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SWOT Analysis of Photocatalytic Materials Towards Large-Scale Environmental Remediation

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Corresponding Author:	Claudia Letizia Bianchi Università degli Studi di Milano: Universita degli Studi di Milano ITALY
Corresponding Author's Institution:	Università degli Studi di Milano: Universita degli Studi di Milano
Corresponding Author E-Mail:	claudia.bianchi@unimi.it
First Author:	Claudia Letizia Bianchi
Order of Authors:	Claudia Letizia Bianchi
	Ridha Djellabi, PhD
	Ermelinda Falletta, PhD
	Roberto Giannantonio, PhD
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SWOT Analysis of Photocatalytic Materials Towards Large Scale Environmental Remediation

R. Djellabi[1], R. Giannantonio[2], E. Falletta[1], C.L. Bianchi[1,*]

[1]Department of Chemistry, Università degli Studi di Milano, Via Golgi 19, 20133 Milano (Italy)

[2]CNR IRSA, Viale Francesco de Blasio 5, 70132 Bari (Italy)

Corresponding author: C.L. Bianchi (claudia.bianchi@unimi.it).

Abstract

After a long process of intense fundamental and scientific research, the question of the suitability of photocatalytic technology to address real environmental problems is still alive. Although photocatalysis has exceptional and unique properties, it still suffers from some technical problems that limit its large-scale transfer. Furthermore, part of the scientific community focuses on research impossible to apply in industry due to both costs and technical difficulties in large-scale transfer, and testing conditions are often very far from real ones. In this report, a SWOT analysis of photocatalytic technology is conducted in order to assess whether its main strengths can enable it to seize relevant opportunities for large-scale investment and commercialization of photocatalytic solutions, despite its weaknesses and external threats. Exploiting and extending all the properties of photocatalysis can transform a plain chemical process in a real and truly competitive technology.

Keywords: Photocatalysis technology; SWOT Analysis; Commercialization; Environmental remediation; Specific applications.

1. Introduction

Since the discovery of Honda and Fujishima in 1972, photocatalysis has passed a long and intensive research path up to date. Most of efforts have being devoted to understand the various phenomena occurring in different photocatalytic systems from the fundamental and scientific point of view. However, the potential of photocatalysis towards business, based on solving real contemporary environmental issues at large scale was rarely addressed. No doubt that the topic of engineering and nanoarchitecting of photocatalytic materials, which is the most important part in the photocatalytic technology, has received the highest attention from scientists [1, 2]. Huge research studies and innovations have been reported on doped TiO_2 to enhancing the visible light absorption and separation of redox charge carries [3]. Other potential competitive semiconductors were also well developed and investigated towards such as g-C_3N_4 [4], ZnO [5], $AgPO_4$ [6], $BiPO_4$ [7] and WO_3 [8]. In addition, the construction of heterojunction semiconductor systems have been overaddressed for many photocatalytic applications mostly in environmental remediation and energy production [9]. Although such enormous research proved an outstanding potential of the photocatalytic technology, the scientific community is still disappointed due to the scarce transfer of this huge research studies to fruition [10] ••. Such a gap between the scientific research and real-world industrial applications is due to the process, technological and economic limitations from one side [11], and the misunderstood concept of how-to-use the photocatalytic technology alternatively to existing technologies to address specific applications. In this report, we stress some limitations of photocatalytic technology, from the materials point of view, and how it could be transferred to real applications in the field of environmental remediation.

Technology Transfer is the critical step to move a technology from research labs to the marketplace. This process involves efforts of scientists, engineers, entrepreneurs, industries, technology transfer specialists and the Public Administration [12, 13] •. Photocatalytic technology, as a whole, including photocatalytic materials, can be applied by means of suitable products, namely photocatalytic plants or devices. In order to perform an assessment about the utility of photocatalytic technology, it is important to state the features that photocatalytic technology has compared to existing systems. In general, it is not fair to assume that the photocatalytic technology is all-that-you-need to properly treat all types of pollutants in air or water in whatever condition i.e. we cannot ask photocatalysis to purify an optically dense sludge containing hundreds of different compounds. We may e.g., first use a process step for sedimentation of suspended solids (so that the water medium is transparent) and/or a further step for the separation of pollutants that can uniquely be removed by photocatalysis and/or a further step which may more easily capture photocatalytic products with respect to reagents (e.g., Granular Activated Carbon – GAC filters).

Generally speaking, the performance of a novel technology may be assessed with respect to existing ones by comparing the functional properties of products which may be provided through their exploitation. A very effective way to show this is reported in **Figure 1**: to the left, we have an existing product featuring a number (M) of useful (positive) functional properties and a number (K) of useless (negative) functional properties, above and below the horizontal axis, respectively; to the right, we have a new (better) product featuring a number (N, N>=M) of useful (more positive, improved effect) functional properties and a number (W, W<=K) of useless (less negative, reduced effect) functional properties. If N>=M, one or more unique, distinctive properties are provided by the novel technology. These properties may enable the solution of specific problems, which are not properly handled by existing technologies.

