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Grand challenges in environmental engineering

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Introduction

Environmental issues such as water pollution, climate change, soil erosion, hazardous wastes, resource depletion, and biodiversity loss have been at the front of global concerns for many years. These environmental problems pose a severe threat to the quality of human life and ecosystem sustainability, and thus protecting the natural environment has become an important task for individuals, organizations, and governments. Encouragingly, environmentalists and engineers have made great achievements in the development of science, theories, and techniques for environmental remediation. As an involved interdisciplinary field, environmental engineering embraces broad scientific disciplines such as chemistry, biology, physics, geology, ecology, engineering (e.g., materials, computers, and civil engineering), mathematics, and economics to develop practical solutions for treating and controlling natural and anthropogenic contaminants across all environmental matrices (i.e., water, air, soil, and sediment), thus sustaining the health of all living things and improving the quality of the ecosystem.

The *Frontiers in Environmental Engineering* significantly push the boundary of environmental protection to a high level. Typically, breakthroughs in wastewater management, air pollution control, soil remediation, and waste utilization have marked the improvement of humanity's standards of living. For instance, the anaerobic ammonium oxidation technology (anammox) innovates the direct oxidation of ammonia to nitrogen gas (N_2) without the generation of toxic nitrous oxide (N_2O, a kind of greenhouse gas) (Dalsgaard et al., 2003; Kuypers et al., 2003; Kartal et al., 2011), which importantly regulates the nitrogen circle in the wastewater treatment process. Carbon dioxide (CO_2), a major part of greenhouse gas, has been recognized as the main reason for climate change. To manage the high carbon emission in the atmosphere, the carbon capture, utilization, and storage technology (CCUS) which involves the capture of CO_2 from anthropogenic sources, and distribution of captured CO_2 to different utilization or storage processes has shown an important role in achieving the carbon-neutral goal (Bachu, 2016; Tapia et al., 2018). Heavy metal(loid) polluted soils attract global public attention owing to growing concerns about the security of groundwater and agricultural products. Phytoremediation has gained increasing attention for its cost-effectiveness, eco-friendliness, and good efficiency. Currently, ~ 500 plant species have been identified as hyperaccumulators of metal(loid)s and employed for soil remediation (Li et al., 2019; Gavrilescu, 2022). Also, the controllable pyrolysis of plastic wastes to form value-added carbon-based functional materials can not only help to manage hazardous solid waste but also reduce the fabrication cost of new materials (Yao et al., 2021; Chen et al., 2022). The close-loop reutilization of solid wastes accelerates the circulation of substances and limits solid wastes' negative environmental impacts simultaneously. Certainly, these achievements that employ different practical techniques for pollution control help to alleviate the pressing environmental problems, but the current status is still far from satisfactory. To build a pollution-free society and a sustainable ecosystem, there remain some grand challenges in environmental engineering.

Grand challenges in environmental engineering

Environmental engineering represents one of the most important domains for a sustainable human society. Success in environmental engineering requires joint efforts by pollution reduction methodology, nanotechnology, engineering design, etc. Herein, several grand challenges in advancing environmental engineering are highlighted to identify future directions in this field. Also, disseminating excellent achievements which aim at meeting these challenges is the central mission of the new journal *Frontiers in Environmental Engineering*.

Challenge 1: Accurate identification of contaminants

Accurately identifying contaminants in the environment is a prerequisite to determining the pollution level and analyzing the effectiveness and mechanism of the degradation process. Currently, it is problematic to detect new pollutants in diverse environmental matrices with a wide concentration range, especially emerging pollutants (e.g., micro(nano)plastics, viruses, pharmaceuticals, bacteria, pesticides, nanomaterials, surfactants, industrial additives, personal care products, and perfluorinated compounds) and their derivatives (Khan et al., 2020). In addition, pollutants with similar physicochemical properties (e.g., density, shape, chemical structure, molecular weight) generally co-occur in the environment, which makes it hard to identify them separately. Therefore, developing advanced analytical methods and facilities with high sensitivity and selectivity to gain precise identification, confirmation, and quantification of different known and unknown pollutants is highly demanded.

