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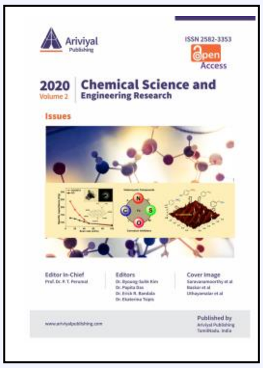

Solar Treatment in the Core of the New Disinfection Technologies

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Abstract: The shortage of obtaining secure potable water remains one of the greatest dares confronting humankind. Even with the mass universal endeavour that has been performed, the potable water fountains of at least 2 billion people are faecally polluted, conducting to more than half a million diarrheal deaths every year, with the majority taking place in poor nations. Consequently, techniques for demobilizing pathogens in the water stay of vital importance for humans. Nevertheless, traditional techniques to supply potable water, even if efficient, show restrictions that hinder their general use. Such treatment processes frequently possess elevated energy and chemical needs, which restricts their implementation for avoiding waterborne diseases. Such drawbacks have conducted for urgent investigation and expansion of advanced substitutional techniques. One such substitutional method is solar disinfection (SODIS), which is viewed as one of the most suitable techniques for assuring potable water in poor regions. This work contributes to present traditional techniques that are being utilized at medium to large scales to treat water and emerging technologies presently in expansion. Further, this communication presents briefly the advantages and shortcomings of such techniques. Special attention is accorded to SODIS, involving a fresh technique lately suggested in such domain.

Keywords: Solar disinfection (SODIS); Polyethylene terephthalate (PET); Reactive oxygen species (ROSs); Photo-Fenton technique; Water treatment; Disinfection

1. Introduction

Protected potable water should remain one of the fundamental health rights throughout the world. Unfortunately, incorrect purification and damaged water reservoirs have been affected by several health issues, like augmenting human mortality, because of gastrointestinal diseases associated with enteric pathogens.[1] During the previous half-century, a broad investigation has been moved towards advancing a cost-efficient and suitable technique for disinfecting water alternatively to chemical treatment methods, such as chlorination, because of the formation of hazardous disinfection by-products.[2] In remote areas, developing nations or ones with a sunny climate, solar disinfection (SODIS) stays one of the household water treatment techniques that may be largely employed.[3-4] In such a process, transparent bottles in polyethylene terephthalate (PET) plastic are filled with the contaminated water and revealed to sunlight for a defined period with a view to demobilize the microbes.[5-6] Such an easy water disinfection manner has been efficiently utilized in diverse areas with illuminated days like South Africa, Cameroon, Senegal, and India.[7]

In such solar-driven treatment methods, microorganisms' demobilization is provoked via the interactive influence of ultraviolet (UVA, UVB) and temperature elevation throughout sunlight subjection.[1] In fact, UVB at wavelengths about 280-320 nm may be ingested directly via genetic material and conduct to severe harm in deoxyribonucleic acid (DNA) molecules and ultimately microbes' demobilization.[1] Escherichia coli is a Gram-negative bacterium that is commonly utilized as a faecal contamination indicator in the majority of microbiological researches.[8-11] Besides, the performance of such a treatment process has been examined towards different microbes like bacteria, fungi, viruses, protozoa and helminths.[1,12-17] Particularly for bacteria,[18-21] the impact of solar light[22-23] may be linked to the endogenous photosensitizers and their capabilities for forming reactive oxygen species (ROSs) when uncovered to solar light which initiate a set of intracellular oxidative responses, provoking demolition to vital components in the cell.[24-27]

The advanced oxidation processes (AOPs) constitute one of the encouraging choices utilized for both disinfecting water and mineralizing organic chemicals.[28-30] One of AOPs, the photo-assisted Fenton method integrates Fe^{2+}, H_2O_2, and light with a view to improving bacterial demobilization; further, such reaction may be seen for disinfecting water below solar light irradiation.[31-32] In such a method, the most efficient agents remain ROSs, particularly non-selective •OH that is generated via consuming H_2O_2.[33] Employing solar irradiation or photon up to 580 nm in photo-Fenton method stays advantageous as it hastens photo-reduction of Fe^{3+}organo-

