Solar photocatalytic treatment of rain: from laboratory scale to real sanitary use in elementary school into economic unfavorable urban areas from Mexico City

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Abstract

Important number of elementary schools in Mexico have not basic sanitary infrastructure: drinking water supply, sewer system or electricity service are not full available for the scholar community. On the other hand, hydric stress is remarkably worry in urban dense poor areas, as the case of the Iztapalapa municipality in Mexico City. In this condition, the development of sustainable technologies such the rainfall harvesting and solar photocatalytic treatment is a promising strategy against the water scarcity. This work shows the design, construction, installation and startup of a solar photocatalytic reactor as treatment of harvested rainfall for final use in an elementary school from an unfavorable economic urban area in Mexico City.

Keywords: Heterogeneous Solar Photocatalysis, TiO_2, rainfall, urban areas.

1. Introduction

The Mexico City metropolitan sector is one of the largest urban agglomerations in the world. With more than 21.2 million metropolitan population (18% of country's inhabitants), Mexico City has an unpredictable model of generation, carrying, supply and availability of basic public services such as drinking water, gas, transportation, food, hospitals, electricity, etc. In this big city, the social disparities and economic inequalities are strong remarkable among their residents. One of the most critical and detrimental situation is observed in the infrastructures of basic services in elementary schools predominantly into unfavorable economic areas. The most recent national census reflects 207,682 elementary schools attending more than 25 million of students among primary and secondary school age children (ages 2 to 15) (INEGI, 2014). Almost 50% of the elementary schools in México do not have drainage networks, 31% show deficiencies in drinking water accessibility, 11.2% express nonexistence of electricity facilities and 12.8% display entire absence of toilets.

Specifically in Mexico City there are 8,141 elementary schools attending around 13,151,297 students. More than a half of those schools (51.8%) belong to the public administration and 3.5% do not have drinking water facilities. Several students are used to return at home during the 30 minutes break between lessons in order to use the own toilets and lavatories if available in their houses. The inexistence of drinking water networks as well as the remarkable hydric stress are part of the sanitary problem for a large number of scholars and teachers. Figure 1 shows the availability´s coverage of basic facilities in elementary schools in Mexico City (INEGI, 2014)

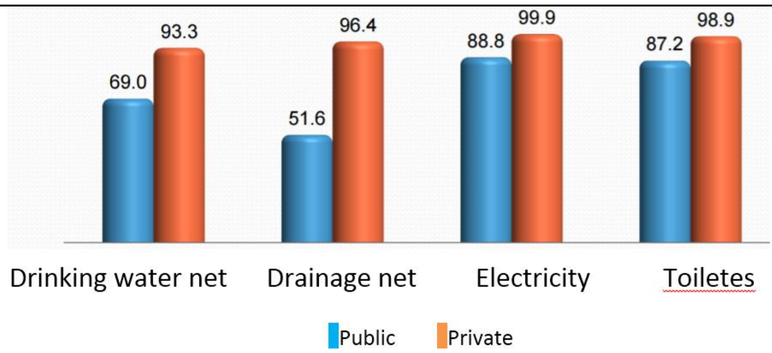

Fig. 1: Availability´s coverage of basic services in elementary schools in Mexico City (INEGI, 2014).

A rainfall-harvesting project is not under consideration as part of the public water supply in any governmental plan. Mexico City wastes approximately 1,000 million of m^3 of rainwater per year. In contrast, the Mexico city´s principal drinking water source, the Cutzamala system, has around 728 million of m^3 of capacity (SACM, 2017). Some estimations show that only 10% of the harvested rainfall is available and used within the same period of collection.

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On the other hand, the solar photocatalytic process has shown effective results as water treatment for effluents containing a huge variety of recalcitrant contaminants. Recent papers shows the increasing interest on this field applying the solar technologies to heat up, purify or pasteurize harvest rainwater at laboratory scale (Saran, 2018; Reyneke, 2017). Some of the most interesting goals for the scientific, engineering and academic community are to increase the efficiency of the harvest systems as well as to reduce the cost of the water treatment by means of sustainable solar technologies. This study shows the application of the well-known and mature solar photocatalytic process TiO_2 based at large scale in a real case of study inside of an elementary school placed into a high hydric stress zone in Mexico City.

