CAN SOLAR WATER-TREATMENT REALLY HELP IN THE FIGHT AGAINST WATER SHORTAGES?

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In the face of increasing global population, rising industrialization and the inescapable reality of climate change, the demand for access to clean, safe water has never been greater. Solar wastewater remediation technologies and solar water-treatment have the potential to contribute significantly towards affordable and sustainable solutions to this seemingly intractable problem. They do this by using solar energy to treat water from sources that previously would have been considered unsuitable for further use. In this article we reveal the basic principles surrounding the design and application of solar remediation reactors for urban wastewater treatment and reuse and then show how even simpler technologies are being used in low-income communities to provide affordable and safe potable water.

Solar technologies in urban wastewater treatment and reuse

Despite the fact that wastewater reuse is a strategy that is gaining wider acceptance and is rapidly expanding, there is still a number of issues to be tackled with respect to the presence of contaminants of emerging concern (CEC, *i.e.* chemical contaminants) in treated wastewater and their potential biological effects. The need to look beyond the conventional contaminants when assessing the hazards of wastewater reuse to ecosystems and to human health is now recognised as *a priorit*y issue in all policy areas at the EU level and beyond. CEC include pharmaceuticals and personal care products compounds, disinfection by-products, *etc.*, as well as their transformation products (TPs) originating during treatment through biotic/abiotic processes [1]. Moreover, the presence of antibiotic-resistant bacteria and resistance genes (ARB&ARG) in wastewater is another issue that should not be overlooked during wastewater reuse [2].

Conventional activated sludge currently applied in urban wastewater treatment plants (UWTPs) is inefficient in eliminating CEC, with their removal being highly variable [3]. Membrane bioreactors have been shown to be effective in removing only CEC susceptible to biodegradation. While the pores in microfiltration and ultrafiltration are too large to reject CEC, the lower pore sizes used in nanofiltration and also reverse osmosis, have been shown to effectively reject significant amounts of CEC. However, membrane technologies generate a residual stream, thereby creating a need for further proper management. Adsorption using activated carbon (AC) has been effectively used for the removal of CEC, but after reaching its maximum adsorption capacity, AC should be regenerated and further reused [4].

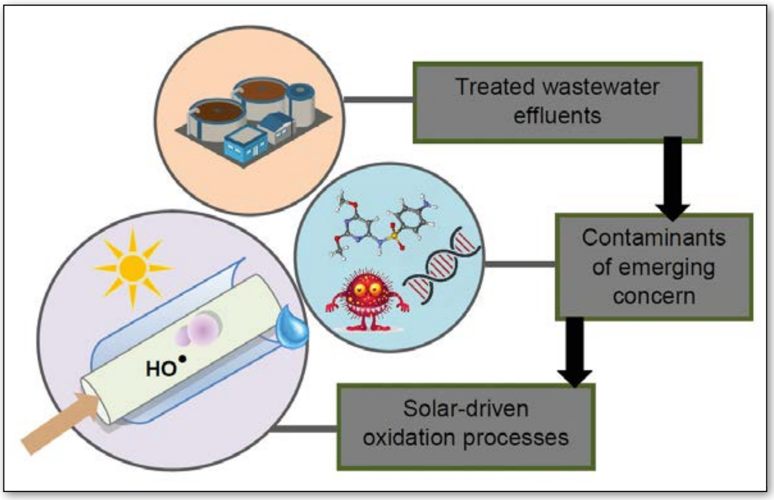
As an alternative, among the advanced oxidation processes, homogeneous solar-driven oxidation processes have experienced popularity over the past few decades in pilot-scale applications for the removal of CEC, including ARB&ARG, present in urban wastewater due to their environmentally friendly application and the prospect of operating under natural solar irradiation hence, lowering the operation cost considerably. Their high efficiency in degrading recalcitrant CEC, while also providing disinfection of the wastewater, is illustrated by the number of studies published in the scientific literature [5]. The optimization of the catalyst and oxidant doses during solar photo-Fenton (which can be summarised briefly as two reactions, *i.e.* first hydrogen peroxide reacts with Fe^{2+} forming hydroxyl radicals HO· , Fe^{3+} and HO^{-}; and second, in the presence of UV-visible radiation, Fe3^{+} ions produced in the previous reaction are photo-catalytically converted to Fe^{2+} with the formation of an additional hydroxyl radical leading to hydroxyl radical generation from hydrogen peroxide) renders the process capable of rapidly removing CEC. The majority of the studies revealed that pH 2.8 is the optimum pH for the photo-Fenton process, while some others showed a positive trend for broadening the process operation pH up to mild neutral conditions, removing thus the burden of the economic limitation of the process associated with the chemical cost for pH rectification. Also, solar/H$_2$O$_2$ oxidation upon its proper optimization was shown to be effective in removing CEC and ARB from urban wastewater [6]. It is noteworthy that a number of TPs may be formed during the application of solar-driven oxidation, while in some cases bacteria have the potential to recover from sub-lethal oxidative stress and induce repair mechanisms. Nonetheless, these can be overcome by conducting prolonged oxidation.