Challenge 2: Cost-effective and safe functional materials/chemicals for pollution control

For most pollutant degradation/control processes, functional materials and/or chemicals are required. For instance, in wastewater purification, adsorbents are usually used to extract organic and inorganic pollutants, catalysts are needed in the photocatalysis, electrocatalysis, thermocatalysis, advanced oxidation processes, and advanced reduction processes, and flocculants are used for the flocculation process. The application of these functional materials/chemicals plays a critical role in enhancing purification efficiency. However, many materials/chemicals are prepared with complicated processes and high costs, which significantly limits their large-scale applications. To this end, developing cost-effective functional materials/chemicals from earth-abundant substances/wastes with facile methods is urgent for sustainable pollution control.

Aside from cost-effectiveness, the environmental risk of functional materials/chemicals also should be concerned. The transformation of functional materials/chemicals would release nanoparticles, metal ions, and organics into the environment, which leads to secondary pollution. Such issues are important for the practical applications of functional materials/chemicals but have not received enough attention. For future studies, it is recommended to design stable functional materials/chemicals and put forward efficient strategies to manage the potential secondary pollution.

Challenge 3: Atomic, molecular, and genetic level understanding for mechanistic studies

The in-depth understanding of pollutant degradation mechanisms remains a big challenge, especially in complex environmental systems. For chemistry-involved remediation processes, it is highly encouraged to uncover the degradation mechanism on an atomic and molecular level by utilizing state-of-the-art experimental (microscopy, spectroscopy) and computational tools (molecular dynamic simulations, density functional theory computations). Moreover, *in situ* techniques are vital to studying environment-sensitive processes like thermocatalysis and electrocatalysis, which can provide meaningful information about (unstable) reaction intermediates and thus enhance the understanding of reaction pathways. Differently, bioremediation processes need the application of molecular-biology-based techniques to investigate the (micro) organism-pollutant interaction on a genetic level. Good knowledge of the underlying degradation mechanism can help to create new knowledge in this field and guide the design of high-performance functional materials/chemicals.

Challenge 4: Integrated technologies

Generally, it is difficult to treat multiple pollutants with an individual method, owing to the differences in pollutants' properties, such as species, density, concentration, toxicity, and chemical resistance. Accordingly, the treatment of most real environmental problems necessitates the development of integrated technologies. Benefiting from the advantage of different methods, integrated strategies can attain upgraded degradation/remediation performance. To date, the coupling of electrochemical, physical, biological, and other processes has been successfully implemented for environmental remediation. The future optimization of integrated technologies should take effectiveness and cost into consideration, as well as the environmental impact.

Challenge 5: Artificial intelligence and environmental engineering

With the speedy development of computational technology, artificial intelligence (AI) techniques like artificial neural networks, adaptive neuro-fuzzy systems, and Fuzzy logic emerge as powerful tools in the management of complicated environmental systems. AI-based prediction models have been successfully used for water/wastewater remediation, air pollution, soil protection, and solid waste management (Yetilmezsoy et al., 2011; Alam et al., 2022; Garg et al., 2022). A main challenge that lies in the further expansion of AI techniques is the availability and selection of valid data, which governs the efficiency, precision, and reproducibility of AI techniques-guided prediction, optimization, and decision-making processes. Also, benchmarks/frameworks are required to recognize the performance of various AI tools in different sections of environmental engineering and to form optimal stand-alone or hybrid AI techniques for applications in real environmental engineering.

Challenge 6: Closed-loop control for waste valorization

In traditional environmental management concepts, solid, liquid, and gaseous wastes are generally recognized as a burden on our society because of their hazardous nature. Alternatively, recent achievements in converting solid, organic, and gaseous wastes into value-added materials, chemicals, and energy fuels have profoundly unleashed the inherent potential of wastes. Such "waste-to-wealth" practices help to build a closed-loop approach for the valorization of wastes and accelerate the circular economy, which also innovates the conventional environmental management process. Jointly considering the environmental, technical, and economic aspects is thus suggested to maximize the waste valorization scheme and benefit sustainable pollutant management.

Conclusion

The area of environmental engineering is important in sustaining the development of the natural ecosystem. There is an increasing demand for progress in advanced theories, methods, materials, techniques and facilities for solving current environmental problems. Such a line of research will positively boost the development of environmental engineering for a healthy and sustainable world.

Author contributions

B-JN is the exclusive author of the Field Grand Challenge article.

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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