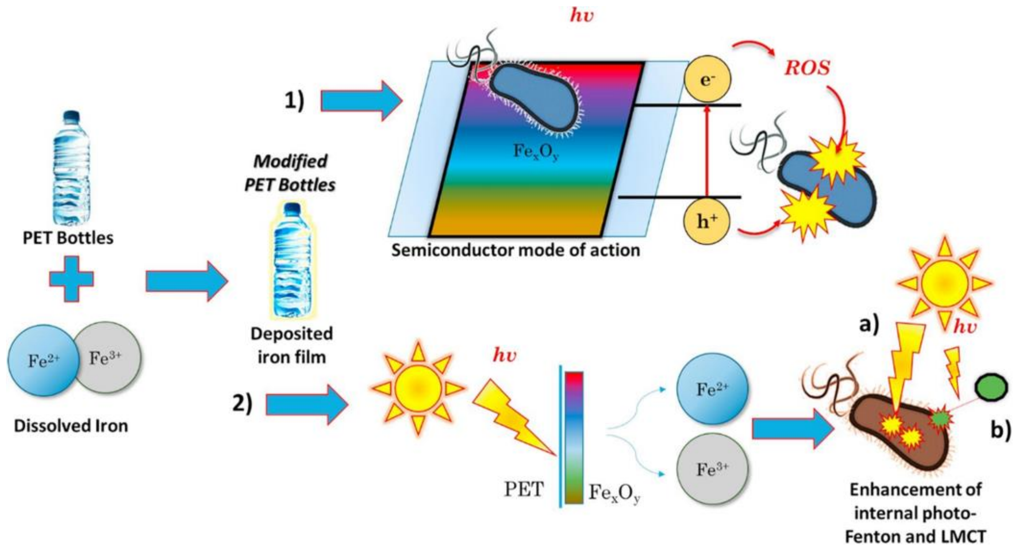

Fig. 1. Suggested demobilization route attempted with the alteration of PET bottles by Fe salts.[1]

complexes and improves the ●OH formation.[1] Thus, if solar light is integrated with other additives like H_2O_2 and iron, it may generate ROSs like ●OH, superoxide radical anion (O2●-) and singlet oxygen (1O2) with capacities for intense demolition in bacterial cells as well as regrowth disposal.[1]

In the (homogeneous) photo-Fenton technique, iron injected into the solution and its interaction among oxidizing agents with organic matters or bacteria happen as follows (Eqs. (1)–(3)) [1]:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + \bullet OH (k = 63\ M^{-1}\ s^{-1}) \quad (1)$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2\bullet + H^+ (k = 3.1 \times 10^{-3} M^{-1}\ s^{-1}) \quad (2)$$

$$Fe^{3+} + H_2O + h\nu \rightarrow Fe^{2+} + \bullet OH + H^+ \quad (k = 2.9\times 10^{-3}\ M^{-1}\ s^{-1}) \quad (3)$$

The photo-Fenton response possesses a limited optimal pH working domain (peak: 2.8);[1] thus, numerous researches have concentrated on elevating its applicability via by passing the iron-related restrictions, i.e. precipitation.[1]

2. Improving SODIS in PET bottles via controlling in situ generations of iron oxide films

Shekoohiyan et al.[1] produced an iron oxide film on the inner surface of PET bottles employed in SODIS, to output more routes of solar-mediated demobilization; in other words, a semiconductor method of work and dominated iron leaching in the setup, which both have proven bactericidal potential. Indeed, the deposition technique employing Fe salts has been examined, evaluating the usage of numerous homogeneous Fe precursors, ($FeCl_3$, $FeSO_4$, and $Fe_2(SO_4)_3$) amounts of iron (0.5–20 g/L) and deposition period (1–8 h) to locate the accurate equilibrium between deposition film thickness and light penetration (Fig. 1). At the optimal circumstances (4 h deposition, 1 g/L $FeCl_3$), SODIS was ameliorated, decreasing 60% the exposure period; an easy washing stage earned an extra decrease (70%) while removing regrowth in volumes from 330 until 1500 mL devices. A strong technique was obtained, apt to reuse its precursor solution nearly 10 times and the device in 5 successive trials, without the request for re-deposition. Moreover, the amendment established to be a crucial iron source to fuel the photo-Fenton method, if H_2O_2 as an electron acceptor was injected into the setup. The amelioration formed by the heterogeneous photo-Fenton technique was about 80% contrasted to the SODIS/H_2O_2 method in plain PET bottles and overrode 85% if juxtaposed to SODIS while being lasting to the elevated oxidative circumstances. From the perspective of implementing in potable water treatment, the technique accomplished well in the lightly acidic area, thanks to the physicochemical implications of natural waters' pH in iron cycling.