2. Real case study: “Luis Braille” primary School

This school is located in Iztapalapa district, one of the most densely populated regions in the northeast of Mexico City as showed in Figure 2. This school belongs to the public administration. Twenty-six teachers attend around 550 students per each two timetables (morning, 8:00–13:00 and evening, 13:00- 18:00). The school has 4 bathrooms, 1 computer zone, 21 classrooms, 1 gymnasium or sport area, 1 parking among others facilities, etc. The Figure 2 shows the school localization and its physical boundaries.

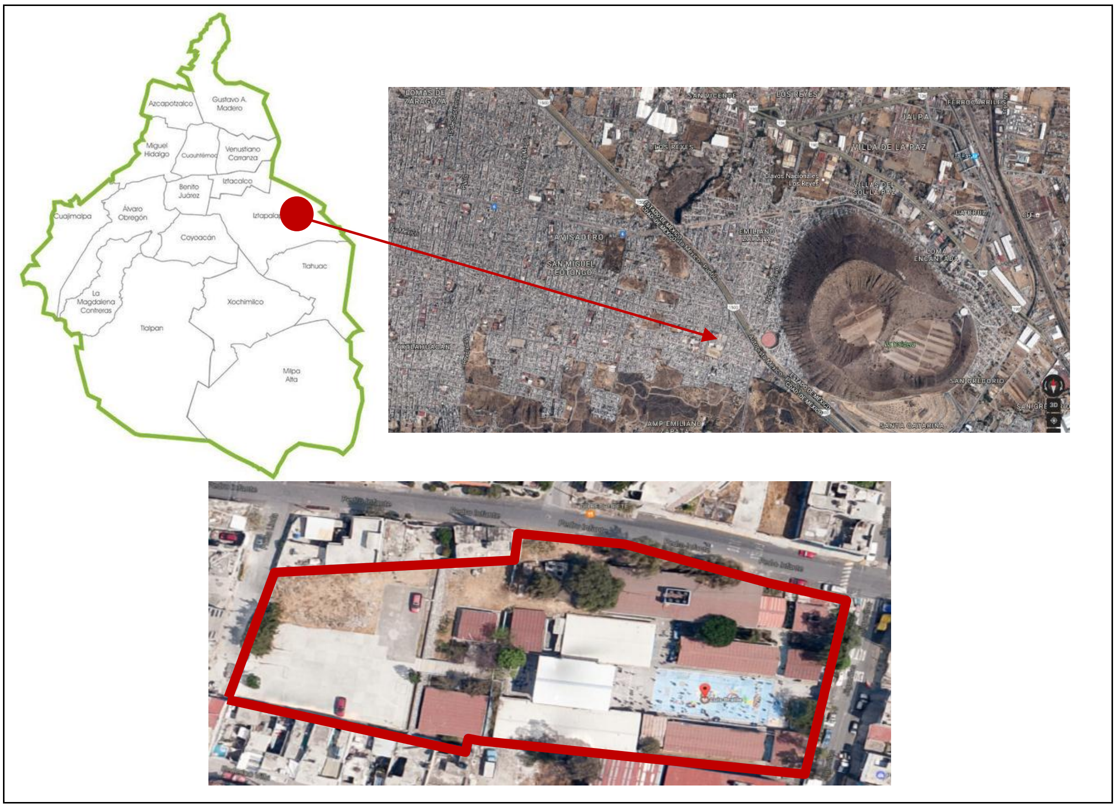

Fig. 2: Luis Braille elementary school in Iztapalapa district.

Municipal drinking water network is not available in this school. Acquisition of 10,000 liters of tap water shipped by a container truck or “pipa” is reach with around 50 dollars per week.

The water container truck does not offer any chemical/biochemical safe certificate of quality. The school has a cistern with capacity of 30,000 L as shown in Figure 3 (central photography). However, the maintenance of this reservoir is scarce and very often it remains empty or dirty.

