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Performance, water quality and enviro-economic investigations on solar distillation treatment of reverse osmosis reject and sewage water

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ABSTRACT

In this work, effective treatment of RO reject and domestic sewage water in a single step using indigenously developed tilted solar distillation unit has been proposed. Behavior of the unit along with its characteristics, treated water quality, environmental benefits and economics has been reported based on experimental observations. Around, 4.79 and 4.48 L/d of treated water are produced by the unit at a thermal efficiency of 48.5% and 45.3% during RO reject and sewage water distillation, respectively. Suspended particles of re-circulated sewage water caused clogging of wick and affected tilted solar distillation unit's performance and efficiency. Smooth operation of the unit is noticed during RO reject distillation. The proposed unit could prevent at least 23.73 tons of CO_2, 158.54 kg of SO_2 and 64.75 kg of NO emissions during its 20 Yr life span. Wick replacement frequency and interest rate have a signification impact on distillation unit's treated water production cost. The proposed distillation unit's treated water production cost is lower than basin solar stills reported in literatures. Treated water is clear, odor free and bacterial free. Physical properties and heavy metal concentrations of treated water are well within the standards for safe drinking water except BOD (Biological Oxygen Demand) and COD (Chemical Oxygen Demand) such that the treated water can be used for other domestic and irrigation purposes. The results obtained from this study confirm solar distillation as an effective and sustainable option for wastewater treatment.

1. Introduction

Fresh water finds various livelihood applications in domestic, industrial and energy sectors of nations around the globe. The quantity and quality of these limited precious fresh water resources are degrading continuously because of over exploitation and wastewater dumping (Manju and Sagar, 2017; Rijsberman, 2006; Rajasulochana and Preethy, 2016). Wastewaters that are generally dumped into water bodies without any pre-treatment are mainly RO (reverse osmosis) reject and domestic sewage water. RO reject is a mixture of pre-treatment chemicals and concentrated feed water. Domestic sewage water represents used water from households. Around, 80.0% of water supplied to households for domestic use returns back as domestic sewage water (Kaur et al., 2012).

Techniques like deep well injection and discharge into surface waters are widely followed for disposing RO reject but these methods have posed severe threats to environment (Ahmed et al., 2000). Wastewater treatment and reuse is the only available option that can close water cycle, reduce water stress and mitigate negative impacts on environment (Vergine et al., 2017). Biological stabilization ponds (Rusan et al., 2007) and activated sludge-extended aeration plant (Al-Lahham et al., 2007) are widely used for treating wastewaters generated from houses and industries. However, these techniques cannot remove toxic heavy metals, nitrogen, phosphorous, organic and inorganic substances from wastewater in a single step (Rajasulochana and Preethy, 2016). Moreover, they cannot tolerate high salinity and heavy metal concentration of RO reject. Hence, evaporation technique is widely recommended for treating RO reject (Giwa et al., 2017).

Energy consumption and CO_2 emission per m^3 of wastewater treated in Indian sewage treatment plants are in the range of 0.40–4.87 kWh and 0.78–3.04 $kgCO_2eq$, respectively (Singh et al., 2016). Similarly, 27.4 kg of oil is required to produce 1.0 m^3 of distillate (treated water) by evaporation process (Kalogirou, 2005). Pollution and treatment cost of existing biological treatment plants and fossil fuel based distillation units can be reduced by utilizing renewable wind and solar energy for their operation (Haralambopoulos et al., 1997; Han et al., 2013; Halaby et al., 2017). Lack of finance, proper infrastructures and skilled work force in wastewater treatment sectors has lead to poor wastewater

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Nomenclature

A_{ts}	aperture area of tilted solar distillation unit (m^2)
h_{fg}	latent heat of evaporation (J/kg)
I_{ts}	global horizontal solar radiation intensity (W/m^2)
$\dot{m}_d$	treated water production (kg/s)
M_Y	annual average treated water production (L)
Q_{ca}	convective heat loss to ambient (W)
Q_{cw}	convection heat transfer from wetted wick to glass cover (W)
Q_{ew}	evaporation heat transfer from wetted wick to glass cover (W)
Q_{la}	conduction heat loss to ambient through insulation (W)
Q_{ra}	radiation heat loss to ambient (W)
Q_{rw}	radiation heat transfer from wetted wick to glass cover (W)
T_a	ambient temperature (°C)
T_{gc}	outer glass cover temperature (°C)
T_v	air-vapor mixture temperature (°C)
T_w	wetted wick temperature (°C)
η_{th}	overall thermal efficiency (%)
η_{ith}	instantaneous thermal efficiency factor

Abbreviations

AOM factor	annual operation and maintenance factor
CC	capital cost (USD)
IR	interest rate
SV factor	salvage value factor
TAC	total annualized cost (USD)
TPC	treated water production cost (USD/L)
UMC	useful material cost (USD)

treatment in Asian continent (Sato et al., 2013). For example, in India, only 10.0% of sewage water is treated effectively and remaining 90.0% is either dumped into water bodies or sold to farmers for carrying out agricultural activities (Kaur et al., 2012). Long term irrigation with wastewater has caused chemo-desertification of fertile land and increased health risks to living beings (Rebhun, 2004; Pereira et al., 2002; Singh et al., 2012).

