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Study of a hybrid photovoltaic-photochemical technology for meeting the needs of safe drinking water and electricity in developing countries: First field trial in rural Mexico

N. Pichel[a,b,*], M. Vivar[c], M. Fuentes[b,c], K. Eugenio-Cruz[d]

[a] Nanotechnology and Integrated BioEngineering Centre, Ulster University, Northern Ireland BT37 0QB, United Kingdom
[b] IMDEA Water Institute, Alcalá de Henares 28805, Spain
[c] Grupo IDEA, EPS Linares, Universidad de Jaén, Linares 23700, Spain
[d] Escuela de Ciencias, Universidad Autónoma Benito Juárez, Oaxaca 68120, Mexico

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ABSTRACT

Developing countries have vast areas and large population groups where access to electricity and safe drinking water is still limited or inexistent. In Mexico, 1.1 million people do not have access to electricity, while more than 3 million people lack access to clean water. However, Mexico presents one of the best locations to exploit solar sources. Therefore, off-grid photovoltaic (PV) systems and solar water disinfection (SODIS) are two promising options to develop rural electrification and to improve the coverage of drinking water access. In this regard, the technology proposed consists of a hybrid photovoltaic and solar disinfection system (SolWat) that comprises a photovoltaic module and a water disinfection reactor fully integrated into a single unit. Its effectiveness was tested for the first time in a rural community of Oaxaca (Mexico), on the basis of natural climatic conditions and available drinking water sources. Main results showed that despite the meteorological conditions were not the most favourable, the strong solar irradiation conditions of Mexico allowed complete inactivation of *E. coli* and total coliforms after 3 h of sun exposure. Furthermore, although the SolWat PV module presented a decrease in I_{SC}, the refrigeration effect of the water being purified on top of the PV cells compensated this loss. In conclusion, the present work confirms the feasibility of the SolWat system to contribute to mitigate the lack of access to safe drinking water and energy in developing countries, since under real operation conditions it was able to simultaneously produce clean water and electricity.

1. Introduction

The lack of safe drinking water and electricity supply is one of the main challenging problems of the 21th century. Some developing countries have large population groups without electricity distribution grids, sometimes due to its remote location and low population density. In the case of Mexico with 190,000 settlements with less than 5000 inhabitants, a total of 1.1 million people, most of them located in indigenous and rural communities, have no access to electricity [1].

Furthermore, more than 3 million people lack access to safe drinking water sources in Mexico, and although it is estimated that 21.7 million rural inhabitants of this country have access to ‘improved’ drinking water sources [2], the qualified as ‘improved’ sources under the international monitoring criteria (protected wells and springs, public taps, household connection, rainwater harvesting) are not necessarily ‘safe’. Hence, the population without access to a real safe drinking water source is likely to be significant higher than the estimated. Despite there are numerous methods to make water drinkable, such as chlorination, ozonation, UV lamps, filtration, etc. they present drawbacks difficult to overcome in developing countries: dependence on chemicals (difficult or expensive to obtain), lack of electricity supply, high cost of infrastructures and maintenance, lack of trained operators or the social rejection of water after treatment because its unsatisfactory taste and odour [3].

Most of the regions in need of electricity and clean water are located between latitudes 35 °N and 35 °S (Fig. 1), where high irradiance conditions make solar radiation an appropriate method for water disinfection. Solar water disinfection is a World Health Organization (WHO) approved point-of-use water treatment technique [4]. SODIS makes use of the bactericidal effect of solar radiation to reduce the faecal microbial load of water. It is simple and inexpensive, does not requires heavy maintenance tasks, neither chemicals nor electricity supply. The

* Corresponding author at: Nanotechnology and Integrated BioEngineering Centre, Ulster University, Northern Ireland BT37 0QB, United Kingdom.
E-mail address: nataliapichelccamb@gmail.com (N. Pichel).

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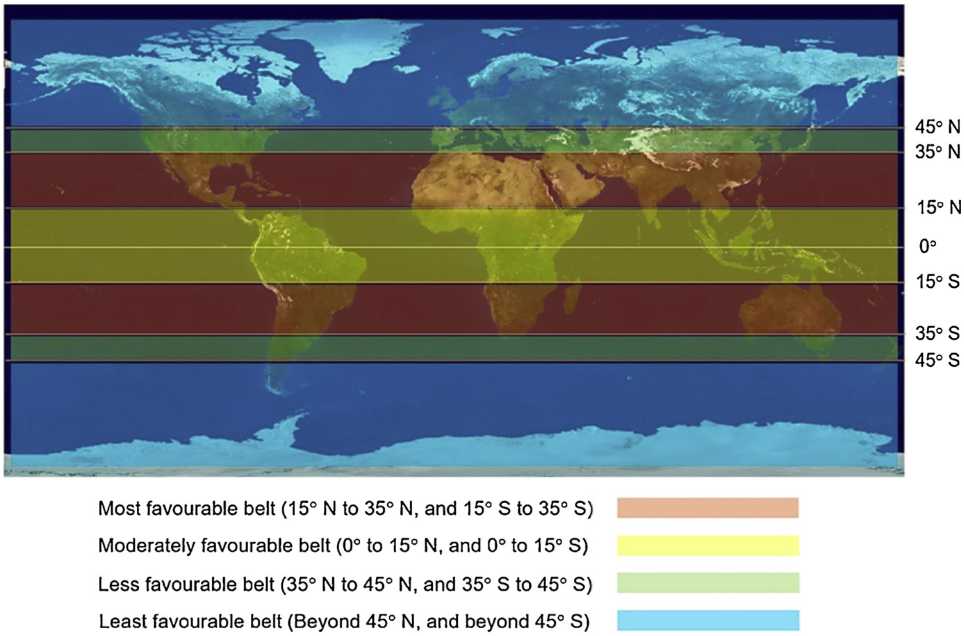