Fig. 3: Sport area (left), cistern (center) and toilet building (right).

3. Design and on-field analysis

Initial step was the visual field inspection of the installations inside the school in order to evaluate the technical feasibility. Figure 4 shows the observations carried out in the parking area by technicians and researchers involucrate in this project. Noteworthy requirements taken into account during the on-field assessment were: a) accessibility of a south oriented large area; b) availability of solar free irradiated space without or as minimum as possible shades; and c) suitability of a large rainwater caption surface. Authorities, teachers and members of the Parents Association, whom showed deep involvement and interest amongst the research project, were also present during the field inspection.

Fig. 4: Parking area (left) and visual-technical inspection (right).

A crucial element of the school founded during the on-field analysis was a free large border wall (20 m length) south oriented in perfect conditions as supporter of the photoreactor. Figure 5 (left) shows this wall. The volcanic stones observed in the image were a “natural” stop limit to the occupation and self-construction progress of the neighborhoods (called in Mexico as “paracaidistas”) long time ago. Nearby this wall, there are no pedestrian cross or student presence due to the eventual occurrence of reptiles or arachnids adapted to the large accumulation of foliage. Thus, this isolated area was an excellent option for the operation of the photoreactor saved of damage for the football balls or other normal items used inside the school. On the other hand, the top roof cover of the playground was also a very important facility observed. Figure 5 (right) shows the roof cover of the playground. The long surface exposed for caption of rainwater allows harvest water previous filtration of dust and small particles following the photochemical treatment.

Fig. 5: Enclosing wall south oriented inside the school (left) and rainfall roof caption surface (right).

4. Rainfall treatment by solar heterogeneous photocatalysis

Advanced oxidation processes are based on the presence and reactivity of the hydroxyl radical (•OH) generated at standard ambient temperature and pressure (25ºC and 1 atm) with or without catalyst and/or presence of chemically reactive energy (Méndez-Arriaga, 2009). Among the AOP's, the heterogeneous photocatalysis with TiO_2, have shown highlighted efficiencies on removal of a wide type of persistent, recalcitrant, and emergent contaminants. Oxidation of organic compounds by means of TiO_2 is achieved by hydroxyl radical generation through the e^-/h^+ pair generated when the semiconductor is exposed to UV radiation.

On the other hand, contaminants present in rain are strong different in composition and content between annual season, stages or places. In an urban environment, most of the pollutant substances presents in rainfall are in relationship to the previous immediate quality of the air due to the "washing" effect during precipitation. In general, the direct employment of harvested rainfall is not preferable without previous physical and/or chemical treatment. Dissolved particulate substances and microorganism coming from the atmosphere are hazardous health compounds. In this project, an additional consecutive physicochemical conventional process (activated carbon and UV irradiation) follows the photochemical treatment train in order to guarantee the drinkable quality of the final effluent. Figure 6 depicts the full treatment train for both usages washbasin and drinking water.

