

Introduction to CO<sub>2</sub> capture and conversionCite this: *Nanoscale*, 2023, **15**, 855Elena Shevchenko,<sup>a,b</sup> Ah-Hyung Alissa Park,<sup>c</sup> Shouheng Sun<sup>d</sup> and Tierui Zhang<sup>e,f</sup>

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An introduction to the *Nanoscale* themed collection on CO<sub>2</sub> capture and conversion, featuring exciting research on advanced nanoscale materials and reactions.

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Greenhouse gases such as carbon dioxide (CO<sub>2</sub>), 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<sub>2</sub> having the lowest global warming potential (GWP),<sup>1</sup> 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<sub>2</sub> emitted to the atmosphere could linger for much longer than that of other greenhouse gasses.<sup>2</sup>

The correlation between the increase in atmospheric CO<sub>2</sub> and higher surface temp-

erature was first proposed by Arrhenius in 1896.<sup>3,4</sup> In 1938, Callendar demonstrated that the Earth's land surface was warming and attributed this phenomenon to the production of CO<sub>2</sub> by the combustion of fossil fuels.<sup>4</sup> In 1971, Sawyer raised the concern that mass discharge of CO<sub>2</sub> from human activities could affect the heat balance of the Earth.<sup>5</sup>

There were about 34.9 Gt CO<sub>2</sub> emitted in 2021.<sup>6</sup> The sustainable natural ways of sequestering CO<sub>2</sub> from the atmosphere through photosynthesis by plants, carbonate formation *via* CO<sub>2</sub> binding with minerals and adsorption of CO<sub>2</sub> by water can provide 37% CO<sub>2</sub> mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C.<sup>7</sup> While forestlands, swamps, soils and oceans can partially remedy the adverse effects of the released CO<sub>2</sub>, they cannot combat climate change. In addition, the elevated levels of CO<sub>2</sub> can affect photosynthesis, carbon partitioning,<sup>8</sup> and acidification of oceans.<sup>9</sup> Therefore, deep decarbonization of the global economy is required for realization of both the 2.0 °C and 1.5 °C scenarios<sup>9</sup> 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<sup>10</sup> 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,<sup>11</sup> scientific breakthroughs in CO<sub>2</sub> 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<sub>2</sub> mitigation is its capture from dilute sources.<sup>12</sup> CO<sub>2</sub> 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<sub>2</sub> release into the atmosphere. Currently implemented large scale post-combustion amine scrubbing technology<sup>13</sup> 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<sub>2</sub> utilization as a feedstock can be seen as a cleaner alternative to hydrocarbons in industrial or chemical processes,<sup>14</sup> its successful implementation at scale faces economic challenges. The issue is that CO<sub>2</sub> is a highly stable molecule that requires significant energy input for CO<sub>2</sub> 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,<sup>15</sup> can play an important role in meeting global energy and climate goals.<sup>16</sup> 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<sup>17</sup> and lower temperature Sabatier<sup>18</sup> reactions producing carbon monoxide and methane (lower value), respectively, from the reaction of CO<sub>2</sub> with hydrogen have attracted

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renewed interest as possible processes for mitigation of CO<sub>2</sub>.<sup>17,19</sup> 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<sub>2</sub> valorization through thermochemical routes become an economically suitable technology at scale.

Upgrading CO<sub>2</sub> to hydrocarbons using renewable energy sources is a promising solution for closing the carbon cycle. The chemical and physical principles of heterogeneous photocatalytic CO<sub>2</sub> transformation are rather well understood; however, significant improvements in the efficiency of optochemical engineering of CO<sub>2</sub> photocatalysis at scale are required.<sup>20</sup> Photoactive catalysts can also be designed from enzymes and bio-organisms such as algae and bacteria. Electrochemical transformation of CO<sub>2</sub> into hydrocarbons is another attractive carbon net-zero process as the electricity required to catalyze the process can be easily obtained from renewable sources.<sup>21,22</sup>

Understanding CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> capture and conversion. Their work focuses on selective CO<sub>2</sub> capture *via* carbonate formation, and CO<sub>2</sub>/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<sub>2</sub> capture and conversion.

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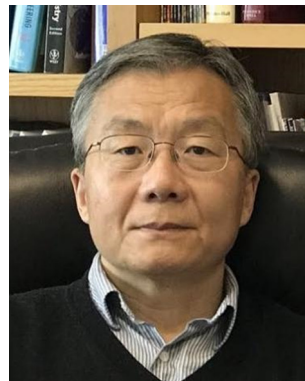
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