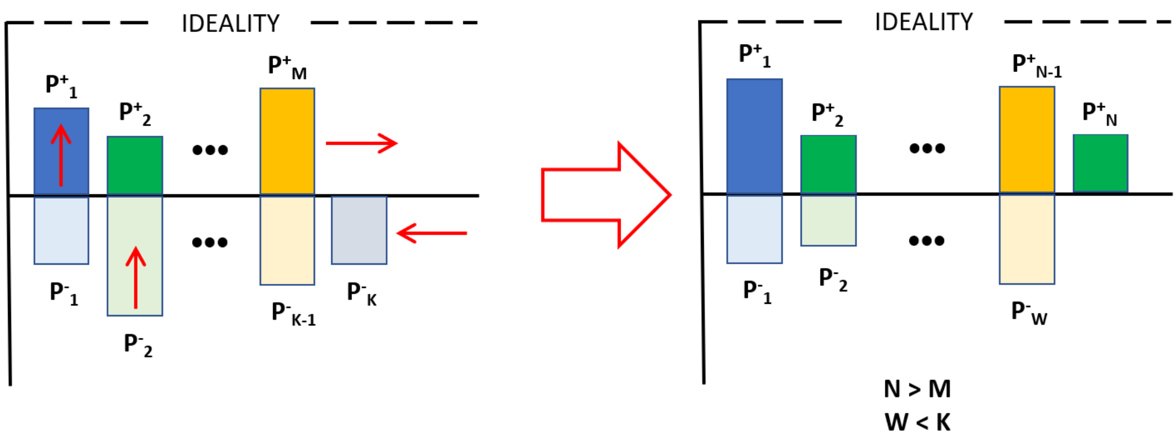

Figure 1 – Product development.

In terms of materials technology, photocatalysis has showed many outstanding and unique characteristics. However, it suffers from a number of technological shortcomings towards environmental remediation. Some of such limitations could be partially or totally overcome and some are a part of the process. In general, it is hard to judge the overall strengths and shortcomings of photocatalytic technology until we know accurately all details about the photocatalytic device, which is its intended use and in which conditions. To transfer the photocatalytic technology to the market, the following question should be properly addressed: can we meaningfully think that a photocatalytic technology may be duly developed to be used in specific applications and, in particular, to address environmental remediation issues? This is the kind of questions that are posed in an industrial environment in order to decide if it is worth to invest money, time and effort to solve a given problem that has an impact on the environment and/or human health and to develop a business by solving it. An entrepreneur will ask for a detailed analysis, starting from a so-called SWOT Analysis which is an approach to identify strengths, weaknesses, opportunities, and threats of a raised technology product for the investment or/and commercialization. The strengths and weaknesses points are assumed usually as internal, while opportunities and threats are considered as external. An appropriate SWOT analysis would be very helpful to transfer the obtained scientific finding to large-scale applied technology. Throughout the coming points, an analysis on the possible transfer of photocatalytic technology to fruition will be discussed, by stressing strengths of this technology, technological shortcomings, market opportunities and possible threats, as summarized in **Figure 2**.

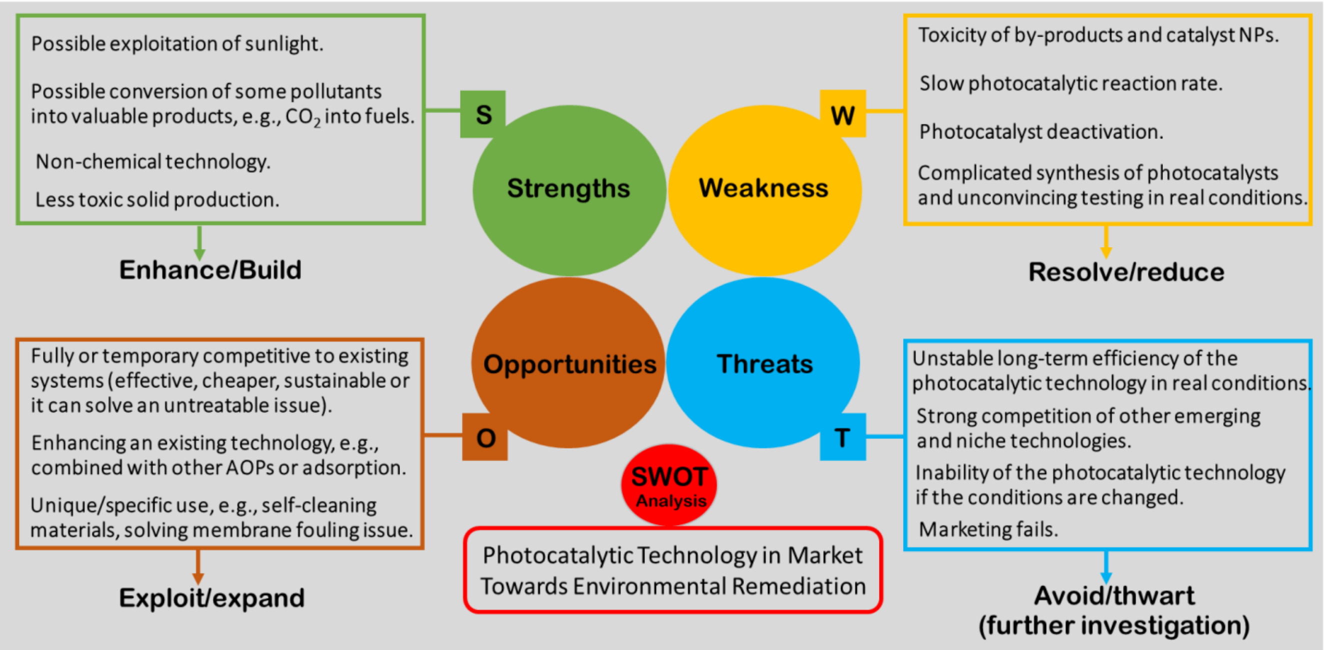

Figure 2. Example of a general SWOT Analysis on the photocatalytic technology towards environmental remediation.