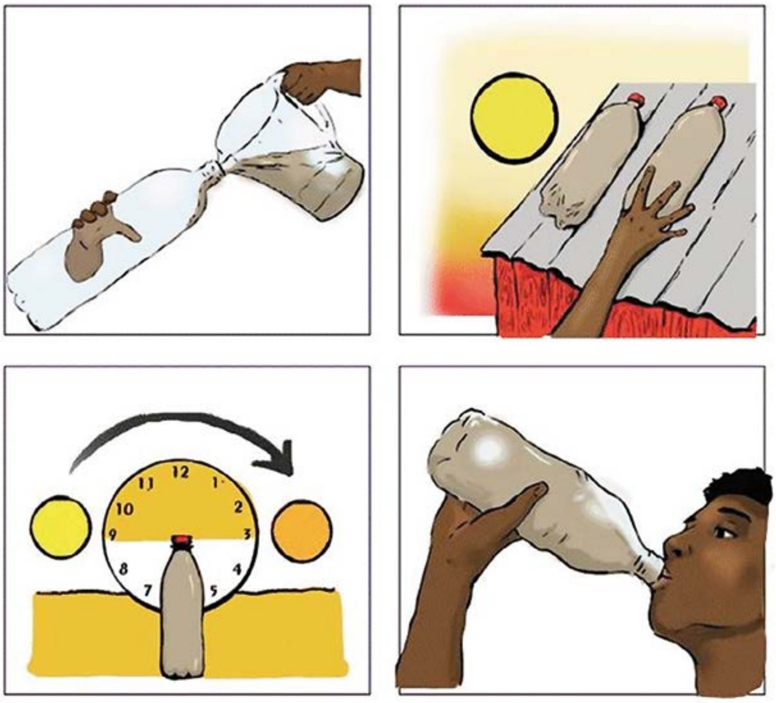
In summary, solar-driven oxidation technologies, upon their optimization, are promising treatment strategies for the removal of CEC, including ARB&ARG, from urban wastewater. Important aspects, such as oxidation time, should be taken into consideration during the application of such processes, in order to ensure both effective removal of CEC and cause permanent damage to susceptible bacteria. Nonetheless, there is a number of knowledge gaps and open questions related to the potential effects that the wastewater reuse practice might induce with regard to the CEC and their TPs. Knowledge on the risks that relate to low-dose exposure of CEC to non-target organisms, crop uptake and the additive and synergistic behaviour of various CEC/TPs in mixtures is only now starting to shape. The European COST Action ES1403 NEREUS http://www.nereus-cost.eu and the H2020-MSCA-ITN-2015/675530 (ANSWER) project http://www.answer-itn.eu address various of these important issues.

