

## Review Article

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# Solar lighting systems applied in photocatalysis to treat pollutants – A review

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**Abstract:** This work summarizes the different natural lighting systems applied for pollutant treatment systems using photocatalysis. The principles and fundamentals of the technologies used are revisited and examples of technologies most used for treatment either at the laboratory or at the pilot plant level are disclosed. This unveils a general panorama of treatment technologies via photocatalysis, using natural sunlight as an illumination source. Aside from these concentrated solar power systems that are invariable for photocatalytic aqueous treatments, reported scientific works are shown about heliostats, parabolic troughs, Fresnel lenses, and direct illuminated systems. As a valuable result of this review, the power used in photocatalytic systems requires higher attention not only in these systems but in laboratories and prototypes. Photocatalysts and their countless configuration variants are limited due to the potential barriers in particle borders, interfaces, and surfaces to cause redox reactions in water and pollutant target molecules. These factors reduce photocatalyst efficiencies for converting light energy to useful electron pair charge carriers for water treatments. The use of solar concentration systems applied to photocatalytic treatment systems can generate enough charge carriers, improving the efficiency of the systems, and making it feasible to scale up various configurations of this treatment pathway. Subsequently, the photocatalyst material and light are both important.

**Keywords:** photocatalysis, solar energy, advanced oxidation, wastewater treatment, parabolic trough reactor

## 1 Introduction

Concentrated solar power (CSP) systems widely vary in terms of configurations and temperatures they can reach. The most common solar concentrator configurations are the parabolic trough [1–3], central tower [4–6], linear Fresnel [7,8], and parabolic disc [9,10]. The designs, individual and collective sizes, and applications of these systems are vast, for example, in households, indoor lighting, and heating [11].

Solar systems can be used in two main ways: (1) direct conversion into electrical energy using photovoltaic cells [12], and (2) solar concentration systems, which subsequently use heat or concentrated lighting for electricity generation or use for systems that require thermal energy in the processes [11]. In the CSP cases, solar energy is collected and transformed into electricity through steam-driven turbines or heat energy within industrial processes substituting liquefied petroleum gas (LPG) or natural gas.

Solar concentration systems are mainly based on the reflection and absorption of solar lighting. Solar concentration technologies are systems that collect solar beams using reflective mirror surfaces installed on heliostats and parabolic troughs. In a relatively small proportion, transmission can also be used in systems such as Fresnel lenses [13–18].

In this work, the use of CSP systems in photocatalytic applications is reviewed [19]. The central tower configuration is unsuitable for photocatalytic processes because of its relatively high power and temperatures. Similarly, parabolic dishes focus solar radiation on a small area. Even more, there is a lack of published works on photocatalysis using linear Fresnel, in addition to the central tower and parabolic dishes. Consequently, the following sections cover the fundamentals of significant technologies and application examples for heliostats, parabolic troughs, and Fresnel lenses.

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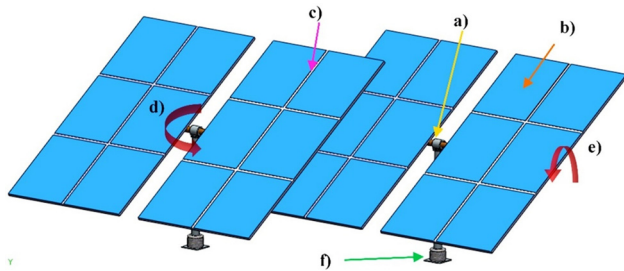
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## 2 Fundamentals of heliostats, parabolic trough, and Fresnel lenses

### 2.1 Heliostats

Heliostats are one of the most widely used solar concentration reflection systems. With working temperatures in the range of 500–800°C (Figure 1), its main limitation is the liquid for heat exchange [5,6,20,21]. Among the main applications for heliostats is the concentration of the central tower as the final point of reception [22]. However, it has its variants since these systems can be found in conjunction with other solar concentration technologies, such as lenses before the concentration endpoint, as secondary receptors in the form of a parabolic disc [23–25], and even in configurations focused on achieving high temperatures with variations in area per heliostat and number of heliostats used together [26,27].