3. Removal performance of rotavirus in potable water treatment plant (WTP)

Rotavirus stays one of the principal waterborne reasons for diarrhoea. Rotavirus type A is responsible for diarrhoea in infants and provokes thousands of deaths annually all over the globe, particularly in developing nations. Rotavirus is very small and is greatly resistant to usual disinfectants; thus, the World Health Organization (WHO) has selected such virus as a reference pathogen in potable water and has suggested its 6-log elimination via the traditional water treatment technology to supply secure potable water. Shamsollahi et al[34] followed various physicochemical properties of raw water at a WTP (Fig. 2) in Tehran (Iran), involving temperature, pH, total organic carbon (TOC) level, and first turbidity, to assess their influence on rotavirus reduction performance in diverse techniques. Further, they evaluated rotavirus elimination performance in clarified water and filtrate to estimate their reduction efficacy. In addition, they implemented the WHO guideline and an empirical quantitative microbial risk assessment (QMRA) model to evaluate likely health hazards founded on a remaining number of rotavirus in finished water. They discovered that TOC level and water temperature are both efficient on remaining rotavirus in clarified water; however, they have no crucial influence on the efficiency of filtration in

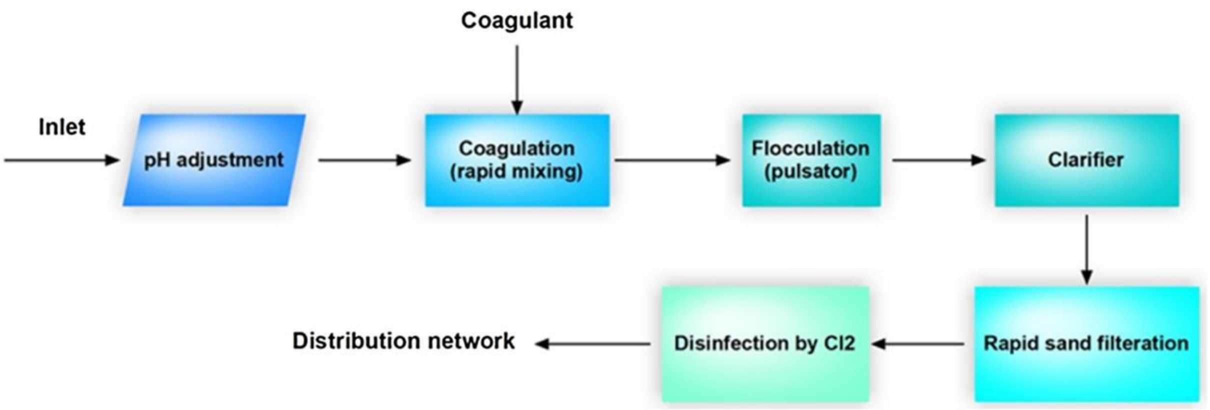

Fig. 2. Schematic flow diagram of processes in potable WTP.[34]

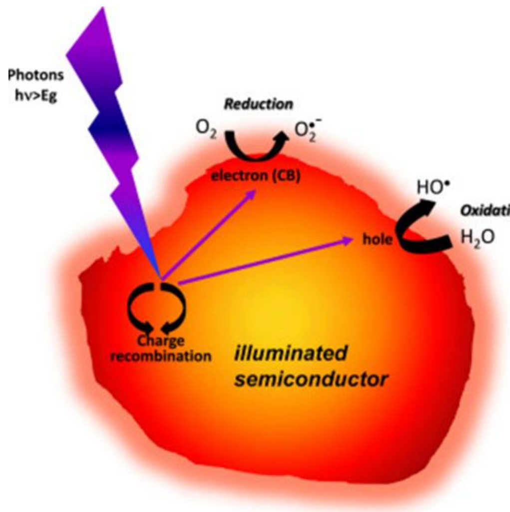

Fig. 3. Simplified scheme of generation of electrons holes and hydroxyl radicals on an illuminated particle of TiO_2.[35]