Solar Water Disinfection

Solar water disinfection, or SODIS as it is more commonly known, is a water treatment technique used in many low-income countries to make biologically-contaminated water safe for drinking. SODIS is often used by rural communities in those parts of the world with abundant sunlight and without realistic hope of access

▼FIG. 1: Solar-driven oxidation can be successful in the removal of contaminants of emerging concern present in urban wastewater (Diagram shows a wastewater treatment plant, where the treated effluents are contaminated among others by contaminants of emerging concern. As an alternative to standard technologies, solar AOPs generating hydroxyl radicals are proposed to oxidise these contaminants).





▲ **FIG. 2: Solar Water Disinfection instructional poster which was designed for use in areas of low literacy.**

to municipally treated distributed water. The technique is deceptively simple. Water is collected from the usual source and then stored in transparent containers, such as glass or plastic bottles, which are then placed in direct sunlight for a minimum of 6 hours. The microbes which cause waterborne diseases are inactivated by the small amount of solar UV-A light, which is transmitted through the container wall. In addition, DNA repair processes which the microbes use to repair the damage caused by the incident photonic energy, are inhibited by the elevated water temperatures (up to 55 °C), which are generated within the bottles thanks to a mini-Greenhouse Effect.

Since its resurgence in the early 1990s, SODIS has been demonstrated to be effective against all of the most important waterborne pathogens and especially those associated with diarrhoeal diseases such as dysentery, salmonella, cholera, gastro-enteritis, hepatitis A, *etc.* [7]. Outside of the solar simulation laboratory, human studies conducted in cooperation with rural communities in Sub-Saharan Africa have shown that children who use SODIS-treated water have lower rates of diarrhoeal disease with incidence of dysentery observed to reduce by between 25%- 50%. One retrospective [8] showed that Maasai children that had been using SODIS in a rural area of Kenya that experienced an epidemic of cholera in 1997, were seven-times less likely to experience a case of cholera than those households that have been relying on usual practices.

The benefits of such solar-based water treatments extend far beyond reduction in childhood disease rates. Studies in Kenya in 2011 [9] showed that children using SODIS-treated water were on average 0.8 cm taller at the end of the 12-month study than children relying on untreated water. Pupil absences in rural Ugandan primary schools children was observed to reduce from 0.9 to 0.2 days per semester [10]. Finally, the use of water treatment, such as SODIS, improves family finances since care-givers are free to participate in income-generating practices, while funds previously used for medicine and patient transport to clinics, become available for other purposes.

Although solar water disinfection is used to provide safe water to marginalised and vulnerable communities in more than 50 low-income countries across the globe, major obstacles to further uptake remain, such as the small treated volume (2L max) afforded by most transparent bottles. The EU Horizon 2020 WATERSPOUTT project (see www.waterspoutt.eu) is addressing this issue by designing and piloting a variety of affordable large volume solar based water treatment technologies.

▼ **FIG. 3: Ugandan primary school children bring their water to school to be solar disinfected.**

Simple solar technologies for low-income communities

If we examine SODIS technology critically some technical limitations are quickly evident. The small volume of water bottles (typically 2-3 L) limit the total volume to be treated although the user can use as many bottles as they wish. Process efficiency depends on a range of environmental parameters including solar irradiance (which, in turn, depends on latitude, time of day, and atmospheric conditions), organic loading turbidity of the water, and the load and nature of the microbial contamination, which affects the time required to reach a certain disinfection level as different microorganisms have different sensitivities to solar disinfection. There are also some questions about the safety of using plastic bottles exposed to sunlight for prolonged times regarding potential leaching of chemical derivates [11]. Furthermore, SODIS is user dependent in terms of the treatment time and there is no quality assurance for the process. Compliance with the recommended protocol can also be a major issue [9].

Recent research has revealed a number of ways to overcome these technical drawbacks or to enhance the conventional SODIS process. These enhancements centre on one or more of the following considerations: (1) maximizing the solar energy collection in the polluted water, (2) accelerating the microbial inactivation efficacy, especially when resistant waterborne pathogens are present; (3) increasing the total volume of treated water provided by a solar system for a given solar exposure time; (4) automating the solar technology to avoid user- and weather-dependence; and (5) finding a compromise between cost, durability and efficiency of the technology.

