Photocatalytic Water and Wastewater Treatment

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Foreword

The challenges which result from water stress and inadequate water-related hygiene have taken on an increasing urgency in the past one or two decades, inextricably linked as they are to the water-food-energy nexus, in the midst of which global climate change now has the potential to create the perfect storm. A recent UN report has warned that 'overcoming the crisis in water and sanitation is one of the greatest human development challenges of the early 21st century'.

It is estimated that about one in every six people in the world today lack proper access to clean drinking water, and double that number lack basic sanitation. The awful result is that 2.2 million deaths per year are related to water poverty, many of these children. This humanitarian tragedy is only forecast to grow worse, with more than half of the world's population forecast to face chronic or critical water shortages by 2050, thereby further limiting food supplies and, in turn, limiting economic and social development. There is no doubt that ensuring an adequate water supply to underwrite a sustainable future presents a challenge to engineers of the first magnitude.

Measures which are adopted to meet the needs of individuals must be sustainable if they are going to be truly effective. The United Nations Conference on Sustainable Development in Rio de Janeiro in 2012 created a vision of 'commitment to sustainable development and to ensuring the promotion of an economically, socially and environmentally sustainable future for our planet and for present and future generations'. Water and sanitation are prominent in the document:

> *We recognize that water is at the core of sustainable development as it is closely linked to a number of key global challenges. We therefore reiterate the importance of integrating water into sustainable development, and underline the critical importance of water and sanitation within the three dimensions of sustainable development…We stress the need to adopt measures to significantly reduce water pollution and increase water quality, significantly improve waste-water treatment and water efficiency and reduce water losses. In order to achieve this, we stress the need for international assistance and cooperation.*

The sustainable solution to these challenges will not lie in new and massive water reservoirs, wells, pipelines, or long-distance river transfers, nor will it solely lie in large-scale salty water desalination. A more sustainable development and use of finite freshwater resources is required, which in turn will bring into existence more sophisticated and resource-circular technologies. For example, regions which become more water-stressed as a result of climate change might choose to rely more and more on brackish ground waters or seawater as a primary source of water, this being energy intensive and potentially contributing to the climate problem which drives it. But preferably they will learn to reduce the consumption of, and recycle and reuse, their existing water resources.

An economically, environmentally and socially sustainable technology for water treatment should be cheap and energy-efficient, with little or no chemical consumption, it should facilitate water recycling and reuse that minimizes the direct disposal of wastewater to the aquatic environment, and it should be a technology which can be easily accessed and deployed over a wide range of physical scales. There are many existing technologies which compete to achieve these aims in specific contexts, such as electrodialysis, membrane filtration, adsorption and precipitation, electrochemical reduction and electro-deionization. However, the same technologies may also consume large amounts of energy and, in the process, transfer pollutants between the different fluid phases, wastes, and by-products which are generated.

Since the early 1970s, photocatalytic advanced oxidation processes via heterogeneous semiconductor materials have emerged as a viable technology for the objectives of sustainability, as well as overcoming the aforementioned limitations, and have been the subject of intensive research - in particular, in water/air purification and water splitting. In this process, photons with energy equal to or greater than the band gap of the material are adsorbed by the particulate catalyst, and this results in the formation of a negative conduction band electron and a positive valence band hole. Both of which can participate in a variety of redox reactions in water treatment, but hydroxyl radicals (both surface and bulk) are often considered the dominant oxidant.

The advantages of photocatalysis over other homogeneous-phase AOPs are well documented. When operated under mild conditions as a tertiary treatment, it offers a simple, low energy and sustainable technology which is able to degrade the persistent organic pollutants still remaining in wastewater following conventional biological and physical treatments into water, carbon dioxide and other small molecules. It can also reduce or oxidize inorganic pollutants to harmless substances, and inactivate microorganisms as an effective disinfection process. The benchmark commercial material, titanium dioxide, is cheap, non-toxic and robust. It requires low energy ultraviolet light for its excitation, promising solar applications. It also avoids the need for the supply of treatment chemicals, which is a strong advantage in remote or resource-limited applications. Recently, a surge in articles in the scientific literature – with over 10,000 research articles published in the last twenty years – underwrites this positive image.

Nevertheless, considerable technology transfer problems remain, perpetuating a widening gap between academic vision and industrial application. This timely treatise therefore tries to throw a bridge across this gap. As with many innovations, a well-defined pathway for transferring this unique technology to industry will allow engineers to reap the potential.

An introduction to photocatalysis is provided in Chapter 1. Applications are outlined to water and wastewater treatment, as well as to photolysis for energy production. An overview of the mechanisms and characterization of charge generation are provided, and strategies for improving photocatalytic activity are discussed.

Chapter 2 presents metal organic frameworks as an emerging vehicle to overcome the limitations of established photocatalysts. Mechanisms of action and performance data are presented for a variety of pollutants in aqueous environments, and their rather unique features suggest novel composites and functionalized structures. Their essential features, superior efficiency and critical limits are reviewed.

In Chapter 3, the focus now switches to the photocatalytic reactors themselves, and their different types and configurations. The treatment process results from the interaction of three main components: pollutants, catalysts and source of photons. It is the differences in these components across a wide range of physical scales that make reactor design in photocatalysis so challenging and at the same time so promising.

Photocatalysis is now showing great promise for the treatment of various wastewater streams such as toxic landfill leachates, which is the subject of Chapter 4. Such leachates are extremely deleterious to the environment. After analyzing the characteristics of the leachates, homogeneous and heterogenous treatment processes employing photocatalysis are reviewed. An investigation is made of the effect of reactor operating parameters, and finally the performance of different types of reactor configuration is evaluated.