2. Main strengths of photocatalytic technology

2.1. Exploitation of sunlight

The strongest point of photocatalysis is the possible use of natural solar light to initiate a photocatalytic environmental remediation, as a renewable, sustainable and for-free resource. Therefore, this unique propriety may lead to save energy for the processing of multiphase contaminants and also for policy reasons which are related to the EU New Green Deal.

2.2. Conversion of toxic pollutants into valuable products

The conversion of multiphase contaminants into valuable feedstock by photocatalysis means is an economic sustainable strategy that is simultaneously able to fight pollution and produce energy/products. The photoconversion of CO_2 into fuels helps at once to moderate global warming and energy-supply issues [14] •. Recovery of noble metals through photodeposition on the photocatalyst surface could be also a unique option, e.g., recovery of silver [15]. Conversion of toxic organic pollutants into valuable chemicals, e.g., conversion of carcinogenic 4-nitrophenol into 4-aminophenol [16].

2.3. Non-chemical technology

The non-use of chemicals is a further strong point of photocatalysis as compared to many existing advanced oxidation processes (AOPs). In particular, photocatalysis does not require H_2O_2 addition, which is a major cost in conventional AOPs. This feature allows to implement continuous environmental remediation processes such as those based on self-cleaning materials which are able to continuously reduce the nearby chemical [17] and microbial [18] • pollution.

2.4. Less toxic solid production

Photocatalysis produces less toxic solid wastes after the treatment if the total mineralization of contaminates is achieved, compared to other technologies, e.g., adsorption, precipitation, etc, which are based on the transformation of pollution from a phase to another phase.

2.5. Removal of low concentration of pollutants

In wastewater treatment stations, technologies for the removal of high and low pollutants loaded waters are combined successively. Mainly, in the primary and secondary treatment stages, chemical and physical technologies that are able to remove highly concentrated pollutants are applied, e.g., coagulation, precipitation, biological oxidation, chemical oxidation ...etc. However, these latter technologies cannot remove pollutants at very low concentration; therefore, the use of technologies having the potential to remove pollutants at low concentration is recommended. In this case, the use of photocatalytic advanced oxidation could be a potential approach for this purpose.

3. Main shortcomings of photocatalytic technology

3.1. Generation of by-products and photocatalyst NPs toxicity

Due to the formation of highly toxic by-products, the photocatalytic process has come under extensive criticism recently. In fact, the issue of by-products formation is a global issue of all AOPs. However, in photocatalytic system, this issue is more pronounced because of the heterogeneous nature of the reaction, compared to homogenous systems featuring a high mass-transfer, e.g., the Fenton reaction. Considering that the radical oxidation of organic pollutants takes place on the surface of the photocatalyst, the re-adsorption of by-products does not always happen for further oxidation and mineralization especially in low mass-transfer systems (supported photocatalysts). A very recent study [19] showed that dioxins and furans, which are classified as persistent organic pollutants (POPs), can be formed during the photocatalytic degradation of Chloro-2-[2,4-dichlorophenoxy]phenol (Triclosan). The release of toxic and carcinogenic volatile organic compounds (VOCs) in air was also reported [20, 21]. The topic of by-products formation in photocatalytic systems was critically discussed in detail by Rueda-Marquez et al. [22] •.

On the other side, the question "how-to-use photocatalysts?" is on the horns of a dilemma. Suspended photocatalysts exhibit super mass-transfer and efficiency but hard recovery and high toxicity of NPs [23]. However, the fixation of photocatalysts on supports leads to overcome the issue of toxicity and NPs recovery but limits several times the mass-transfer and efficiency. On top of that, the release of supported nanoparticles from objects or the degradation of photocatalysts could take place as well. 1

3.2. Slow reaction process and low ROSs transformation

By considering the working conditions (type of light, concentration of the pollutants, type and mass of catalyst, presence of interfering species, pH, etc), it could be deduced in general that the photocatalytic technology alone is not fast enough to be competitive with respect to other existing technologies. And this may be interpreted according to what we know about the kinetics of photocatalysis [24] •. Many studies reported that the degradation of some *mg* of pollutants may require several hours even at well-controlled lab conditions, which requires a lot of light energy. An example of these studies is that of Maniakova et al. [25] who have compared the efficiencies of N-TiO_2 heterogeneous photocatalysis and homogeneous photo-Fenton towards the oxidation of pharmaceuticals in wastewaters. Shortly, the study reports that solar photo-Fenton showed 98% removal within 1 h, with cumulative solar energy per unit of volume of 5.6 kJ/L. However, solar N-TiO_2 system showed only 30% removal in 3 h along with 13.3 kJ/L.

An effective photocatalytic treatment is based on both ROSs generation and transformation (interaction with targeted pollutants). Many research studies reported the formation of high yields of ROSs in some give conditions using electron spin resonance (ESR), but there are worries regarding their transformation to the pollutants due to the unwater reactions and low mass transfer. For example, both •OH and $SO_4^{\bullet-}$ can be generated significantly in alkaline solution, however, both of them react quickly with ^{-}OH species limiting their transformation [26]. In addition, many ROSs show high affinity towards the interfering ions.

3.3. Photocatalyst deactivation

Industrial applications require continuous processing. Unfortunately, photocatalytic materials suffer from the issue of surface deactivation after a certain time of use which requires to stop the process and a regeneration step is needed. In most reported cases, deactivation is significantly connected to the over-adsorption of pollutants, coke or/and formed organic and inorganic by-products [56, 57]. It can be more pronounced if the accumulated pollutants/by-products are more resistant to the photoproduced ROS on the photocatalyst surface [27]. Overall, the deactivation depends also on the efficiency of photocatalysts for the oxidation of some pollutants at a given concentration.