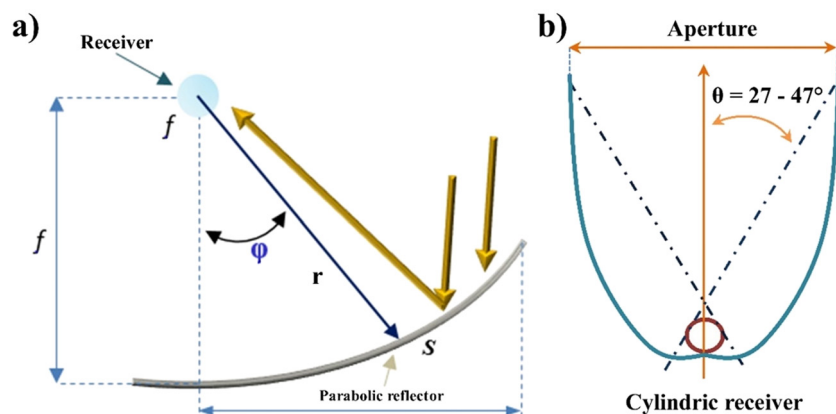
**Figure 1:** Heliostat structure and main components: (a) support for mirror base, (b) reflective surfaces, (c) reflective surface support, (d) rotation axis, (e) inclination axis, and (f) support base.

Figure 1 shows that the heliostats are made up of three main components: (1) the reflecting surfaces (Figure 1b), (2) the supporting structure (Figure 1a, c, and f), and (3) the solar tracking system (Figure 1d and e). The reflective surfaces are directed towards the area of concentration or where the solar energy is going to be used, but the reflective surfaces are also required to be oriented perpendicular to the sun to improve the capture of solar beams.

### 2.2 Parabolic trough and compound parabolic trough

Parabolic trough concentration systems are mainly applied in conjunction with thermal transmission fluid and working temperatures are between 100 and 400°C [21]. On the other hand, compound parabolic trough type collectors, depending on their configuration, are used as secondary concentration surfaces [2] and for concentration in flat, round, or plate receivers. The main advantage of compound parabolic channels is that they can have wide reception angles; in other words, without the need for solar trackers, they can concentrate solar energy, giving way to the use of these geometries in indoor lighting, high-intensity photovoltaic systems, and solar concentrators without solar tracking [28–31].

The collectors of the compound parabolic trough (Figure 2) have as their main parameter  $\theta$  or  $\varphi$ , representing the opening angle concerning the axis. According to Madala and Boehm [31], Kalogirou [32], and Jaaz et al. [1], they require to be in the range of 27–47° with a channel width of  $A$  (aperture).  $f$  represents the focus and also the focal distance.  $R$  is the position radio-vector that varies along the reflective surface. The diameters of



**Figure 2:** The parameters and proportions for (a) parabolic trough and (b) compound parabolic channel collector.

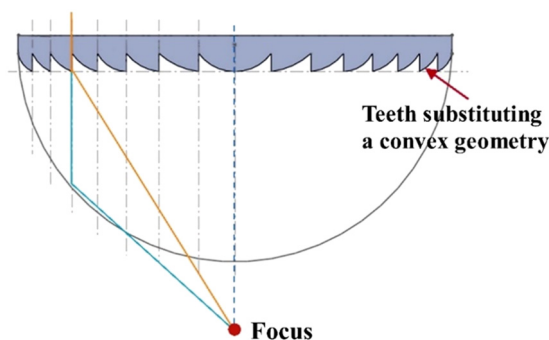
this type of structure have broad range distances, which usually are about meters in perimeter.

## 2.3 Fresnel lens and optic fibers

The concentration technologies can be classified depending on the mechanism they use to achieve the concentration, among which it is mainly presented: reflection, refraction, and dissection. The first two stands out as having diverse applications. For example, refraction systems are commonly used through mirrors. On the other hand, refraction systems find their highest application in systems such as convex or concave lenses, which have already been used for various applications. However, they had some limitations. It was not until 1822, when *Agustín Jean Fresnel* (1788–1827) officially presented a lens with the characteristics of a convex lens (Figure 3), which had improvements in terms of ease of manufacture and reduction in heating failures, and since then it has been used for various applications such as solar systems [33], among others.