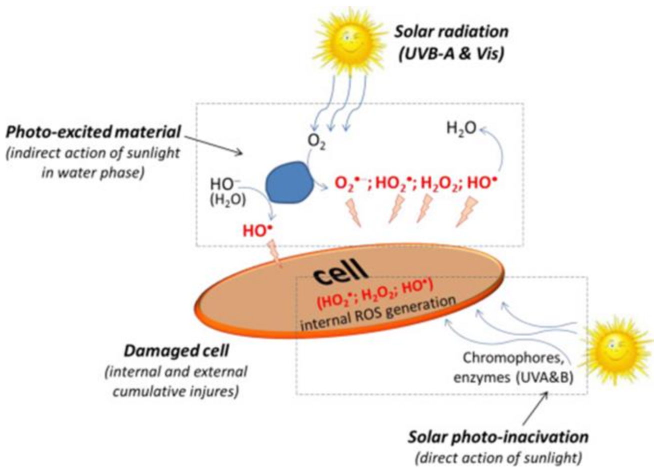

Fig. 4. Schematic diagram of general mechanisms of action of sunlight for water photocatalytic disinfection. [35]

eliminating rotavirus. Via clarification and filtration, maximum rotavirus elimination performance was 97.2% and 4.5% in April and January, respectively. It was illustrated that TOC and water temperature possess an important impact on clarification virus performance; therefore, filtration efficacy was independent of these factors. Their findings depicted that provoked danger via remaining rotavirus stays in a tolerable span and as well illustrated that the key method in eliminating virus is the clarification, which may be touched via raw water quality.

4. Disinfection water via solar photocatalysis

Malato et al.[35] discussed the usage of sunlight to generate •OH radicals via TiO_2 (Fig. 3).They defined the reacting devices requested for carrying out solar photocatalysis and the variables that dictate the kinetics of photocatalysis like initial concentration of reactant, mass of catalyst, pH, temperature, radiant flux and level of oxygen. Further, they discussed many procedures for enhancing the photocatalysis performance of TiO_2. In addition, they described solar devices engineering problems for photocatalytic water treatment and the implementation of the solar photocatalytic technologies to demobilize microbes existing in water, focusing on the routes involved throughout the methods (Fig. 4), mostly hydroxyl radical and singlet oxygen formation, and on trial setups developed to regulate such disinfection process. On the other hand, heterogeneous photocatalysis remains an interesting manner for obtaining hydrogen in a proper fashion. Recently, diverse photocatalytic devices for hydrogen production with concomitant reduction of organic matter have been examined at lab-scale; however, little has been known concerning such setups at bigger scale. Further, Malato et al.[35] depicted the concomitant photocatalytic hydrogen formation and organic matter elimination under direct solar irradiation and at pilot-plant scale at the Plataforma Solar de Almeria.

5. Novel solar disinfection (SODIS) techniques: An encouraging choice to purify water

Pichel et al.[36] deeply reviewed the issues of obtaining potable water and suggested an exhaustive survey of traditional and advanced water treatment techniques.[37-39] Further, they presented SODIS as one of the most suitable processes for potable water treatment[40-47] in developing lands, comprising the SOLWAT setup (The novel technique composed of a hybrid solar water purification and