3.4. Complicated synthesis of photocatalysts and unconvincing testing

This point is not properly considered as one of the shortcomings of the photocatalytic technology itself but rather it is a result of the over-focusing of researchers on the fabrication of outstanding novel photocatalytic materials to understand, from the scientific point of view, their surface properties and photocatalytic mechanisms, at the expense of technological and real-use aspects. Throughout the literature, the reader will find hundreds of types of photocatalysts for environmental remediation. However, the majority of these materials is not suitable for real use, not because of efficiency or stability, but due to the use of expensive reagents along with very long and complicated synthesis procedures to prepare few grams of photocatalytic nanomaterials. For example, the synthesis of photocatalytic materials with hydrothermal and solution combustion processes could be difficult and costly at large scale [28]. Regarding the tests to evaluate the photocatalysts, most of research studies report the photoactivity of materials towards the removal of single pollutants under well-controlled lab-scale conditions that are far away from the real environment. A still pending question: would those reported photocatalytic materials give similar efficiency in real conditions? Both the complicated synthesis of materials and the insufficient testing of materials in quasi-real conditions would discourage the commercialization of the photocatalytic technology. Some nanomaterials showed great photocatalytic effectiveness in suspension but there is not enough data to say if these photocatalysts could have a satisfactory efficiency when fixed on supports to avoid the toxicity of NPs.

4. What the scientific community has done to overcome the technological issues of photocatalysts?

Certainly, many research groups are struggling to overcome the common technological shortcomings of photocatalytic technology by emphasizing the engineering of photocatalytic materials or/and photoreactors [29] ••. If we wipe up the literature, we can find on the top of the list that the combination of photocatalytic technology with other technologies (e.g., AOPs, adsorption, electrochemical and chemical) may solve many technological problems and synergistically speed up the overall process.

For example, the combination of photocatalysis with adsorption is an example of fact. The coating of activated carbon with TiO_2 has widely been suggested to overcome some limitations of adsorption and photocatalysis by increasing the lifetime of photocatalyst/activated composite, reduced release of toxic by-products, synergism of adsorption with ROSs oxidation in the same platform and easy recovery of materials [30, 31]. With the exception of activated carbon, many materials with high surface area including clays [32], zeolites [33], carbonaceous biomass [34] and synthesised MOFs [35] have been used as sorbing platforms to support photocatalytic NPs. Another example of hybrid systems is the so-called sono-photocatalysis, combining sonolysis and photocatalysis for enhanced ROSs yield generation, to prevent the fast deactivation of photocatalysis through *in situ* sono-regeneration and better mineralization of by-products [36] •.

To regenerate the inactivated photocatalysts, several routes have been suggested such as chemical washing, heating or UV irradiation. The combination of photocatalysis with vacuum ultraviolet or non-thermal plasma to increase the lifetime of photocatalysts have also been reported. The engineering of smart photocatalytic materials to prevent the fast deactivation has been reported in some conditions, e.g., it was reported that, unlike P25 TiO_2, β-Ga_2O_3 is able to open the aromatic ring of intermediates in gas phase which prevents the deactivation of photoactive surface [27].

Many research groups have interested recently in fabricating water-floating materials to treat wastewaters under solar conditions [37-39]. In fact, this class of materials could overcome many technological issues, and their application is very plausible compared to suspended and supported photocatalysts as they can offer a better irradiation/oxygenation, easy recovery and reuse, and can be used to treat highly pollutants concentrated or oily wastewaters.

The evaluation of the effectiveness of photocatalytic systems towards the purification of mixed pollutants in different phases is the right way to bridge the scientific research with real applications: some groups have being interested in testing the photocatalytic technology towards the depollution of mixed pollutants in water [40] or air [41] phases.

5. Marketing opportunities and threats

The main opportunities are the chances to exploit the positive, unique characteristics of photocatalysis to provide solutions of problems, which have an impact on the environment and human health, including the delivery of products to the market to make business. Opportunities may be caught by who owns unique photocatalytic know how and technology i.e. who is able to solve the weak points of photocatalysis (i.e. materials featuring very high activity in the visible range, very stable and robust supported catalytic systems, cheap and fast catalyst regeneration processes, more sustainable than other technologies – according to LCA/Circular Economy, etc.). In some cases, photocatalysis may be used as a temporary alternative to existing systems: in sunny periods of the year or regions with extended sunshine, solar photocatalysis could be a good substitute for chemical AOPs in the whole treatment system.

Many unique properties of photocatalysis could be further developed and transferred to specific use in real applications, e.g., (i): the photocatalytic conversion of some toxic compounds into valuable products. (ii): the incorporation of photocatalysis to reduce the common issue of fouling in ultrafiltration membrane systems [42] •. (iii): the coating of construction tiles with photoactive nanomaterials to get self-cleaning materials a most favourable option that has attracted industrial interests [43] •, etc.

The development of industrial-scale photocatalytic technologies may face some threats, which is quite normal. The competition of other emerging technologies might limit the marketing of photocatalytic products. The ability of a photocatalytic product could lose its effectiveness after a long-time use. Photocatalytic activity may be lost if the starting conditions are changed, e.g., if a huge change in the composition of wastewaters occurs, wherein some compounds may hinder the photoactivity.

Market success also depends on trust so that one or more killer applications of photocatalysis must first be demonstrated.