In this sense, the main design developments in recent years are low-cost solar reactors for SODIS deployment [12]. These systems favour the collection of global solar UV radiation, using compound parabolic collectors (CPCs). CPCs are low-concentration collectors which were used initially for thermal applications and combine some characteristics of parabolic trough concentrators and flat stationary systems. Due to their shape, CPC mirrors collect solar radiation in static conditions with a high collection rate of solar diffuse-radiation. They use non-imaging optics to concentrate solar radiation into a diffuse focus and distribute solar radiation homogeneously into the photo-reactor (where the water is to be disinfected). Hence CPCs permit a highly efficient use of the solar photon flux in the water by utilising both diffuse and direct solar radiation even on cloudy days. CPCs are static collectors, which maintain a constant concentration factor (CF = 1) for all values of sun zenith angle within the acceptance angle limit. Solar CPC mirrors are usually manufactured from anodized aluminium to improve UV collection, as its reflectivity in the UV spectrum is high, ranging from 87% to 92% depending on surface aging. This material is also highly resistant to the environmental conditions. These characteristics make CPC-based solar reactors more efficient and less-dependent on ambient weather conditions for water disinfection. Another advantage of solar exposure in CPC reactors is the increased water temperatures achieved. These thermal effects accelerate the solar disinfection performance by the enhanced mild heat (*i.e.* up to 50-60°C) provided during solar exposure using these collectors [13,14]. The use of solar flow CPC reactors allows us to maximize the solar dose and can include UV feedback sensors for automated control [15]. Current research on SODIS-based reactors for drinking water disinfection carried out within WATERSPOUTT

◂ **FIG. 4:** Solar CPC reactor for solar water disinfection. CPC shape with ray tracing at different solar times (left) and photo of a CPC mirror (right).

▾ **FIG. 5:** View of several solar CPC reactors with different design concepts installed at Plataforma Solar de Almería, Spain.

H2020 project will help the deployment of solar water disinfection for low-income and vulnerable communities, with the expectation of providing low-cost and effective solutions to disinfect fresh or collected water (*i.e.* harvested rainwater) to improve water quality at household level.

Concluding remarks and future directions

In summary, solar applications for the treatment and remediation of water from a wide variety of sources and for numerous end-use purposes, is a topic of great interest and exciting developments. Water is a fundamental component of life and is an essential requirement in industry. As global warming progresses, and access to water becomes a greater source of conflict it is encouraging to think that solar treatment can provide a solution to both the technological and socio-political challenges that lay ahead. ■

About The Authors:

Pilar Fernández-Ibáñez is Lecturer at Ulster University (UK, 2017), after being Senior Researcher at Plataforma Solar de Almería of CIEMAT (Spain, 2003-2016) and head of the Solar Treatment of Water Unit. Pilar is an expert on solar technologies for water purification with wide experience in advanced oxidation processes for the removal of microbiological pathogens and hazardous chemical contaminants from water, using solar reactors. Her research focuses on real field applications of solar technologies for drinking water, wastewater disinfection and irrigation reuse of treated wastewater. Pilar has participated in 16 EU research projects in this area, has 120 peer-reviewed scientific publications and 150 conference publications.

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Despo Fatta-Kassinos is an Associate Professor at the Department of Civil and Environmental Engineering, and the Director of Nireas-International Water Research Center, of the University of Cyprus. Her research focuses on the understanding of the fate and behaviour of contaminants of emerging concern during advanced biological and chemical oxidation wastewater treatment. She serves as Editor of the Journal of Environmental Chemical Engineering (Elsevier), and she is the Chair of the COST Action ES1403 (NEREUS), and the project coordinator of the ANSWER project (H2020-MSCA-ITN-2015/675530 with a budget of €3.7M). She has over 120 peer-reviewed scientific publications, 100 conference publications, and she has co-edited various environmental books published by Springer.

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