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# Grand challenges present great opportunities in environmental catalysis

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## Challenges

We are living in a time full of grand challenges that stifle us from achieving Sustainable Development Goals: climate change, resource depletion, water shortage, food crisis, and pandemic diseases, just to name a few. The ever-growing productivity of our society brings wealth and quality of life, but also induces pollution and other environmental issues that have often been major causes of the grand challenges we face today (Lou et al., 2022). These impact people unequally, depending on their wealth and living environments, thus further exacerbating the disparities among populations. Addressing these challenges calls for a holistic approach integrating more efficient pollution control, cleaner production, and greener processes. Environmental catalysis, by developing catalysts having environmental significance, emerges to play a key role in meeting these challenges (Rodríguez-Padrón et al., 2019). Catalytic processes are used to transform contaminants in water, soil, and air for pollution prevention and remediation, produce green energy, reduce $CO_2$, recycle and reuse waste, and rapidly detect pathogens in the environment. All these can be achieved *via* catalysis, the process that increases the rate of a reaction through the action of a catalyst, with greater efficiency and selectivity at the expense of less material and energy input. Identified below are some examples that may illustrate the opportunities in environmental catalysis and the great potential it holds to help building a sustainable future for all.

## Opportunities

Environmental catalysis has long been applied in pollution control by degrading pollutants in different environmental media. Fenton's reagent, developed in the 1890s, is one of the most well-known and probably the longest-used environmental catalysis methods. Hydroxyl radicals produced by $H_2O_2$ disproportionation with ferrous ions as the catalyst have been used as an advanced oxidation process (AOP) to degrade contaminants in water. Similarly, catalytic activation of persulfate has been devised to produce various reactive oxygen species and sulfate radicals that can be applied in AOPs to degrade a variety of contaminants in water and soil (Lee et al., 2020). Advanced reduction processes (ARPs) have also been proposed for wastewater treatment by producing highly reactive reducing radicals through activation of reducing agents by ultraviolet (UV) light, electron beam or ultrasound (Vellanki et al., 2013), which exhibit high reactivity with certain pollutants in water.

Catalysis offers specificity and efficiency required to address various contaminants of emerging concern (CEC) that cannot be readily treated by conventional technologies. Some CECs are biologically active, even when they are present in the environment at extremely low concentrations; these include natural hormones and a variety of chemicals mimicking hormonal activities, also known as endocrine disrupting chemicals (EDCs). Efficient treatment of such bioactive micropollutants to no-harm endpoints requires specificity and efficiency that only environmental catalysis can afford. A variety of studies have developed enzyme catalysis procedures to degrade EDCs in water, soil, and biosolids, including natural and synthetic hormones, pharmaceuticals, and personal care products (Zhong et al., 2019). Enzyme catalysis is just one form of biocatalysis that, broadly speaking, also includes the use of whole cells to speed up reactions. In this regard, the microbial processes widely used in municipal wastewater treatment are environmental biocatalysis technologies. Microbes are involved in nitrification and denitrification processes to pull excessive nitrogen out of water. Bioremediation has also been widely practiced, which involves microbes to metabolize pollutants in soil and water, including chlorinated solvents, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pesticides, and arsenic (Arora, 2019).

Environmental catalysis has also been tapped to degrade chemicals of persistent nature that cannot be easily degraded otherwise. One prominent example is per- and polyfluoroalkyl substances (PFAS) that have heightened the public concern because of their global distribution, environmental persistence, bioaccumulation, and toxicity. PFAS, often referred to as "forever chemicals", are particularly recalcitrant because of their strong C-F bonds, and thus their degradation for treatment purpose is extraordinarily challenging. Recent studies have indicated the effectiveness of electrochemical oxidation (EO) in degrading PFAS in water. EO is essentially one form of electrocatalysis in which the anode serves as the catalyst that facilitates the transfer of one electron from PFAS to yield radicals that further react with hydroxyl radicals and other reactive species also produced on the anode (Shi et al., 2019). PFAS were also found effectively transformed during enzyme-catalyzed oxidative humification reactions (ECOHRs) (Luo et al., 2018) and UV-based ARPs (Cui et al., 2020). Microbial processes degrading PFAS have also been reported recently (Zhang et al., 2022).