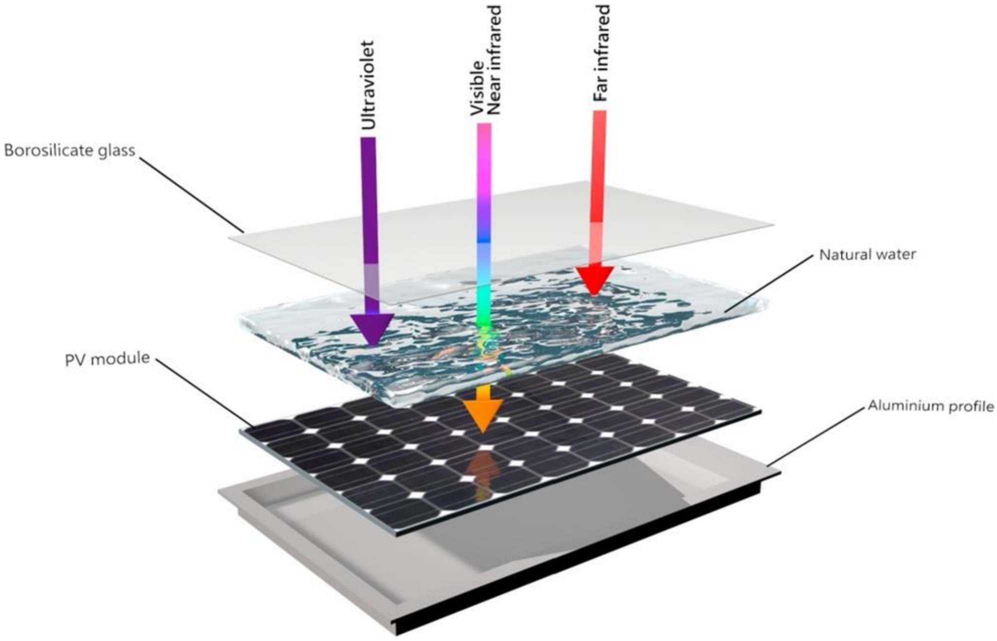

Fig. 5. Schematic diagram of the SOLWAT setup[48] illustrating the combination of the PV module on the bottom with the water disinfection device on the top and the usage of the full solar spectrum (the UV and far-infrared fractions are employed for disinfecting water, and the visible and near-infrared fractions are employed for electricity production).[36]

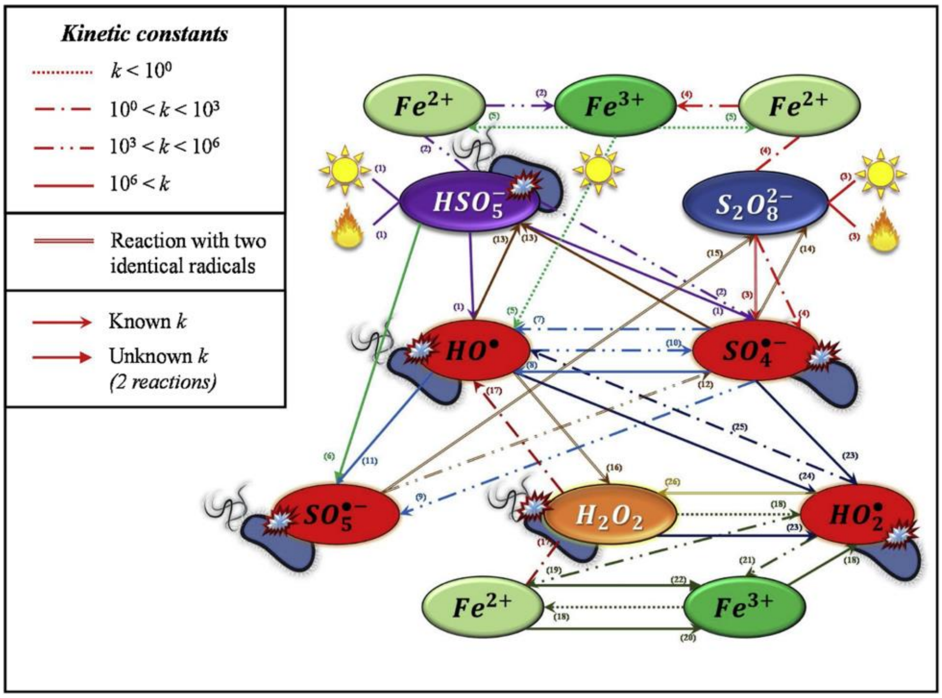

Fig. 6. Overall mechanistic proposal for the three-factor activation of PMS/PDS, and the subsequent bacterial disinfection. White fonts indicate the more stable species (PMS, PDS, H_2O_2) and black fonts the rest; red circles signify the radical species and green the iron ions.[49]

photovoltaic (PV) system (SOLWAT) that is completely combined into a single unit and utilizes the solar spectrum more efficaciously (Fig. 5)), a fresh technique presented in such a domain.