Although it could be said that the main approaches around Fresnel lenses refer to their use in concentrating solar systems [34], it is also possible to find them in various applications, such as the following:

- i. In high-efficiency photovoltaic systems. For example, Feng et al. [35] used a Fresnel concentration system in a particular rectangular area to power a photovoltaic panel, designing the geometry used by the Fresnel lens. Also, Kumar et al. [36] reported an efficiency study of a thermal/photovoltaic system with a Fresnel system.
- ii. Interior lighting [15] arrangement of Fresnel lenses for lighting a building taking advantage of the incident light on the walls [37].
- iii. Use in greenhouses [38] for lighting at the same time as use in photovoltaic systems [39].



**Figure 3:** A diagram that simplifies the geometry of a Fresnel lens based on a convex lens.

- iv. Alternative energy generation as hydrogen production [40].
- v. Concentration for high temperatures, linear concentration system with dual-axis tracking [41–43], use of Fresnel lens for high-temperature concentration result in water heating [44–47], solar stoves [48–52].

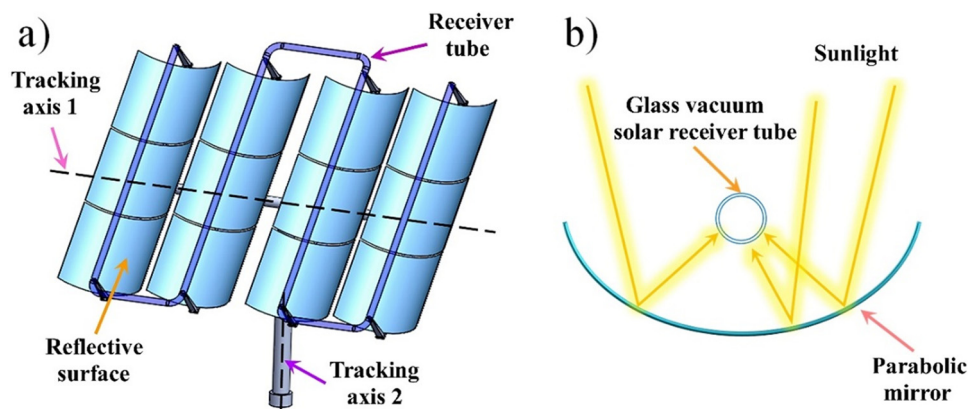
The application types depend on the configuration of the lens since it is possible to find configurations with a focal area, linear point, or at several points, as well as a flat, curved, or fragmented curved geometry in mirror strips, as an example of linear Fresnel type applications with mirrors [53].

On the other hand, fiber optics have served as a medium for interior lighting with sunlight [54] in conjunction with technologies such as parabolic trough [55] or with Fresnel lens since direct beams are necessary to have a better transfer [15,56,57]. Its operation uses refraction, which implies that the light is reflected in the walls of the interior of the fiber at a certain angle. Therefore, the optical fiber may or may not be hollow. In addition, there are optical fibers with metal coating on the outside to improve their refraction [58].

Solar tracking is necessary for Fresnel lenses considering their design (Figure 3). In the case of high-intensity photovoltaic systems, they are located in the center since the photovoltaic cells are proportionally smaller than the lenses. They require to avoid deviations, not only due to high temperatures, but also because they have transmission wiring and a cooling system, which can be affected by the system being out of the focal point. Correspondingly, in the case of hydrogen generating cells, which use similar operating principles. Also, similar is the case of optic fiber coupled systems, which have their transmission system placed at a central point. This is a main restriction for broader use because they depend on accurate tracking in two axes to preserve efficiencies, in addition to the requirements for the components located in the focal point to resist high light intensities and temperatures.

## 3 Photocatalysis systems with solar illumination

In this section, we put together photocatalytic materials and the fundamentals of concentration systems, which are considered for the design of photocatalytic reactors. Illuminated photocatalytic reactors from natural sources have migrated from collector heating systems. This system



**Figure 4:** A parabolic trough with solar tracking. (a) Diagram showing a panoramic view and (b) schematic side view of the reflecting surface.

type tried to heat a specific heat exchange fluid for various applications. They were also based on passive indoor lighting systems from natural sources.

Although the growth in articles related to photocatalysis is focused on the manufacture of materials, a small percentage is related to photocatalysis reactors and, to a lesser extent, those using solar reactors or solar lighting sources, delimiting the possible learning and knowledge for their scaling to larger treatment systems [59].

### 3.1 Parabolic trough reactors

The configuration with a parabolic trough (Figure 4) was one of the first used and that, to date, is still used for the treatment of water and air via photocatalysis.