Water starved regions of the globe have abundant solar radiation potential and it can be tapped for wastewater treatment (Shatat et al., 2013) and water pasteurization (Duff and Hodgson, 2005). Basin solar stills are capable of producing parasite and Arsenic free drinking water from polluted water (Onyegegbu, 1984; Jasrotia et al., 2013). Dewatering of wastewater sludge (Haralambopoulos et al., 2002) and recovery of antioxidants from oil mill wastewater (Sklavos et al., 2015) have also been successfully carried out using basin solar still. The distillate obtained from basin solar still has 80.0% lower COD (Chemical Oxygen Demand) and 90.0% lower TKN (Total Kjeldhal Nitrogen) compared to raw oil mill wastewater (Potoglou et al., 2003). (Velmurugan et al., 2008, 2009; Farahbod et al., 2013) have treated industrial effluent using basin solar stills. Asadi et al. (2013) used stepped solar still for distilling kitchen and palm oil wastewaters. However, contamination of condensate with polluted water or wastewater is highly possible in basin solar stills during feed water addition to basin (Hanson et al., 2004).

From above literatures, it could be inferred that solar distillation is an effective technique for wastewater treatment and basin solar stills have been widely used for this purpose. However, studies dealing with solar distillation of raw domestic wastewaters (sewage water and RO reject) which are the major source for fresh water body pollution are very scarce. Hence, in the present research, feasibility of solar distillation technique for sewage water and RO reject treatment using indigenously developed tilted solar distillation unit with reject recirculation has been explored experimentally. Low area occupancy (Tiwari and Somwanshi, 2018) and reduced chance of condensate contamination with feed water (as flow is only by capillary action) makes tilted solar distillation unit more competitive and superior to basin solar stills. The major objectives of the present research work are as follows:

a. Performance assessment of tilted solar distillation unit during raw sewage water and RO reject distillation by estimating its treated water production rate and thermal efficiency.
b. Water quality analysis of raw and treated water to estimate pollutant removal efficiency of solar distillation unit and to confirm the suitability of treated water for reuse and safe disposal.
c. Enviro-economic analyses of tilted solar distillation unit to assess its harmful gas emission mitigation potential and treatment cost at various interest rate and operating conditions.

2. Tilted solar distillation unit – System description and operating principle

The tilted solar distillation unit developed for sewage water and RO reject distillation is presented schematically in Fig. 1. It consists of insulated stainless steel distillation chamber, aluminium wastewater trough, tempered glass cover, treated water collection trough and necessary provisions for treated water and reject water drain (Sharon et al., 2017). Absorber surface of distillation chamber is lined with black blended woolen wick of porosity 66.0%. Blended woolen wick used in this study is nothing but felt sheet which is very slow to deterioration and wear (Natindco, 2017). Moreover, it can be polished and reused (Natindco, 2017) which makes it highly suitable for wick based solar wastewater distillation process. The distillation unit is placed at an tilt angle of 13° (latitude of Chennai) from horizontal over an mild steel frame facing due south direction to trap maximum solar radiation throughout the year. Tilt angle closer to the latitude of corresponding site is considered to be optimum for higher year round distillate production in solar stills due to minimal reflection of incident solar radiation from glass cover (Khalifa, 2011). Overhead tank of 40.0 L capacity is used to store and supply wastewater to aluminium trough kept inside the distillation chamber. One end of black blended woolen wick is immersed inside aluminum wastewater trough such that the wastewater to be treated gets distributed uniformly over the wick by capillary action. The aperture area of distillation unit is around 1.18 m^2. Specifications of important parts associated with tilted solar distillation unit are presented in Table S1 of supplementary material.

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.solener.2018.07.033.

Transparent tempered glass cover of solar distillation unit facilitates passage of solar radiation through it during sunshine hours, as a result wetted wick lined absorber surface gets heated up and water vapors are formed. Condensation of formed vapors occurs over the inner surface of