Fig. 1. Global distribution of solar irradiation into belts (Pérez-Denicia et al., 2017).

conventional method consists of placing plastic bottles (typically polyethylene terephthalate, PET) under the sun for at least 6 h [5], and its effectiveness to contribute to mitigate the incidence of waterborne diseases has been widely demonstrated [6–10] reporting a range of 16 % – 57 % reduction of the incidence of diarrhoea, including cholera, in the communities adopting this practise [11].

SODIS is currently daily used by 4.5 million people in 50 countries [11–13]. Nevertheless, one disadvantage offered by potential users is the small amount of treated water provided by the plastic bottles (the conventional SODIS reactor). Generally, bottles have volumes of 0.5–2 l of capacity. Other limitation is the long time needed to treat water. SODIS guidelines recommend 6 h of sun exposure in sunny days and two days if cloudy [5]. Another disadvantage refers to the tasks associated with SODIS compliance that implies behaviours changes in the final user: user must organize bottles, wash and fill them with water, put them into the sun and collect the water afterwards [13]. Moreover, sunlight can transform the plastic material of bottles into photoproducts than can migrate from the containers into water. This constitutes a significant barrier for the increase usage of SODIS, despite photodegradation products or other harmful substances have not been detected in concentrations above the limit set for drinking water quality [14–16].

Oaxaca, a federative community located in the south of Mexico, presents the lowest levels of progress in terms of electricity and water access of the country, with the highest rates of housing occupants without electric power (2.87 %) and piped water (13.05 %) [1]. However, Mexico has one of the best locations to exploit solar sources. As it can be observed in Fig. 1, Mexico is completely within latitudes 35 °N to 35 °S, one of the most favourable belts that lies for solar technologies applications, with solar radiation levels of approximately 5.35 kW h/m^2 [17]. Therefore, mini grid or stand-alone photovoltaic systems and solar water disinfection, are two promising options, both exclusively based on solar energy usage, to develop rural electrification and to improve the coverage of safe drinking water access.

In this regard, the technology proposed, based on the exclusive utilization of solar radiation, consists of an autonomous hybrid photovoltaic and solar water disinfection system (SolWat) which comprises two devices, a PV module and a water disinfection reactor fully integrated into a single unit which uses the solar spectrum more efficiently (visible + near infrared for photovoltaic electricity generation and far infrared + UV for solar thermal and UV water disinfection), and that has the capability of providing renewable energy and safe drinking water simultaneously. The SolWat system is up-scalable so its size could be modified according to the needs (the final amount of treated water and energy) of the place where it will be installed. It is a safer system in relation to plastic bottles since it is made by inert materials that do not alter the chemical quality of the water. It could be automatized minimizing water handling by the final user, thus reducing the tasks associated with conventional SODIS and decreasing the risk of contamination of treated water. In addition, the SolWat system provides other benefits such as the no dependence on chemicals and electricity supply, the use and generation of renewable energy, plus the compact and long lasting characteristics with a simple and low cost design.

The feasibility of this technology has been demonstrated in previous works [18,19], which show that the SolWat system integrates the functions of solar water disinfection and photovoltaic electricity generation. These studies also showed that the SolWat disinfection results are always higher than the conventional SODIS reactor (PET bottle) for all the faecal indicator analysed (*E. coli*, total coliforms, *Enterococcus* spp. and *Clostridium perfringens*) and regardless of the UV and temperature conditions. Pichel et al. (2018) [20] have also demonstrated that under strong climate conditions, these faecal indicators are completely inactivated after 3 h of solar treatment, reducing by half the treatment time recommended for conventional SODIS reactors (6 h). In addition, the cited works show that the PV module integrated into SolWat does not lead to major losses caused by the reduced solar irradiation received (lower current, I) as such losses are compensated by the cooling effect of the water layer being purified on top of the module (higher voltage, V), which is maximum at the beginning of the treatment process.

Despite previous works allow to better understand the behaviour of the SolWat technology which was tested simulating, as far as possible, real operation conditions (natural water source containing wild bacteria strains, natural solar radiation and no controlled temperature), its performance has not yet been assessed on field as a feasible drinking water and electricity point-of-use system at household level in rural and/or remote communities of developing countries. So, the aim of the present work is **to assess for the first time the effectiveness of the new hybrid technology SolWat on field**, on the basis of natural climatic conditions (UV levels and ambient temperature) and available