Photocatalysis has long been a major topic of research in environmental catalysis. Numerous studies in the past few decades have focused on water treatment by AOPs enabled by heterogeneous photocatalysis with semiconductor catalysts, such as titanium dioxide ($TiO_2$) (Lou et al., 2022). The particulate catalyst absorbs photons with energy equal to or greater than its band gap, resulting in the formation of a conduction band electron and valence band hole pair. The electrons or holes thus formed are able to participate in a suite of redox reactions relevant to water treatment and disinfection, with hydroxyl radicals considered the dominant oxidant. Studies in this area have evolved to improve the semiconductor catalyst performance by modifying $TiO_2$ or using alternative materials for better harness of solar irradiation and higher quantum yield, although their applications appear to trail behind, partly hindered by technology transfer barriers (Loeb et al., 2019).

The use of catalysis for air pollution control has been remarkably successful in consumer market. The heterogeneous catalysts capable of simultaneously converting carbon monoxide, unburned hydrocarbons and nitrogen oxides have been used for nearly 40 years in three-way converters (TWCs) to control automobile emissions (Yentekakis and Dong, 2020). Catalytic conversion technologies have also been developed to control the emissions of other specific air pollutants and greenhouse gases, such as volatile organic compounds (VOCs), $SO_x$, $H_2S$, dioxins, and aromatic hydrocarbons from industries and waste incineration, and biogas from landfill and wastewater treatment plants. Catalytic emission control is still under active research for improved performance with reduced cost.

In the face of the grand challenges, environmental catalysis plays a key role not only in pollution control and remediation, but also in recycle and reuse of waste. Heterogeneous catalysis and biocatalysis have been used to convert plastics and other carbonaceous wastes into usable monomers, fuels, synthesis gas, and adsorbents under more sustainable conditions than thermal degradation (Mark et al., 2020). The ongoing studies are focused on the development of catalytic processes to reach higher recovery rates and valorization. More complicated waste like biosolids from wastewater treatment or animal production can also be recycled for its agronomic value in the form of land application, while avoiding the economic and environmental costs associated with disposal by landfill or incineration. Biocatalysis has been used to ameliorate the nutrient value of biosolids and alleviate the risk of contaminant release (Li et al., 2022). Microbial fuel cell involving biocatalysis and electrocatalysis produces electricity while removing nitrogen and carbon from wastewater. A recent study reported a scheme using electrocatalysis to pull nitrate from wastewater and convert it into a concentrated form of ammonium that can be used as fertilizer (Gao et al., 2022).

In addressing the grand challenges, environmental catalysis does not stop at only cleaning and reducing the mess after it has been produced, but also plays a central role in developing cleaner production and greener processes that reduce environmental footprints by utilizing renewable, cheap, and readily available raw materials while generating few to no undesired by-products. Biocatalysis usually acts under mild reaction conditions, and cascade enzymatic processes have been increasingly applied to produce industrial products, pharmaceuticals, and biofuel from plant-based materials with reduced cost and environmentally friendly processes (Bell et al., 2021). With the discovery of sustainable electrocatalysts having enhanced activity and increased stability, electrocatalysis can now efficiently split water to generate hydrogen as green energy, as well as reduce $CO_2$ to produce low-carbon fuels (Liu et al., 2022). Photocatalysis is also under active research for production of $H_2$ or low-carbon fuels from photo-water splitting and $CO_2$ reduction, although the efficiency of both processes still needs improvement for application (Loeb et al., 2019).

There are many catalysis studies that have environmental ramifications other than pollution control and cleaner production. Catalysis occurring in the natural environment induces redox transformations of both organic and inorganic substances, and thus profoundly impacts their environmental fate and risks. Studies aimed at understanding such natural catalysis processes are of paramount importance for more sensible environmental risk assessment and may inspire design of more efficient catalysis processes. Catalysis has also been used in chemical and biological analyses that have environmental significance. For example, enzyme catalysis is involved in both enzyme-linked immunosorbent assay (ELISA) and polymerase chain reaction (PCR) based methods for detection of SARS-CoV-2 (Covid-19) in human and various environmental samples.