Since they are concentration systems by parabolic channels, solar monitoring is necessary for two axes, which has delimited its applications. The main characteristics of these systems, based on the works of Borges et al. [60] and Braham and Harris [61], are as follows:

1. Dual-axis solar tracking.
2. Tubes as collectors of diameters not exceeding 6 cm.

3. They are usually coupled in several units.
4. Continuous circulation of the pollutant carrying flow to treat.

The main photocatalyst used in this configuration is  $\text{TiO}_2$  in suspension or deposited on different substrates [62], which became popular since the 1990s. This configuration has been studied for the treatment of pollutants, but also another important part is the evaluation of radiation adsorption. Curcó et al. [63] focused on evaluating the radiation adsorption in this system type specifically for photocatalysis applications, which demonstrates the impact since, so far, no similar studies have been found in the other variants of photocatalysis reactors with solar energy.

Table 1 shows examples of published works of parabolic troughs applied for photocatalysis. They show different treated pollutants, treatment times, collector areas, volumes to be treated, and photocatalysts used. It is difficult to compare similar treatment systems directly and their efficiency depends on various factors. Hence, Table 1 enlists only some study cases of this system type. This configuration type is frequent since most photocatalysts are in suspension, which leads to easy interchange with other photocatalysts.

**Table 1:** Photocatalysis systems with the parabolic collector as a solar concentrator

Ref.	Area ( $\text{m}^2$ )	Volume (L)	Photocatalyst/concentration	Pollutant	Degradation (%)	Time (min)
[60]	0.75	0.15	Fly ash $3 \text{ g}\cdot\text{L}^{-1}$	Methylene blue	90	300
	29.1	180	Ti- $\text{TiO}_2$ /supported	4-Chlorophenol	10	10
	1	—	Pt- $\text{TiO}_2$ /supported	Gaseous toluene	79	5.7
[61]	382	838	$\text{TiO}_2/0.14 \text{ g}\cdot\text{L}^{-1}$	Sodium pentachlorophenolate	100	20
	0.04	1	$\text{TiO}_2/0.49 \text{ g}\cdot\text{L}^{-1}$	<i>Escherichia coli</i>	100	27

Photocatalysts, as a colloid of nanoparticles, show the best performance in pollutant degradation compared to their coatings. This is far beyond only the increase in the effective contact area with the solution. There are other factors to consider, such as possible additional heat treatments for the coatings, blockage by external adsorption on the surface of ionic subproducts of the target molecules, presence or absence of pores in the coatings and the solution access to them, effective distance between the origin and destination of oxidizing–reducing intermediaries (hydroxyl or superoxide), the illumination access to the semiconductor generating the electron–hole pairs, and so forth.

### 3.2 Compound parabolic trough reactors

After parabolic trough systems, compound parabolic trough systems (Figure 5) are the most used, and many articles can be found. This is probably because the same technology of the compound parabolic trough helps to have better ranges for solar concentration. So, they are a one-axis tracking system that could move to follow the sun's path [28–31,61]. In some latitudes, near the equator, the compound parabolic trough could remain static without losing solar irradiance.

The main characteristics of these systems, according to Amat et al. [64], Malato et al. [66], and Waso et al. [67], are as follows.

1. Solar tracking on one axis.
2. Tubes as collectors with diameters in the range of 8–18 cm.
3. They are usually coupled in several units.
4. Continuous circulation of the pollutant carrying flow to treat.

Table 2 shows examples of photocatalysis systems using compound parabolic collectors, indicating that it

is more common for this configuration to find systems connected in series. However, it is necessary to consider that, compared to the parabolic collector, the intensities that can be collected are lower when reducing the concentration area. This is because, usually, the sizes of the concentrators are barely larger than those of the collectors.