A life-cycle analysis (LCA) is essential for the development of any sustainable process for water treatment in practice, and such an analysis is presented in Chapter 5 for a solar-driven photocatalytic process for wastewater treatment. Following an overview of the LCA framework, the goal, the scope and the system boundary are all defined. Titanium dioxide as a ubiquitous photocatalyst is given special attention. Key findings on the environmental impacts for solar-driven photocatalytic wastewater treatment are presented.

In the final two chapters, an analysis of patents in the photocatalytic treatment of water and wastewater is presented. Such an analysis helps to reveal insights into the ongoing work in a particular field of technology.

In Chapter 6, photocatalytic materials are first presented. Following an overview of trends in patents, an analysis of patent registration over time and the activity of key players is made. This suggests that Japan first established itself as a pioneer, but nowadays China has assumed the dominant role. Solar energy and nanotechnology are seen as two areas in particular that have received increasing attention in the patent arena.

Finally, in Chapter 7, the patent focus thus switches to solar energy and nanotechnology. Registration and destination data regarding the key players are analyzed, and once again the dominance of China (and her universities in particular), Japan and the USA in this area is revealed. Today, titanium dioxide remains the most widely used nano-material for photocatalysis. In the patent landscape, it is seen that research institutions rather than industrial companies are leading the way.

When Dr Alireza Bazargan invited me to write this foreword, I was very happy to oblige. I remember an Iranian friend of mine once told me a beautiful story about the Iranian sense of honour. I had learned that in Persia, a transaction could be secured on the basis of a single human hair given by the lender to the creditor, which was returned to the lender on completion, without the need for a contract. This meant that a single strand of hair could be used as a form of honourable security. So with that, Ali, I graciously return your strand.

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Oxford, March 2022.

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About the Editor

Dr. Alireza Bazargan was born in Tehran, Iran, and moved to Canada with his family at a young age. After spending most of his childhood and adolescence in Toronto and Vancouver, he returned to Iran and soon after participated in the highly competitive nationwide university entrance exam. After being ranked in the top percentiles among hundreds of thousands of participants, Dr. Bazargan was able to gain admission into the Chemical Engineering Department of Sharif University of Technology.

Near the end of his BSc studies, Dr. Bazargan was awarded a scholarship by IAESTE/DAAD to carry out a research internship at Technische Universität Kaiserslautern in Germany. Subsequently for his Masters, Dr. Bazargan was the recipient of the esteemed TOTAL scholarship allowing him to enter École Nationale Supérieure des Mines de Nantes (now IMT Atlantique) which is one of France's elite grande écoles, to obtain a degree in Project Management for Environmental and Energy Engineering (PM3E).

In order to complete his MSc thesis, Dr. Bazargan received a scholarship from the Hong Kong University of Science and Technology (HKUST), ranked as one of the top 40 universities in the world. Thereafter, Dr. Bazargan received admission from Oxford University for conducting his PhD under the supervision of Prof. Nick Hankins. As fate would have it, the trip to Oxford did not come to pass, but it planted the seed from which the relationship between Dr. Bazargan and Prof. Hankins formed.

Next, Dr. Bazargan accepted a full scholarship from HKUST, in order to continue his research under the supervision of one of the world's most cited chemical engineers, Prof. Gordon McKay. As part of his doctorate, Dr. Bazargan received an additional scholarship to carry out a portion of his work at the University of Cambridge, UK. At Cambridge, Dr. Bazargan was a member of the Paste, Particle and Polymer Processing Group (P4G) in the Department of Chemical Engineering and Biotechnology. Dr. Bazargan received his PhD in January 2015.

Currently, Dr. Bazargan is a faculty member at the School of Environment, University of Tehran, where since 2019 he has been the Head of the Waste Management Research Group as well as a member of the Water and Wastewater Treatment Group. In addition to academic duties such as teaching and supervising graduate students, during his time at the University of Tehran, Dr. Bazargan has founded the Resource Efficiency Laboratory which he currently directs.

As a proponent of a lively academic-industrial interface, Dr. Bazargan co-founded Pyramoon Water and Energy Engineering Company in 2019, which strives to develop novel environmental technologies. The company's accomplishments in the span of just a few years since its inception include the construction of several desalination plants (cumulative capacity of over 20 million liters per day), and the design and development of numerous products such as Dissolved Air Flotation (DAF) with embedded filtration, novel vortex separation units for grit removal, and 3D-printed static mixers to name a few.

Throughout his career, Dr. Bazargan has been the recipient of numerous awards and honors including awards for best presentation, best paper, top instructor and a gold medal among numerous others. In 2015, Dr. Bazargan was inducted into Iran's National Elites Foundation. In the same year, he won the International Young Waste Researcher Award. In 2017, he was a recipient of the Kazemi Ashtiani prize, and in 2018, his first edited book ***A Multidisciplinary Introduction to Desalination*** became a #1 New Release Best Seller on Amazon.com. Since 2020, Dr. Bazargan has also been a contractor and consultant to the United Nations Development Program, whereby he provides the UN offices in Iran with expert opinion.

During the years, Dr. Bazargan has provided professional services to numerous companies and organizations including The Science and Technology Vice Presidency of the Government of Iran, The Nanotechnology Initiative Council of Iran, The Golrang Industrial Group, Hard Tech Startup Accelerator, Noor Vijeh Company, and Peako STEP Ltd as its exclusive representative in Iran for Biomass Gasification units. Dr. Bazargan is a native speaker of English and Farsi, has a working proficiency in French, and a basic understanding of Mandarin Chinese and Arabic. Naturally, his colorful past and experiences have made him uniquely suited for collaborations with international researchers and multinational companies alike.