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Introduction to CO_2 capture and conversion

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An introduction to the *Nanoscale* themed collection on CO_2 capture and conversion, featuring exciting research on advanced nanoscale materials and reactions.

Greenhouse gases such as carbon dioxide (CO_2), methane, nitrous oxide, and fluorinated gases (hydrofluorocarbons, sulfur hexafluoride, nitrogen trifluoride, perfluorocarbons) are entering the atmosphere in different quantities as a result of anthropogenic agricultural and industrial activities. All these gases can trap heat in the atmosphere resulting in global warming. Despite CO_2 having the lowest global warming potential (GWP),[1] a measure used to compare the abilities of different gases to trap heat in the atmosphere, it is the most significant greenhouse gas because of its longevity in the atmosphere and the enormous amount released into the atmosphere as a result of large scale burning of fossil fuels for energy and manufacturing uses. The potential impact from CO_2 emitted to the atmosphere could linger for much longer than that of other greenhouse gasses.[2]

The correlation between the increase in atmospheric CO_2 and higher surface temperature was first proposed by Arrhenius in 1896.[3,4] In 1938, Callendar demonstrated that the Earth's land surface was warming and attributed this phenomenon to the production of CO_2 by the combustion of fossil fuels.[4] In 1971, Sawyer raised the concern that mass discharge of CO_2 from human activities could affect the heat balance of the Earth.[5]

There were about 34.9 Gt CO_2 emitted in 2021.[6] The sustainable natural ways of sequestering CO_2 from the atmosphere through photosynthesis by plants, carbonate formation *via* CO_2 binding with minerals and adsorption of CO_2 by water can provide 37% CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C.[7] While forestlands, swamps, soils and oceans can partially remedy the adverse effects of the released CO_2, they cannot combat climate change. In addition, the elevated levels of CO_2 can affect photosynthesis, carbon partitioning,[8] and acidification of oceans.[9] Therefore, deep decarbonization of the global economy is required for realization of both the 2.0 °C and 1.5 °C scenarios[9] that restrict warming to 2.0 °C or 1.5 °C above preindustrial levels in order to mitigate the most dangerous and irreversible effects of climate change. This will require both climate policy reinforcements[10] and innovation in materials design and technologies. However, since major changes in industrial practices and human behavior are not expected to occur in the next few decades,[11] scientific breakthroughs in CO_2 capture, conversion, storage, and utilization are the most promising game-changers that can alter the trajectory of rapid deterioration of the global environment.

One of the biggest obstacles in CO_2 mitigation is its capture from dilute sources.[12] CO_2 capture from dilute sources using advanced sorbents and its further conversion into carbon-based chemicals and fuels is recognized as a necessary step in addressing the continuous increase in CO_2 release into the atmosphere. Currently implemented large scale post-combustion amine scrubbing technology[13] based on formation of carbonate salts with amines suffers from a few drawbacks such as high consumption of water, degradation of solvents and corrosion of the equipment. High surface area sorbents, including macromolecule structures, are currently being explored as a class of materials to replace amine scrubbing technology.

While CO_2 utilization as a feedstock can be seen as a cleaner alternative to hydrocarbons in industrial or chemical processes,[14] its successful implementation at scale faces economic challenges. The issue is that CO_2 is a highly stable molecule that requires significant energy input for CO_2 valorization. For example, dry methane reforming, a conversion process of carbon dioxide and methane (the two main gases responsible for global warming) known since 1928,[15] can play an important role in meeting global energy and climate goals.[16] However, catalytic dry methane reforming takes place at very high temperatures and high pressures which challenges the stability of the catalysts. The water–gas shift[17] and lower temperature Sabatier[18] reactions producing carbon monoxide and methane (lower value), respectively, from the reaction of CO_2 with hydrogen have attracted

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renewed interest as possible processes for mitigation of CO_2.[17,19] These reactions also require high temperatures and restriction of the production of undesired products. More active, stable, and selective catalysts are needed to make CO_2 valorization through thermochemical routes become an economically suitable technology at scale.

Upgrading CO_2 to hydrocarbons using renewable energy sources is a promising solution for closing the carbon cycle. The chemical and physical principles of heterogeneous photocatalytic CO_2 transformation are rather well understood; however, significant improvements in the efficiency of optochemical engineering of CO_2 photocatalysis at scale are required.[20] Photoactive catalysts can also be designed from enzymes and bio-organisms such as algae and bacteria. Electrochemical transformation of CO_2 into hydrocarbons is another attractive carbon net-zero process as the electricity required to catalyze the process can be easily obtained from renewable sources.[21,22]

Understanding CO_2 capture and conversion has been essential in our efforts to build a carbon neutral/negative society and to achieve energy sustainability. Recent studies have shown that CO_2 can be captured from industrial waste in more energy efficient manners and be converted more selectively *via* various catalytic processes to reusable chemicals and fuels. This themed issue invites experts in the field to publicize the latest state-of-the-art progress they have made in CO_2 capture and conversion. Their work focuses on selective CO_2 capture *via* carbonate formation, and CO_2/carbonate conversion *via* thermochemical, electrochemical, photochemical, and biological means to reusable forms of carbon. The collection also includes papers aiming to understand structure–property correlation to further improve the capture and conversion efficiencies. We hope you enjoy reading these articles and find them useful in your on-going endeavors in CO_2 capture and conversion.

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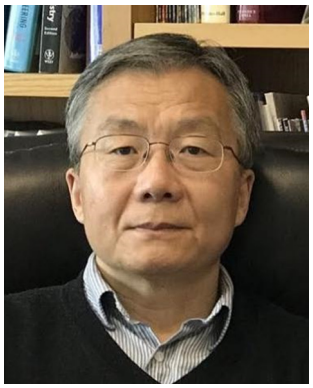
Ah-Hyung (Alissa) Park is the Lenfest Earth Institute Professor of Climate Change and Department Chair of Earth and Environmental Engineering & Professor of Chemical Engineering at Columbia University. She is also the Director of the Lenfest Center for Sustainable Energy at the Earth Institute. Her research focuses on sustainable energy and materials conversion pathways with an emphasis on integrated Carbon Capture, Utilization and Storage (CCUS) technologies addressing climate change. The Park group is also working on direct air capture of CO_2 and negative emission technologies including BioEnergy with Carbon Capture and Storage (BECCS) and sustainable construction materials with low carbon intensity. Park has received a number of professional awards and honors including the Shell Thomas Baron Award in Fluid–Particle Systems at AIChE PTF (2022), the US C3E Research Award (2018), the PSRI Lectureship Award at AIChE PTF (2018), the ACS Energy and Fuels Division – Emerging Researcher Award (2018), the International Partnership Award for Young Scientists of Chinese Academy of Sciences (2018), the ACS WCC Rising Star Award (2017), and the National Science Foundation CAREER Award (2009). Park has led a number of global and national discussions on CCUS including the Mission Innovation Workshop on Carbon Capture, Utilization and Storage in 2017 and the National Petroleum Council CCUS Report in 2019. She is currently a member of the National Academies Committee on Carbon Utilization Infrastructure, Markets, Research and Development. Park is a Fellow of the American Institute of Chemical Engineers (AIChE), the American Chemical Society (ACS), the Royal Society of Chemistry (RSC) and the American Association for the Advancement of Science (AAAS).



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