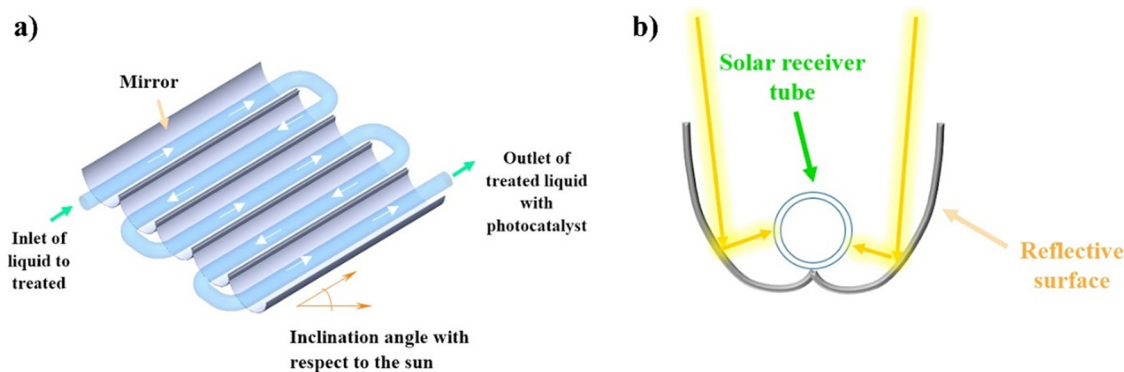
### 3.3 Flat collectors

Until now, only concentration systems had been considered for feeding photocatalytic reactors. However, another variant is the flat collector (Figure 6), which, unlike the other applications, does not have reflective surfaces or refraction for the lighting concentration. Although they have their limitations, it is considered a viable option for photocatalysts either in suspension or substrates. Their main advantage is that they do not need a solar tracker since they take advantage of diffused light [68].

In Figure 6, the sky-blue color is the substrate plate. The light blue color within the rectangle is the aqueous liquid with the contaminants. The white down arrows indicate the sense of the flow and the dark blue arrow show the contaminant flow. The large yellow arrows indicate the direct incidence of sunlight on the liquid. The photocatalyst is on the substrate surface, below the film of the descendant water (pink arrow).

Among the main characteristics of flat collectors are those mentioned by Fendrich et al. [59] and Bahnemann [68], which are as follows.

1. They can be used without solar tracking, providing direct and diffused light.
2. No solar collector is needed.



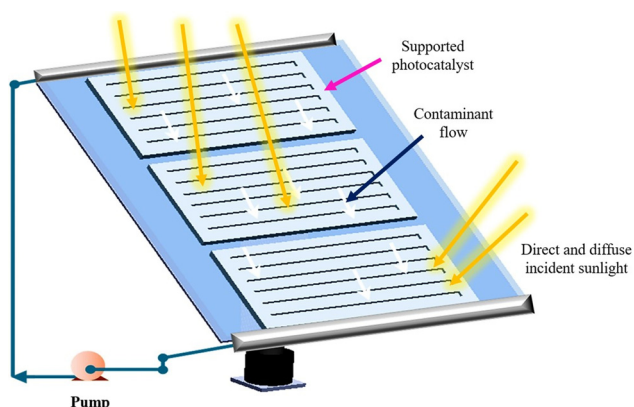
**Figure 5:** (a) Reactor with concentrated natural lighting by parabolic channel, continuous flow, and suspended photocatalyst. The inclination of the reactor depends on the system location. (b) Cross-sectional view of the composite parabolic collector showing the configuration of the reflective surface and the circular receiver.

**Table 2:** Photocatalysis systems with the compound parabolic collector as a solar concentrator

Ref.	Area (m <sup>2</sup> )	Volume (L)	Photocatalyst/concentration	Pollutant	Degradation (%)	Time (min)
[64]	—	0.25	TiO <sub>2</sub> /0.2 g·L <sup>-1</sup>	Toluenesulfonic acid	27	350
[65]	1	30–40	TiO <sub>2</sub> /1 g·L <sup>-1</sup>	Oil mill wastewater	89*	—
[66]	1.03**	201	TiO <sub>2</sub> /0.2 g·L <sup>-1</sup>	Imidacloprid, formetanate, and methomyl	100	150
[67]	—	0.9	TiO <sub>2</sub> -rGO/1.5 g·L <sup>-1</sup>	<i>Klebsiella pneumoniae</i>	—	240

\*Reports percentage reduction in COD.

\*\*6 units each with an area of 1.03 m<sup>2</sup>.