## Outlook

Rapid advancements in chemistry, biochemistry, and material science are enabling more efficient and sustainable catalysis and better understanding of the catalytic mechanisms. The immense progress of advanced characterization techniques in combination with rapidly growing computation power and algorithms provide powerful tools for elucidating the mechanisms involved in catalysis. This coupled with the advance in nanotechnology and controllable synthesis enable rational design of multi-component catalysts with nanostructures manipulated towards ultra-active, selective, durable, and cost-effective heterogenous catalysis applicable to innovative photo-, electro-, and thermochemical processes particularly useful in addressing the grand challenges.

The trend in photocatalysis focuses on efficient utilization of solar irradiation with improved catalytic performance towards sunlight-driven pollutant decomposition and a solar based economy. This can be achieved by design and modification of photocatalysts at the nanoclusters and single atom level with newly available synthesis and characterization tools and improved understanding of the catalytic processes. Photocatalytic $CO_2$ reduction is of a particular interest, because solar energy is infinite, while atmospheric $CO_2$ is a major cause of climate change. Solar-driven reduction of $CO_2$ into chemicals and fuels offers the promise of addressing global warming and energy crisis simultaneously. Taking advantage of nano-clusters and single-atom catalysis, more efficient catalysts are also being developed to activate $H_2O_2$ and persulfate for environmental applications of AOPs (Wu and Kim, 2022), as well as to innovate catalysis for emission control and other applications (Li et al., 2020).

Electrooxidation is an electrocatalysis technology promising for distributed water treatment applications, because it is operable at ambient conditions, applicable to a wide variety of pollutants, and easy to manipulate and automate. The application of electrooxidation in water treatment is however limited by the availability of suitable anode materials that have to meet a few stringent requirements in stability, conductivity and electrocatalytic activity. In particular, a high overpotential for oxygen evolution is desired, so that less energy is spent on water oxidation, contrary to the application of electrocatalysis for water splitting where lower oxygen evolution potential is optimal. Research efforts continue to innovate electrodes and system integration for various electrocatalysis applications (Liu et al., 2022), including contaminant decomposition, waste recycling, solar and wind energy harness, and electrosynthesis.

Biocatalysis research is also rapidly advancing, fueled by progress in protein engineering, genomic database mining and computational methods. Advances in enzyme discovery, *de novo* design, and directed evolution expand the range of accessible biochemical reactions catalyzed by enzymes having high efficiency and selectivity (Bell et al., 2021). Multistep enzyme cascades can now be designed to achieve goals previously unattainable, including the production of chemicals and biofuel from plant-based materials and the decomposition of persistent organic pollutants more efficiently without forming harmful byproducts. There is also a trend of utilizing enzyme-mimicking nanomaterials to overcome the limitations of applying natural enzymes in industrial and environmental applications. In particular, peptides have recently been used in construction of simple biomolecular nanozymes, also known as bionanozymes, for biocatalysis applications (Makam et al., 2022). The peptide sequences are simpler than their natural counterparts but retain sufficient complexity for folding and function. This enables fine tuning the catalytic center and mechanism, and thus paves a way for designing and fabricating highly selective and efficient bionanozymes for specific applications, for example, degradation of micropollutants at very low concentrations.

The advance in catalyst design and synthesis provides more means to develop highly efficient, yet low-cost catalysis applicable to pollution control and remediation. This is particularly meaningful, because low-cost catalysis makes technologies like water disinfection and soil remediation more universally available. Under-developed regions often suffer more from environmental pollution problems, causing environmental health disparities. Low-cost catalysis technologies can help to address this fundamental disparity, a major factor contributing to social inequalities. Nanozymes, metal-organic frameworks, and doped carbon materials are examples of potential low-cost catalysts. Progresses in these areas will bring more environmental applications of low-cost catalysis.

Environmental catalysis is a multidisciplinary research subject that is rapidly advancing. Taking advantage of the ongoing science and technology advancements in related fields, researchers from various disciplines are developing more efficient and sustainable catalysis applicable to pollution control, cleaner production, and greener processes. These will collectively contribute to a holistic approach to addressing the grand challenges that we are facing today in order to attain a sustainable future for all. This report only identifies a few examples illustrating the opportunities and potential of environmental catalysis, whose scope is still evolving and may only be defined by the many researchers devoting to its study. The critical role of environmental catalysis in the realm of sustainable development represents a remarkable privilege, as well as a significant responsibility, vested in those conducting research in this vibrant, developing field.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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