Conclusion

Although, the literature is stuffed with many recommendations to solve some issues, the future of photocatalytic technology is still unclear yet for large-scale investment. Testing the photocatalytic technology under well-controlled unrealistic lab conditions under homogenous and strong light irradiation might not be a convincing solution. It is expected that the performance of photocatalysts will be greatly reduced in real uncontrolled conditions and the deactivation will be faster in real environments. Therefore, for better photocatalytic technology investment and transfer to real application, the photocatalytic processing from the efficiency of photocatalysts to the deactivation and regeneration steps as well as the solutions to raised technological issues should be tested in real conditions. Sustainability, manufacturing cost of innovative photocatalytic materials and cost-of-ownership (e.g. EE/O) of photocatalytic systems must be duly considered. Test standards should be established in a priority in both academia and industry, thus the unconvincing procedures and testing methods should be avoided. Photocatalytic technology must not be seen as the what-is-needed to solve an environmental problem. It may represent a process step in the frame of a more complex environmental remediation process that, as a whole, may solve a given problem.

Continuous investigation and communication with the industrial side are always helpful to find fruitful ways to apply photocatalysis.

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References

(•) Special interest

(••) outstanding interest

[1] C. Xu, P.R. Anusuyadevi, C. Aymonier, R. Luque, S. Marre, Nanostructured materials for photocatalysis, Chem. Soc. Rev., 48 (2019) 3868-3902.

[2] C.M. Hussain, A.K. Mishra, Handbook of Smart Photocatalytic Materials: Environment, Energy, Emerging Applications and Sustainability, Elsevier (2020).

[3] K. Perović, M. Kovačić, H. Kušić, U. Lavrenčič Štangar, F. Fresno, D.D. Dionysiou, A.L. Bozic, Recent achievements in development of TiO_2-based composite photocatalytic materials for solar driven water purification and water splitting, Materials, 13 (2020) 1338.

[4] Y. Yang, X. Li, C. Zhou, W. Xiong, G. Zeng, D. Huang, C. Zhang, W. Wang, B. Song, X. Tang, Recent advances in application of graphitic carbon nitride-based catalysts for degrading organic contaminants in water through advanced oxidation processes beyond photocatalysis: A critical review, Water Res., (2020) 116200.

[5] C.B. Ong, L.Y. Ng, A.W. Mohammad, A review of ZnO nanoparticles as solar photocatalysts: synthesis, mechanisms and applications, Renew. Sustain. **Energy** Rev., 81 (2018) 536-551.

[6] Y. Naciri, A. Hsini, A. Bouziani, R. Djellabi, Z. Ajmal, M. Laabd, J. Navío, A. Mills, C. Bianchi, H. Li, Photocatalytic oxidation of pollutants in gas-phase via Ag_3PO_4-based semiconductor photocatalysts: Recent progress, new trends, and future perspectives, Crit. Rev. Env. Sci. Tec., (2021) 1-44.

[7] C. Pan, Y. Zhu, A review of $BiPO_4$, a highly efficient oxyacid-type photocatalyst, used for environmental applications, Catal. Sci. Technol., 5 (2015) 3071-3083.

[8] P. Dong, G. Hou, X. Xi, R. Shao, F. Dong, WO_3-based photocatalysts: morphology control, activity enhancement and multifunctional applications, Environ. Sci. Nano, 4 (2017) 539-557.

[9] J. Low, J. Yu, M. Jaroniec, S. Wageh, A.A. Al- Ghamdi, Heterojunction photocatalysts, Adv. Mater., 29 (2017) 1601694.

[10] S.K. Loeb, P.J. Alvarez, J.A. Brame, E.L. Cates, W. Choi, J. Crittenden, D.D. Dionysiou, Q. Li, G. Li-Puma, X. Quan, The technology horizon for photocatalytic water treatment: sunrise or sunset?, Environ. Sci. Technol., 53 (2019) 6, 2937–2947. •• The authors in this report, have discussed critically the issues of photocatalytic technology transfer for water remediation. They examined critically the research progress and they proposed sone suggestions for scientists to bring photocatalysis technology to fruition.

[11] A. Serrà, L. Philippe, F. Perreault, S. Garcia-Segura, Photocatalytic treatment of natural waters. Reality or hype? The case of cyanotoxins remediation, Water Res., (2020) 116543.

[12] J.E. Allan, A. Ferreri, S. Grande, R. Giannantonio, F. Matteucci, Technology Transfer in Nanotechnology, Publication Office of the European Union, Luxembourg2019.