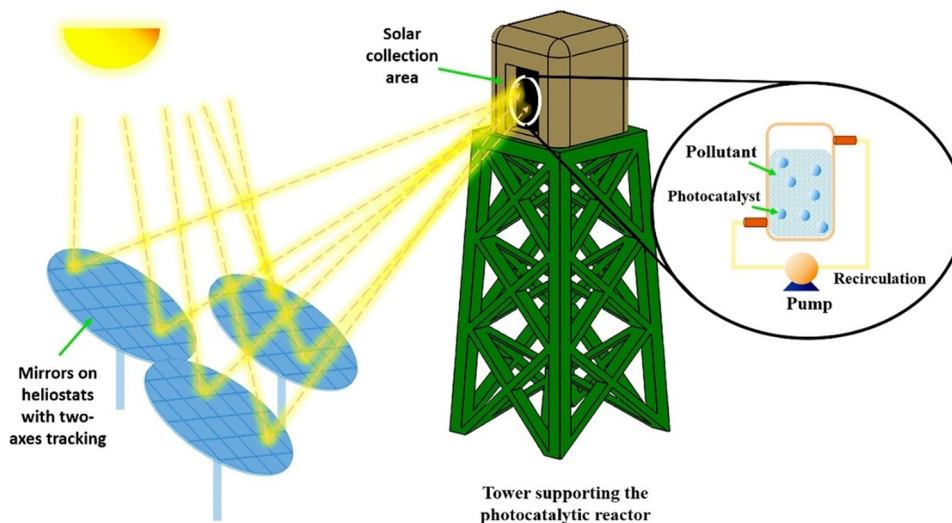
**Figure 6:** Planar photocatalytic reactor with non-concentrated solar energy, having laminar flow recirculation, with photocatalyst on plates.

3. Can be used in large areas.
4. Continuous circulation of the pollutant flow to be treated.

### 3.4 Reactors with reflective surfaces as solar concentrators

Reactors with reflective surfaces as solar concentrators could be considered among the most powerful systems, considering that this configuration was initially used for central tower concentrators to generate electrical energy (Figure 7) [20,69]. Therefore, the power can be several thousand W·m<sup>-2</sup>. So, in this case, recirculation systems are necessary to cool the pollutant. Reeves et al. [70] used parabolic discs, with a diameter of 1.5 m, directed towards the reactor with a capacity of 300 mL, using a TiO<sub>2</sub> solution. Also, the luminous intensities were regulated. The pollutant was degraded to mineralization. According to Reeves et al. [70], the following can be found among the main features of these devices.

1. Solar tracking is necessary for heliostats or parabolic discs.
2. Flat solar collectors can be used.



**Figure 7:** Diagram of the recirculation reactor and the outer test tower.

3. They could be considered as the systems with the highest potential in possible lighting capabilities.
4. Continuous circulation of the flow of the pollutant to be treated.
2. They can be used for on-site reactions either at the focal point or at the collector base.
3. They can be easily coupled to existing reactors indoors if guided by optical fiber.

This system is interesting because it has a powerful concentration and, altogether with considering a suitable photocatalyst, it is possible to take advantage of the capabilities of the concentration system as a whole, that is, have a photocatalyst that can be efficient with high intensities.

### 3.5 Reactors with parabolic disc/Fresnel lens concentrators

Among the concentration lighting systems at a focal point are concentrator systems with parabolic discs and Fresnel lenses (Figure 8). Although initially, they were configurations designed for interior illuminations [54], little by little, they have been evolving until they were considered configurations for lighting photocatalysis reactors [71,76]. Since it is a system of focal concentration, it requires dual-axis tracking. Among the advantages, they can be set in indoor reactors and coupled with existing reactors. Although depending on the configuration, they can be arranged on-site [72,77], *i.e.*, at the focal point of the configuration or the base of the collector [78]. The main characteristics of this reactor type are as follows:

