewater with the standard limits

Parameter	Unit	MBBR outlet	Solar parabolic trough outlet		Wastewater discharge standards (as per CPCB, 2016)		
			During sunny conditions	During cloudy conditions	Inland surface water	Public sewer	Land for irrigation
pH	--	7.8	7.5	7.3	5.5 – 9.0	5.5 – 9.0	5.5 – 9.0
BOD_5 (at 20°C)	mg L^{-1}	24.70	8.55	19.50	30	350	100
COD	mg L^{-1}	41.40	11.01	24.22	250	--	--
Fecal coliform	MPN /100 ml	22 x 10^6	Nil	2500	1000	10,000	1000

The wastewater management requires removal efficiency, effectiveness and affordability. Overall, this integrated system is much more efficient and cost effective than others reported in the peer-review literature, but there is still an affordability problem related to the economic conditions of the community. Therefore, support from the government will be needed to realize implementation of this process.

4. CONCLUSION

It is concluded that the designed integrated bio-solar process can be used effectively for the organic matter degradation and disinfection of municipal wastewater and can be further reused for various applications like irrigation, industrial sector, ground water recharge and for municipal water supply. Its simple design enables integration into existing treatment plants without disruption to current processes. The use of solar light, combined with the biological treatment technology, can offer economically reasonable, chemical free and practical solutions to the processing of municipal wastewater where solar intensity is readily available. Overall, this integrated process is able to remove up to 95-97% COD, 95-98% BOD, 99.99% total coliform and 100% fecal coliform from the domestic wastewater during sunny as well as cloudy cover conditions with 50% carrier filling ratio and 750 mg L^{-1} of TiO_2 dosing. This integrated system is much more efficient and cost effective than others processes, but there is still an affordability problem related to the economic conditions of the community. Therefore, the government support is important for its effective implementation.

REFERENCES

Abegglen C, Ospelt M, Siegrist H (2008) Biological nutrient removal in a small scale MBR treating household wastewater, Water Res. 42: 338–346.

APHA, American Public Health Association (2012) Standard Method for Water and Wastewater Examination, 22nd edn, American Public Health Association Washington DC

Barwal A and Chaudhary R (2014) To study the performance of bio-carriers in moving bed biofilm reactor (MBBR) technology and kinetics of biofilm for retrofitting the existing aerobic treatment systems - A Review, Reviews Environ. Sci. Bio/technol. (13): 285–299

Barwal A and Chaudhary R (2015) Impact of carrier filling fraction on oxygen uptake & transfer rate, volumetric oxygen transfer coefficient and energy saving potential in a lab-scale MBBR, Water Process Eng. 8: 202–208

Calkins J, Buckles JD, and Moeller JR (1976) The role of solar ultraviolet radiation in “natural” water purification. Photochem. Photobiol. 24: 49–57.

Conroy RM, Elmore-Meegan M, Joyce T, McGuigan KG, and Barnes J (1996) Solar disinfection of drinking water and diarrhoea in Maasai children: a controlled field trial. Lancet 348: 1695–1697.

Caslake FL, Connolly DJ, Menon V, Duncanson CM, Rojas R, Tavakoli J (2004) Disinfection of contaminated water by using solar irradiation, Appl. Environ. Microbiol. 70(2): 1145-1150

Chakrabarti S, Dutta B (2004) Photocatalytic degradation of model textile dyes in wastewater using ZnO as semiconductor catalyst. J. Hazard Mater. 112: 269–278.

CPCB (2016) General Standards for discharge of environmental pollutants http://cpcb.nic.in/GeneralStandards.pdf (accessed on 08.01.2016)

Clean India Mission (2016) Ministry of Drinking Water and Sanitation, Swachh Bharat Mission-Gramin. http://sbm.gov.in/sbm_new/ (accessed on 06.01.2016)

Davies-Colley RJ, Bell RG, and Donnison AM (1994) Sunlight inactivation of enterococci and fecal coliforms in sewage effluent diluted in seawater. Appl. Environ. Microbiol. 60: 2049–2058.

Daude D, Stephenson T (2004) Cost-effective treatment solutions for rural areas: design and operation of a new package treatment plant for single households, Water Sci. Technol. 48: 107–114.

Dababneh BF, Shquirat WD, Abbassi BE (2012) Coliform-specific solar disinfection of treated wastewater. Pol. J. Environ. Stud. 21(6): 1577-1581.

Ehrampoush MH, Moussavi GHR, Ghaneian MT, Rahimi S, Ahmadian M (2011) Removal of methylene blue dye from textile simulated sample using tubular reactor and TiO_2/UV-C photocatalytic process, Iran. J. Environ. Health. Sci. Eng. 8(1): 35-40.

Ichinari T, Ohtsubo A, Ozawa T, Hasegawa K, Teduka K, Oguchi T, Kiso Y (2008) Wastewater treatment performance and sludge reduction properties of a household wastewater treatment system combined with an aerobic sludge digestion unit. Process Biochem. 43: 722–728.

Massoud MA, Tarhini A, Nasr JA (2009) Decentralized approaches to wastewater treatment and management: applicability in developing countries. J. Environ. Manage. 90: 652–659.

Nakajima J, Fujimura Y, Inamori Y (1999) Performance evaluation of on-site treatment facilities for wastewater from households, hotels and restaurants, Water Sci. Technol. 39: 85–92.

Qualls RG, Flynn MP, Johnson JD (1983) The role of suspended particles in Ultraviolet disinfection, J. Water Poll. Control Fed. 55(10): 1280-1285

Queluz JGT, Sánchez-Román RM (2014) Efficiency of domestic wastewater solar disinfection in reactors with different colors, Water Utility J. 7: 35-44

Ren X, Shon HK, Jang N, Lee YG, Bae M, Cho K, Kim IS (2010) Novel membrane bioreactor (MBR) coupled with a nonwoven fabric filter for household wastewater treatment. Water Res. 44: 751–760.

Sinton LW, Finlay RK, Lynch PA (1999) Sunlight inactivation of fecal bacteriophages and bacteria in sewage-polluted seawater, Appl. Environ. Microbiol. 65: 3605–3613.

Sinton LW, Hall CH, Lynch PA, Davies-Colley RJ (2002) Sunlight inactivation of fecal indicator bacteria and bacteriophages from waste stabilization pond effluent in fresh and saline waters. Appl. Environ. Microbiol. 68: 1122–1131.

Singh C, Chaudhary R, Thakur RS (2011) Performance of advanced photocatalytic detoxification of municipal wastewater under solar radiation - A mini review, Int. J. Energy Environ. 2(2): 337-350

Singh C, Chaudhary R, Gandhi K (2013) Preliminary study on optimization of pH, oxidant and catalyst dose for high COD content: solar parabolic trough collector, Iranian J. Environ. Health Sci. Eng., 10(1): 13

UN Water (2015) The United nations inter agency mechanism on all freshwater related issues including sanitation - Water, sanitation and hygiene, http://www.unwater.org/topics/water-sanitation-and-hygiene/en/. (accessed on 21.12.2015)