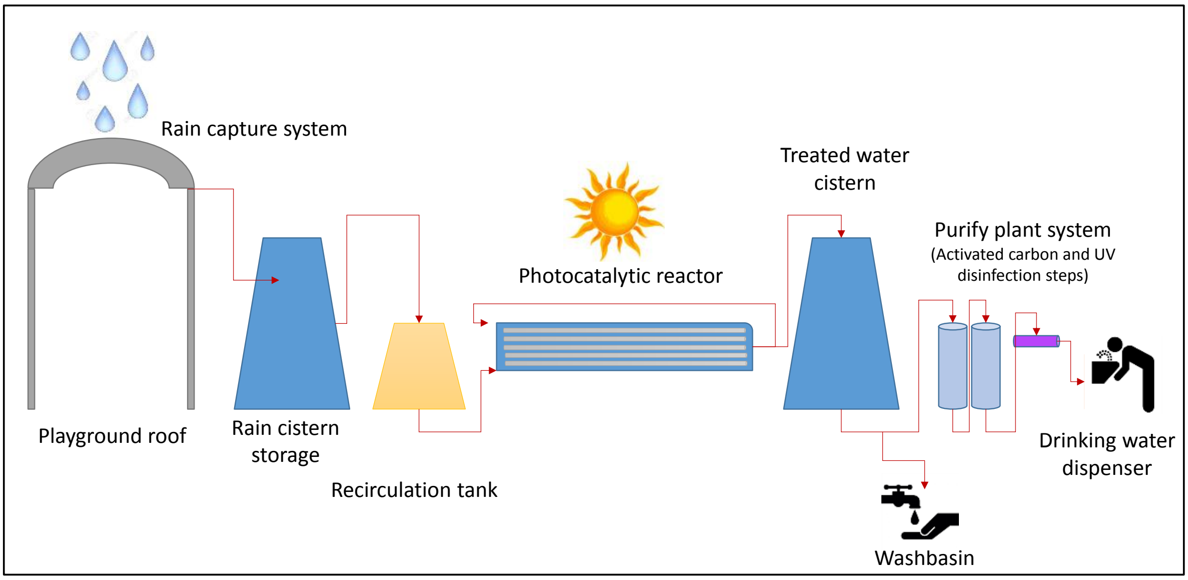

Fig. 6: Full treatment train (solar photocatalytic reactor and conventional physicochemical filters) for harvested rainwater

5. Solar photocatalytic reactor design

The solar photocatalytic reactor was designed with 10 compound parabolic collectors (CPC´s) disposed in parallel configuration. The basic components of the photoreactor are:

- i) centrifugal pump (½ HP),
- ii) storage cistern of harvested rainfall of 10,000 L of capacity (243 cm length, 238 cm extern diameter, 8.2 mm thick),
- iii) sixty Duran glass pipes (5.08 cm inner diameter and 150 cm length) with TiO_2 (Degussa P25) thermally attached
- iv) storage cistern of treated water of 10,000 L of capacity(243 cm length, 238 cm extern diameter, 8.2 mm thick).

Grupo Iddea Co. designed the layout of photoreactor and the virtual sketch (Figure 7a and 7b respectively), developed the hydraulic and electric systems and installed the full prototype.