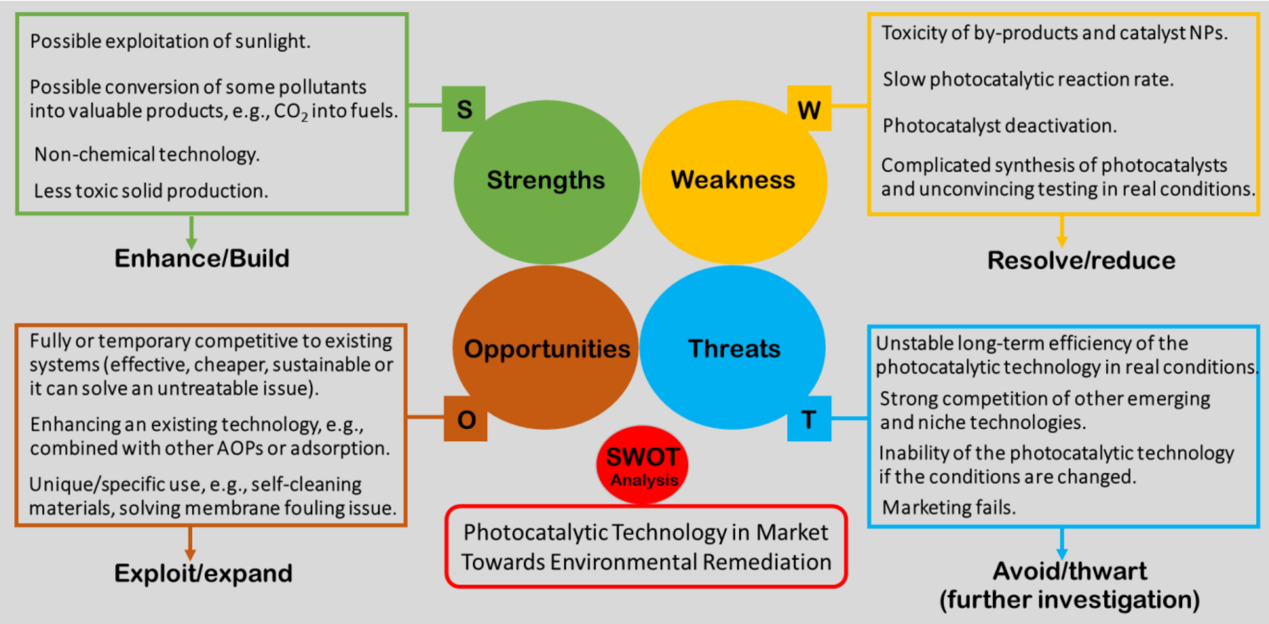
[13] F. Matteucci, R. Giannantonio, F. Calabi, A. Agostiano, G. Gigli, M. Rossi, Deployment and exploitation of nanotechnology nanomaterials and nanomedicine, AIP conference proceedings, AIP Publishing LLC, 2018, pp. 020001.• This report discusses very interesting thoughts about the factors that affect the technology transfer.

[14] Y. Dong, P. Duchesne, A. Mohan, K.K. Ghuman, P. Kant, L. Hurtado, U. Ulmer, J.Y. Loh, A.A. Tountas, L. Wang, Shining light on CO_2: from materials discovery to photocatalyst, photoreactor and process engineering, Chem. Soc. Rev., 49 (2020) 5648-5663.• This is an excellent review showed the research progress on the developpemt of photoactive materials and photo-reactors for CO_2 conversion to fuels.
[15] M. Qiao, X. Wu, S. Zhao, R. Djellabi, X. Zhao, Peroxymonosulfate enhanced photocatalytic decomposition of silver-cyanide complexes using g-C_3N_4 nanosheets with simultaneous recovery of silver, Appl. Catal. B, 265 (2020) 118587.
[16] X. Zhao, X. Liu, C. Yi, J. Li, Y. Su, M. Guo, Palladium nanoparticles embedded in yolk–shell N-doped carbon nanosphere@ void@ SnO_2 composite nanoparticles for the photocatalytic reduction of 4-nitrophenol, ACS Appl. Nano Mater., 3 (2020) 6574-6583.
[17] G. Cerrato, F. Galli, D.C. Boffito, L. Operti, C.L. Bianchi, Correlation preparation parameters/activity for microTiO_2 decorated with SilverNPs for NOx photodegradation under LED light, Appl. Catal. B, 253 (2019) 218-225.
[18] C.L. Bianchi, G. Cerrato, B.M. Bresolin, R. Djellabi, S. Rtimi, Digitally Printed AgNPs Doped TiO2 on Commercial Porcelain-Grès Tiles: Synergistic Effects and Continuous Photocatalytic Antibacterial Activity, Surfaces, 3 (2020) 11-25.
[19] S. Schröder, M.-F. San-Román, I. Ortiz, Dioxins and furans toxicity during the photocatalytic remediation of emerging pollutants. Triclosan as case study, Sci Total Environ., 770 (2021) 144853.
[20] I. Dhada, M. Sharma, P.K. Nagar, Quantification and human health risk assessment of by-products of photo catalytic oxidation of ethylbenzene, xylene and toluene in indoor air of analytical laboratories, J. Hazard. Mater., 316 (2016) 1-10.
[21] T. Zadi, M. Azizi, N. Nasrallah, A. Bouzaza, R. Maachi, D. Wolbert, S. Rtimi, A.A. Assadi, Indoor air treatment of refrigerated food chambers with synergetic association between cold plasma and photocatalysis: Process performance and photocatalytic poisoning, Chem. Eng. J, 382 (2020) 122951.
[22] J.J. Rueda-Marquez, I. Levchuk, P.F. Ibañez, M. Sillanpää, A critical review on application of photocatalysis for toxicity reduction of real wastewaters, J. Clean. Prod., 258 (2020) 120694.
•The authors in this review discussed critically the issue of the formation of by-products in water during photocatalytsis treatement. The authors concluded that photocatalysis might not be a promising technology for the degradation of organic pollutants in water because of the issue of toxic by-products.
[23] E. Friehs, Y. AlSalka, R. Jonczyk, A. Lavrentieva, A. Jochums, J.-G. Walter, F. Stahl, T. Scheper, D. Bahnemann, Toxicity, phototoxicity and biocidal activity of nanoparticles employed in photocatalysis, J. Photochem. Photobiol. C, 29 (2016) 1-28.
[24] D.F. Ollis, Kinetics of photocatalyzed reactions: Five lessons learned, Front. Chem., 6 (2018) 378.
• D.F. Ollis has discussed the kinetics of heterojuncton photocatalysis. This report might be helpful for scientists to speed up the kinectics of photocatalysis.
[25] G. Maniakova, K. Kowalska, S. Murgolo, G. Mascolo, G. Libralato, G. Lofrano, O. Sacco, M. Guida, L. Rizzo, Comparison between heterogeneous and homogeneous solar driven advanced oxidation processes for urban wastewater treatment: Pharmaceuticals removal and toxicity, Sep. Purif. Technol., 236 (2020) 116249.
[26] L. Wang, Q. Zhang, B. Chen, Y. Bu, Y. Chen, J. Ma, F.L. Rosario-Ortiz, R. Zhu, Some issues limiting photo (cata) lysis application in water pollutant control: a critical review from chemistry perspectives, Water res., 174 (2020) 115605.
[27] P. Chen, W. Cui, H. Wang, J. Li, Y. Sun, Y. Zhou, Y. Zhang, F. Dong, The importance of intermediates ring-opening in preventing photocatalyst deactivation during toluene decomposition, Appl. Catal. B, 272 (2020) 118977.