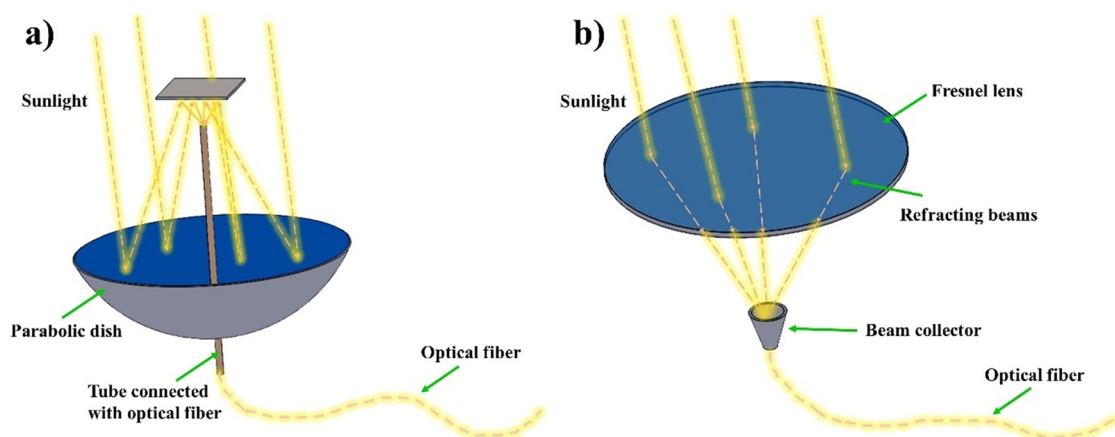
1. Solar tracking is necessary for the parabolic disc or Fresnel lens.

Table 3 shows some works about photocatalytic reactors using different solar lighting systems, such as Fresnel and parabolic troughs. Different photocatalysts and pollutants have been tested using solar concentration systems. The Z-scheme semiconductor heterojunctions are broadly investigated [79], such as  $g\text{-C}_3\text{N}_4/\text{WO}_3$ , but  $\text{TiO}_2$  and  $\text{ZnO}$  stand up for engineering applications because of a balance between cost, efficiencies, lifetime, and other parameters.

### 3.6 Reactors with optical fiber-guided lighting

Reactors with illumination guided by optical fiber (Figure 9a) can be applied in conjunction with technologies, such as Fresnel lenses, but they are mainly used in illuminating inside the reactor. This is considered an advantage at a technical level since the fiber only transmits the illumination (Figure 9b). Electric current is not necessary inside the optical fiber, facilitating the designs, maintenance, and other technical aspects [76,80,81].

A variant of these systems is those that use optical fiber to support the photocatalyst. The advantage is that photons can be absorbed directly by the catalyst [82–86]. The main features are as follows:



**Figure 8:** (a) The diagram shows the representation of the concentration systems formed by a parabolic disc collector that redirects the solar beams to a specific central point, which redirects them to an optical fiber with the help of a reflective surface. (b) Schematic representation of collector with the same principle with the difference that a Fresnel lens is used instead of a parabolic disc.

**Table 3:** Photocatalysis systems using Fresnel lens, parabolic trough, or optical fiber for lighting

Ref.	Area (m <sup>2</sup> )	Volume (L)	Photocatalyst/ concentration	Pollutant	Degradation (%)	Time (min)
[71]	1	Fresnel lens	TiO <sub>2</sub> 0.1–1.5 g L <sup>-1</sup>	CO <sub>2</sub> 1 MPa	Conversion to other products	180
[72]	0.75	Parabolic trough	BiVO <sub>4</sub>	Methylene blue	100	60
[73]	6	Optical fiber	TiO <sub>2</sub>	Ethylene	87	200
[74]	1	Optical fiber	TiO <sub>2</sub>	CO <sub>2</sub>	60–50	500
[75]	0.2	Fresnel lens and optical fiber	Microalgae cultivate	CO <sub>2</sub> and illumination	—	—

1. It is considered a system for lighting the reactor for concentration, so it needs a light source that can be natural or artificial.
2. Photocatalysts can be used in solutions or supported on surfaces, and, considering their flexibility, a wide variety of configurations is possible.
3. Its illumination capacity depends mainly on the light source and is limited by distance from the source to the point of use.
4. Continuous circulation of the flow of pollutants to be treated, although for the moment, on a laboratory scale.

Table 3 shows some works about photocatalytic reactors using optical fiber lighting systems, altogether with those using concentration. In this case, the preponderant photocatalyst has been TiO<sub>2</sub>, possibly, to ensure reliable efficiency. Also, the time used in these tests was usually higher than that commonly used in other photocatalysis reports.