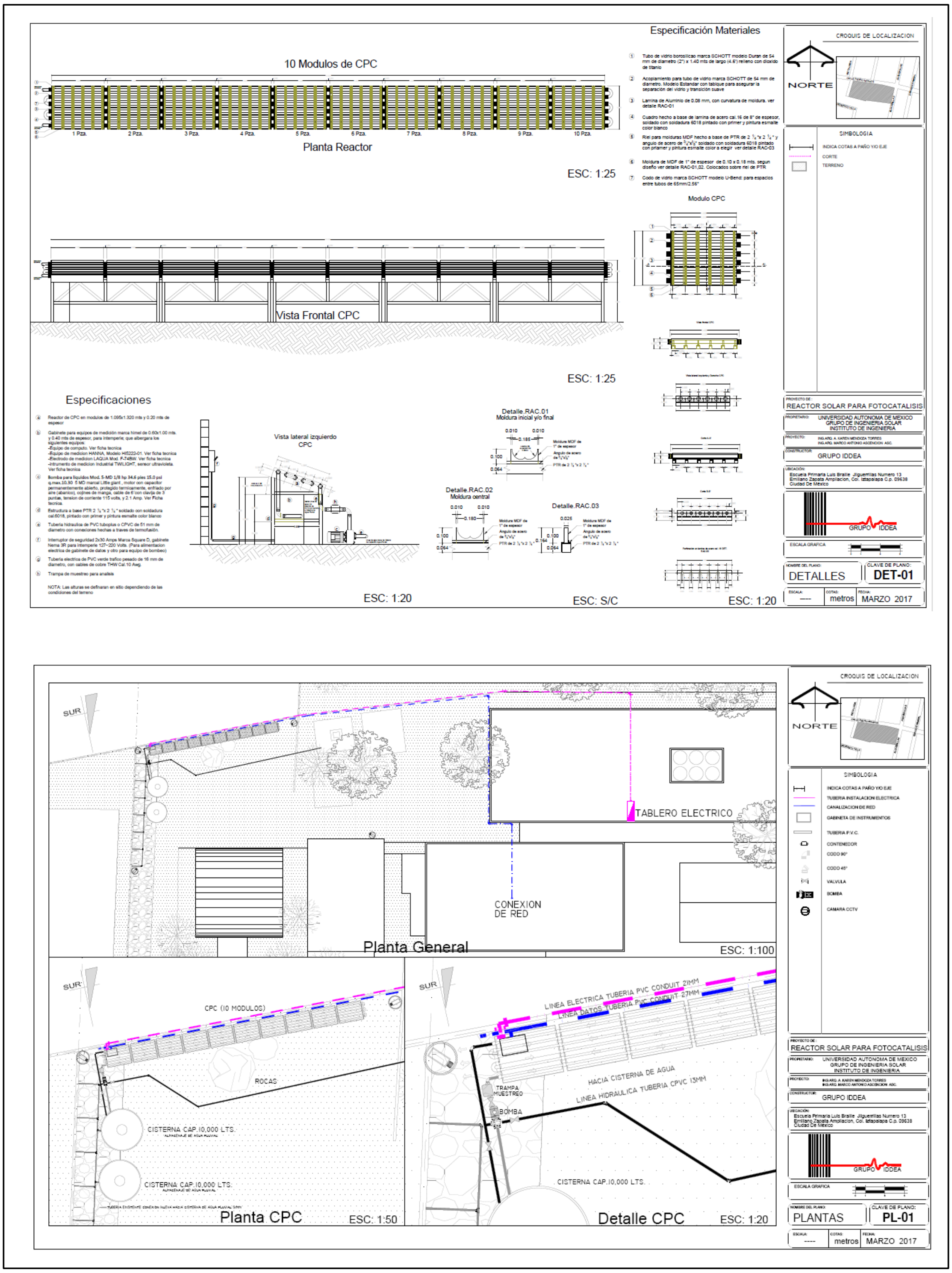

Fig. 7a: Layout and compound parabolic collector details

Fig. 7b: Digital sketch of the photocatalytic treatment system

6. Reactor construction, installation and startup

The photochemical reactor was constructed and installed in several stages per separated sections of the overall system following specific aims:

a) Fabrication of metallic structures for support and base of photo-reactors (see Figure 8);

b) Design of Compound Parabolic Collector and profile manufacture in fiber board outdoor material by jet stream water cutting system (see Figure 9 left and center);

c) Conformation of the high reflective mirror geometry through 99.5% aluminum film (see Figure 9, on the right);

d) Titanium dioxide (Degussa P25) thermal impregnation (150ºC, 4 h) on the internal pipe glass wall (5.08 cm ID Schott Duran glass);

e) Assembly of metallic structures and reflective aluminum mirror (see Figure 11);

f) Installation of hydraulic and pump system comprising the potable treatment system and final use (facet/dispenser) devices (see Figure 12);

g) Design of rain capture system on the roof of the outdoor play area (see Figure 13, left and center);

h) Installation of on-line measurement instruments (pH, OD, conductivity, salinity, temperature, total solids suspended, etc) and computational acquisition system (see Figure 13, right).

Figure 8 shows the manufacturing process for the construction of the metallic base of photoreactors including a finish detail of praimer and paint covering in order to avoid the outdoor damage.

Fig. 8: Metallic structures constructing.

Figure 9 depicts the one sun concentration geometry of the composed parabolic collector (CPC) of the photoreactor as well as the water jet cutting for construction of ribs to support the aluminum film along linear focus of the CPC.

Fig. 9: 1 sun CPC geometry (left), jet stream water cutting system (center), aluminum film adjust (right).

Figure 10 shows the shipping stage of all the premanufactured and separated pieces and devices from the laboratory at Engineering Institute in Coyoacan district until the elementary school in Iztapalapa municipality for the installation of the prototype. The Figure 10 also depicts the enthusiasm and collaboration of the students and academic community, which was interested to learn on the photochemical concepts and operation of the prototype.