Rodríguez-Chueca et al.[49] proved the possibility to improve SODIS treatment via addition of peroxymonosulfate(PMS) and peroxydisulfate (PDS) through the formation of sulfate (and hydroxyl) radicals following numerous activation pathways. The diverse promoters were i) sunlight irradiation, ii) mild heat (40°C), and iii) µM amounts of Fe^{2+}, all present throughout actual field SODIS tests, or voluntarily added alongside PMS/PDS. In a primary procedure, the promoters were investigated separately, in pairs and finally all together in a combined process(CP). In all the circumstances, PMS depicted a higher performance than PDS in E. coli removal, needing lower concentration and a faster reaction time towards total bacterial inactivation. Consequently, the CP (Oxidant/Fe^{2+}/Sunlight/40°C) attained total bacterial inactivation (6-logU) in 30 min when PMS was utilized, whilst it took twice as long with the PDS. These impacts could be more improved when PMS with H_2O_2 is employed, and barely 20 min are requested for total bacterial removal. Besides total disinfection, the CPs were appropriate to remove micro-contaminants in µg/L concentration (drugs, pesticides, etc.) throughout solar treatment. Finally, the performance of the treatment methods was successfully tried in a lake water matrix, in a feasibility experiment as a possible potable water treatment method. The economic analysis greatly supports the usage of such oxidants. Even if the injection of PMS or PDS elevates the price of treatment, it is not necessary to introduce additional chemicals or external activators; iron is ubiquitous in natural water and may work as activator, while during SODIS sunlight irradiation could furnish UV and mild water heating, hence act as an efficient disinfection technology. Finally, Rodríguez-Chueca et al.[49] suggested a mechanistic insight for the CPs(Fig. 6), as an overview of the producing reactions conducting to bacterial demobilization.

6. Conclusions

From this work, the following conclusions can be drawn:

1. The pre-treatment of the internal surface of PET bottles with an iron precursor solution conducted to the deposition of an iron layer, which improved bacterial demobilization during exposure to solar light. The iron hydrolysis and oxide attachment to the walls conducts to two controlling manners of action of iron oxides, as semiconductors and as iron sources for leaching into the solution. Each possesses its importance andgermicidal potential [Shekoohiyan et al. 2019]. Tweaking the deposition method and conditioning factors showed that there is a delicate equilibrium among the wanted quantity of iron deposed on the surface, which remains the requested accelerator for killing pathogens and penetrating light, because light should penetrate the film. In other words, 1 g/L for 4 h was the optimal deposition process. Even if comparatively small, the quantity of iron and its fixation onto the inner surface conducted to stable efficacy (up to 1.5 L of reactortried), and durable under many reuses (5 times) with minor losses in bactericidal capacity, and importantly higher than SODIS alone. In an identical fashion, reusing the precursor solution for around 10 times was aneconomic characteristic of the system. Equally significant to the immediate disinfection is the elimination of bacterial regrowth. Such novel pathways may demolish microbes at diverse degrees than simple SODIS, hampering their re-activation capacity. On the other hand, a considerable amelioration was reached while $H_2O_2$was introduced into the setup. The dominated liberation of Fe induces the photo-Fenton technique which quickly diminishes bacterial charge and still keeps its reusability. Via means of the in situ formed photo-Fenton response, a few ppm of H_2O_2 can hugely ameliorate the killing level of the setup. This property was very crucial in disinfecting real surface waters, since the matrix circumstances (mainly the pH) hinder the killing capability. In spite of that, since naturally acidic waters exist in developing nations or easy manners to slightly acidify water (e.g. fruit juice), implementing such technique needs more research for future utilizations.

2. Traditional potable water treatment techniques may reduce rotavirus efficaciously, meet the WHO guideline value for rotavirus in potable water and diminish infection hazard under the danger level proposed by WHO. Consequently, in countries with classical WTP sites with convenient maintenance, the rotavirus cannot provoke important health worries from potable water. The elimination efficacy is among 97.3 and 99.99% and most of the rotavirus population may be reduced throughout clarification, which is deeply following the performance of coagulation and flocculation. Elevating TOC and diminishing water temperature may reduce clarification performance for solid-liquid separation whose indicator remains particle count in clarified water. The performance of rapid sand filtration stays more susceptible to water temperature; thus, keeping the reduction efficacy of pre-filtration techniques at a fixed degree via modifying coagulant dosage and mixing intensity to maintain the turbidity of clarified water below 0.1 NTU may recuperate tolerance in the efficacy of filtration.[34]

3. The findings from solar photocalytic techniques depicted by Malato et al.[35] appeal more focus on industrial usages. Implementing solar photocatalysis would possess a useful effect on nature, public health and a greener economy; however, many hurdles require to be overpassed like: novel photoreactors designed particularly designed for disinfecting water and hydrogen formation; optimizing running parameters, especially, the solar radiation-catalyst interaction and long-term reliability of solar operation.

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Conflicts of Interest

The authors declare no conflict of interest.

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