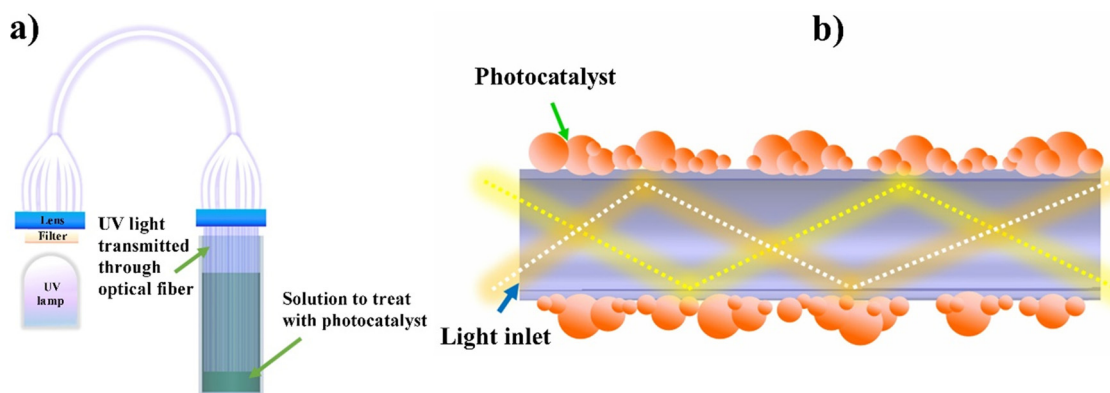
Industrial challenges and perspectives are innumerable. Many industrial-level prototypes have been constructed worldwide by companies and research institutions. Considering that the waters requiring treatment

also have countless variants, the photocatalytic tested reactors have many designs and variants in materials. All of them share some similarities, such as photocatalyst material, maximizing exposed area, use of nanoparticles, minimizing the distance between the light source and surface, use as one of the last stages of the water treatment, affectation by incrustations of salts or biofilm formation, and so forth.

These types of solar concentration reactors are devoted to photocatalysis. Other photocatalytic reactions well documented in the scientific literature are almost nonexistent at such a scale with the technology developed explicitly for their characteristics. CO<sub>2</sub> reduction, water splitting, hydrogen and oxygen evolution reactions, etc., are scarcely tested in outdoor big-scale infrastructure. Hopefully, their efficiencies and photocatalyst will allow such facilities in the future.

## 4 Conclusion

In scientific literature, much is discussed about photocatalytic materials, but it has been forgotten that the



**Figure 9:** (a) Reactor fed by a concentration system of natural or artificial source, transporting the lighting via optical fiber, for the treatment having the optical fiber within the solution to be treated and the photocatalyst in suspension. (b) Representation of a fiber optic system with a photocatalyst coating.



performance of photocatalysis systems is directly related to the luminous intensities. So, it is necessary to consider the type of photocatalyst, its concentration, whether or not it is supported, and the luminous intensity on which the efficiencies depend. On the other hand, so far, it has been possible to see different types of concentrators applied to photocatalysis and it is known that not all manage to concentrate the same luminous intensities, with some systems being more potent than others. For example, if the luminous intensities of parabolic and parabolic compound collectors are compared, their intensities are lower than that of systems with several mirrors, parabolic discs, and Fresnel lenses. Although comparing, the plate surfaces are still lower in capabilities in terms of lighting, it is also a factor to consider when designing a photocatalytic reactor using natural sunlight. For example, the parabolic trough and compound parabolic trough systems can have higher light intensities, although with a more complex tracking system. It depends on whether or not such systems are viable based on the photocatalyst and the pollutant to be treated, among other technical and economic factors.

It is known that the performance of the photocatalyst is directly proportional to the lighting provided. However, something that needs to be distinguished is to what extent it is feasible to increase the illumination so that the photocatalyst is used best. This is because it is necessary to be able to identify the capabilities of the catalyst to design together a viable lighting source to achieve the use of all the capacity of the photocatalyst without wasting resources in cooling systems that would not be necessary. This implies illuminating only using what is sufficient for the photocatalyst.

Starting from considering essential knowledge of the photocatalyst and its capabilities, this work remarks on the transcendence of lighting in photocatalytic systems. These systems on small, middle, and large scales can have and maintain higher efficiencies throughout their lifetimes, emphasizing lighting during the installation and maintenance services. The photocatalyst efficiencies depend on the illumination power, wavelength above the  $E_g$ , and smaller particle sizes warrant higher surfaces with photon to electron-hole events. Finally, considering CSP systems for lighting photocatalytic facilities is a beneficial multiplying factor in water treatment systems.

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