Fig. 10: Transport of prefabricated pieces and helpfulness involvement of enthusiastic student in the school

Figure 11 illustrates the integration of one module consisted on the metallic base, aluminum reflectors and Duran glass pipes with catalytic activity. Ten modules with 6 glass pipes were hang on the wall south oriented making sure horizontal level and 19° inclination in each module.

Fig. 11: Parts joint and aliening-fastening on the wall

Figure 12 depicts a section of the hydraulic system including the harvest rain container, the closed recirculation tank and the treated water cistern together with the centrifugal pump and PVC pipelines to the photoreactor.

Fig. 12: Hydraulic system and pump test.

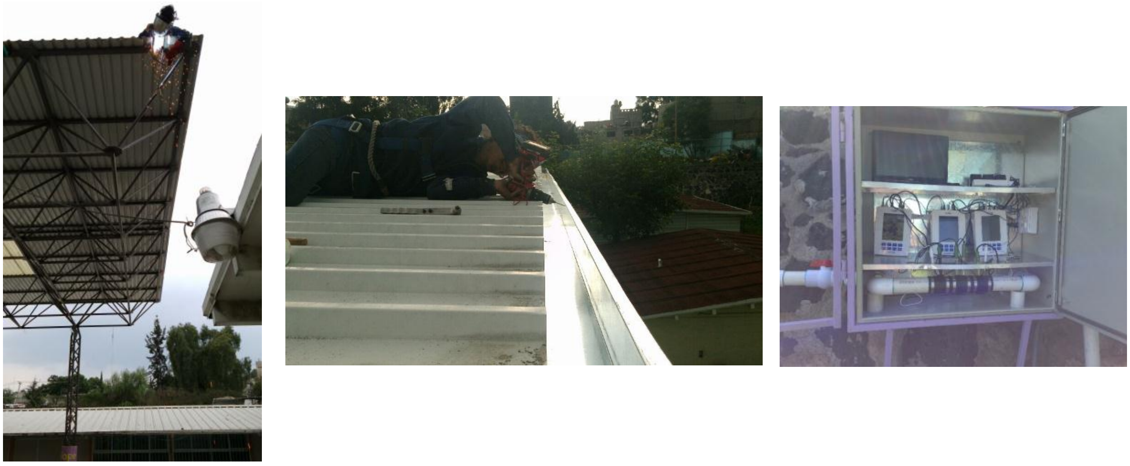

Fig. 13: Rainwater collection system (left and center) and on-line chemical measure instruments (right).

The harvest rain system was built with a semi-squared laminate canalization (20 m length) welding on the metallic top structure of the roof to 10 m altitude as depicted in Figure 13 (left and center). After that, the PVC pipeline reached connection to the storage tank with 45° inclination and previously crossing three cellulose glass paper filters consecutively attached.

The harvest rainwater flowed through the system till the pH, dissolved oxygen and conductivity sensors placed on the left side of the photoreactor. The measures during the photocatalytic treatment were recorded on line as well as the data of the UV-radiometer simultaneously acquired. Figure 13 (right) shows the chemical parameters measure system.

Fig. 14: Photochemical treatment system coupled to potable water train system and drinking water dispensers

Figure 14 shows the complete photocatalytic prototype including the conventional purification water system and the drinking water dispenser. The design, construction and startup of the prototype lasted 6 months. Following steps into the project consist on the assessment of the initial chemical quality of the harvest rainwater including the evaluation of inorganic ions (phosphorus, sulfates and nitrates among others), metals and organic compounds as well as the characterization of microorganism eventually presents. Effect of the photocatalitic treatment and optimization of residence solar irradiated time is also part of the goals during next rainy season during May, June, July and August 2018. Part II of this paper covers such results into the forthcoming ISES congress.

7. Conclusion

The solar photocatalytic science is a mature high efficient demonstrable knowledge applied for environmental remediation yet able to reach industrial scales and commercial proposes. However still there is a lack of examples with studies in real contexts to assess the potential scopes of this technology as the solar thermal and photovoltaic technologies did many years before. The solar photocatalytic research opens the opportunity to contribute against the water contamination and scarcity in unfavorable and marginal urban sectors.

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