[28] G. Iervolino, I. Zammit, V. Vaiano, L. Rizzo, Limitations and prospects for wastewater treatment by UV and visible-light-active heterogeneous photocatalysis: a critical review. Top Curr. Chem. (2020) 378:7 (2020) 225-264.
[29] M.G. Alalm, R. Djellabi, D. Meroni, C. Pirola, C.L. Bianchi, D.C. Boffito, Towards Scaling-up Photocatalytic Process for Multiphase Environmental Applications: A Review, Catalysts (2021) 11, 562.
•• This a recent review addressing the technological issues and scaling-up of photocatalysis for air and water purification.
[30] G. Zeng, H. You, M. Du, Y. Zhang, Y. Ding, C. Xu, B. Liu, B. Chen, X. Pan, Enhancement of photocatalytic activity of TiO_2 by immobilization on activated carbon for degradation of aquatic naphthalene under sunlight irradiation, Chem. Eng. J., 412 (2021) 128498.
[31] Z. Bian, Y. Feng, H. Li, H. Yu, H. Wu, Adsorption-photocatalytic degradation and kinetic of sodium isobutyl xanthate using the nitrogen and cerium co-doping TiO_2-coated activated carbon, Chemosphere, 263 (2021) 128254.
[32] C. Li, N. Zhu, S. Yang, X. He, S. Zheng, Z. Sun, D.D. Dionysiou, A review of clay based photocatalysts: role of phyllosilicate mineral in interfacial assembly, microstructure control and performance regulation, Chemosphere, (2021) 129723.
[33] G. Hu, J. Yang, X. Duan, R. Farnood, C. Yang, J. Yang, W. Liu, Q. Liu, Recent developments and challenges in zeolite-based composite photocatalysts for environmental applications, Chem. Eng. J., (2021) 129209.
[34] R. Djellabi, B. Yang, K. Xiao, Y. Gong, D. Cao, H.M.A. Sharif, X. Zhao, C. Zhu, J. Zhang, Unravelling the mechanistic role of TiOC bonding bridge at titania/lignocellulosic biomass interface for Cr (VI) photoreduction under visible light, J Colloid Interface Sci., 553 (2019) 409-417.
[35] Q. Wang, Q. Gao, A.M. Al-Enizi, A. Nafady, S. Ma, Recent advances in MOF-based photocatalysis: environmental remediation under visible light, Inorg. Chem. Front., 7 (2020) 300-339.
[36] J. Theerthagiri, S. Lee, K. Karuppasamy, S. Arulmani, S. Veeralakshmi, M. Ashokkumar, M.Y. Choi, Application of advanced materials in sonophotocatalytic processes for the remediation of environmental pollutants, J. Hazard. Mater., (2021) 125245.
• This report shows an overview on progression of sonophotocatalysis in environmental remediation, advanced materials and future views.
[37] Z. Xing, J. Zhang, J. Cui, J. Yin, T. Zhao, J. Kuang, Z. Xiu, N. Wan, W. Zhou, Recent advances in floating TiO2-based photocatalysts for environmental application, Appl. Catal. B., 225 (2018) 452-467.
[38] M.J.M. de Vidales, A. Nieto-Márquez, D. Morcuende, E. Atanes, F. Blaya, E. Soriano, F. Fernández-Martínez, 3D printed floating photocatalysts for wastewater treatment, Catal. Today, 328 (2019) 157-163.
[39] R. Djellabi, X. Zhao, M.F. Ordonez, E. Falletta, C.L. Bianchi, Comparison of the photoactivity of several semiconductor oxides in aerogel floating and suspension systems towards the reduction of Cr(VI) under visible light, Chemosphere, (2021) 130839.
[40] E. Evgenidou, Z. Chatzisalata, A. Tsevis, K. Bourikas, P. Torounidou, D. Sergelidis, A. Koltsakidou, D.A. Lambropoulou, Photocatalytic degradation of a mixture of eight antibiotics using Cu-modified TiO_2 photocatalysts: Kinetics, mineralization, antimicrobial activity elimination and disinfection, J. Environ. Chem. Eng., 9 (2021) 105295.
[41] M. Stucchi, F. Galli, C.L. Bianchi, C. Pirola, D.C. Boffito, F. Biasioli, V. Capucci, Simultaneous photodegradation of VOC mixture by TiO_2 powders, Chemosphere, 193 (2018) 198-206.
[42] H. Zhang, Y. Wan, J. Luo, S.B. Darling, Drawing on Membrane Photocatalysis for Fouling Mitigation, ACS Appl. Mater. Interfaces. 13 (2021) 13, 14844–14865
• A recent excellent review on the role of photocatalysis to solve membrane fouling.
[43] C.L. Bianchi, G. Cerrato, C. Pirola, F. Galli, V. Capucci, Photocatalytic porcelain grés large slabs digitally coated with AgNPs-TiO_2, Environ. Sci. Pollut. Res., 26 (2019) 36117-36123.

• This is a succesful example of photocatalytic technology transfer to real specific application as self-cleaning ceramic materials (under the project name of Digitalife, ENV/it 00140). These materials are used in building sector.

Graphical abstract



Replies to Reviewers comments:

Reviewer 1: In this work, the authors performed a SWOT analysis of photocatalytic technology to assess whether its main strengths can enable it to seize relevant opportunities for large-scale investment and commercialization of photocatalytic solutions. Some contents are interesting. However, there are several concerns that need to be addressed before it may be considered for acceptance. Specific suggestions are provided below.

Thank you for your suggestions and relevant comments.

1. The title didn't reflect the content of the article well.

As suggested, the title was changed as follows:

SWOT Analysis of Photocatalytic Materials Towards Large Scale Environmental Remediation

2. More examples of photocatalytic materials in practical commercial applications are recommended to be introduced.

As suggested, most potential competitive photocatalytic materials for environmental remediation were indicated in the text (introduction section, page 2).

Other potential competitive semiconductors were also well developed and investigated towards such as g-C3N4 [4], ZnO [5], AgPO4 [6], BiPO4 [7] and WO3 [8].

3. More background on "SWOT analysis" are recommended to be added.

As recommended by the reviewer, the following definition was included in the revised version (page 4)

A SWOT analysis is an approach to identify strengths, weaknesses, opportunities, and threats of a raised technology or product for the investment or/and commercialization. The strengths and weaknesses points are assumed usually as internal, while opportunities and threats are considered as external. An appropriate SWOT analysis would be very helpful to transfer the obtained scientific finding to large-scale applied technology.

4. It is recommended to add some tables to more intuitively reflect the key content.

Thank you for valuable recommendation, due to a limited number of pages allowed (we already passed the allowed number of words), we are not able to include further tables and contents due to format restrictions. However, SWOT analysis scheme in Figure 2 completely reflects the key points.

5. The references are a little weak, the following work on improving the potential of photocatalytic materials in practical applications may be helpful to the authors: Water Research 184 (2020) 116200.

The above relevant reference about g-C_3N_4 for environmental remediation was included in the text.

Reviewer 2: In this manuscript, the authors summarized the present situation of the photocatalytic materials and their applications in CO2 reduction, photosynthesis and environmental remediation, especially the challenges towards the commercialization in industry. I think it is very helpful for both the scientific community and industry to understand the big difficult and large gap between the laboratory research and the real demands. Photocatalysis cannot do everything and meet all the demand, however, it's useful if it can be appropriately used in a right way. So, I recommend the accept of this manuscript after minor revision. It's suggested that the authors to make further improvement according to the listed few aspects.

Thank you very much for positive comments and suggestions.

1. Although huge data on photocatalysis has been reported, most of them are hard to compare as lack of unique test standards. Most of the testing apparatus or method are set up by the researchers themselves. The dosage of the catalysts, light intensity, spectra of the light, and reaction temperature are not consistent. And how the NPs are used in real environment

purification have not been adequately investigated, which greatly affect the performance of photocatalysts. It's suggested that the authors can supply more in detail.

As suggested by the reviewer, more details about the above statements were included in the revised version. 'The well-controlled lab conditions can boost the irradiation of photocatalyst surface and mass transfer, and also prevent the unwanted reactions (e.g., adsorption of interfering ions on the surface of photocatalyst). Therefore, for better photocatalytic technology investment and transfer to real application, the photocatalytic processing from the efficiency of photocatalysts to the deactivation and regeneration steps as well as the solutions to raised technological issues should be tested in real conditions.'

2. The generation of by-products and photocatalyst NPs toxicity depends upon the conditions how the photocatalysts are used, the dosage, light intensity, light spectra and the original pollutants.

Yes, indeed, we totally agree with the reviewer, by-products formation and NPs toxicity depend on the photocatalytic system for give conditions (type of pollutants in air/water, concentration, interfering species…etc). Some details were added to the text.

3. Generally, it's effective to treat the low-concentration of ppm-ppb scale pollutants both in air or in water. In this case, it's difficult to use other techniques to remove the ppm-ppb concentration pollutants chemically or physically. So, we need to select the right cases to use it.

Thank you very much for this important point. We totally agree that the removal/oxidation of low concentration of pollutants could be achieved by the photocatalytic technology, unlike many existing technologies. This point was included in the revised version of the paper as one of the strengths (page 6):

2.5. Removal of low concentration of pollutants

In wastewater treatment stations, technologies for the removal of high and low pollutants loaded waters are combined successively. Mainly, in the primary and secondary treatment stages, chemical and physical technologies that are able to remove highly concentrated pollutants are applied, e.g., coagulation, precipitation, biological oxidation, chemical oxidation ...etc. However, these latter technologies cannot remove pollutants at very low concentration, therefore, the use of technologies having the potential to remove low pollutants concentration is recommended. In this case, the use of photocatalytic advanced oxidation could be a potential approach for this purpose.

4. Test standards should be established in a priority both in academia and industry, thus the unconvincing testing methods could be avoided and promote their industrialization.

This point was briefly considered as a recommendation (conclusion section).

Reviewer 3: This manuscript reported a SWOT analysis of photocatalytic technology. The main strengths, weaknesses, opportunities and threats were mentioned. However, the analysis is general and not deep enough, which is basically the known common conclusion. Lack of specific cases and data support, so it is impossible to draw quantitative models or conclusions. Major revision is needed.

Thank you for your comments, many further discussions were added to the revised version and some specific cases were mentioned. Due to a limited number of pages allowed, the authors cannot mention supporting data and large analysis.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: