Charged sorbents for efficient CO_2 removal

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Confronting the climate change crisis requires us to go beyond just reducing our greenhouse gas emissions, as we must also develop technologies that allow us to remove greenhouse gas from the atmosphere for us to realistically achieve net-zero emissions targets and to thus limit global warming. Negative emission technologies with a cumulative CO_2 capture capacity of 450–1000 gigatons (Gt) between 2010 and 2100 are required to achieve the more stringent 1.5°C temperature rise target.[1] The idea of direct air capture (DAC), using CO_2 scrubbers containing a sorbent material that selectively binds CO_2 from ambient air, was one of the earliest methods developed for plausibly removing CO_2 from the atmosphere, and was first explored as a tool for managing climate risk back in the 1990s by Klaus Lackner.[2] The sorbent material can be regenerated by heating and/or applying a vacuum, thereby allowing CO_2 to be extracted from the atmosphere and then collected for geologic sequestration or conversion. In more recent years, motivated by the climate crisis, substantial advances have been achieved in DAC technology, with an aspiration of constructing economically viable large-scale DAC systems for capturing gigatons of CO_2 from the atmosphere annually. The ability to deploy DAC systems at a massive scale is critical for realizing the carbon removal capacity required to mitigate the impacts of anthropogenic greenhouse gas emissions and achieve global climate change targets.

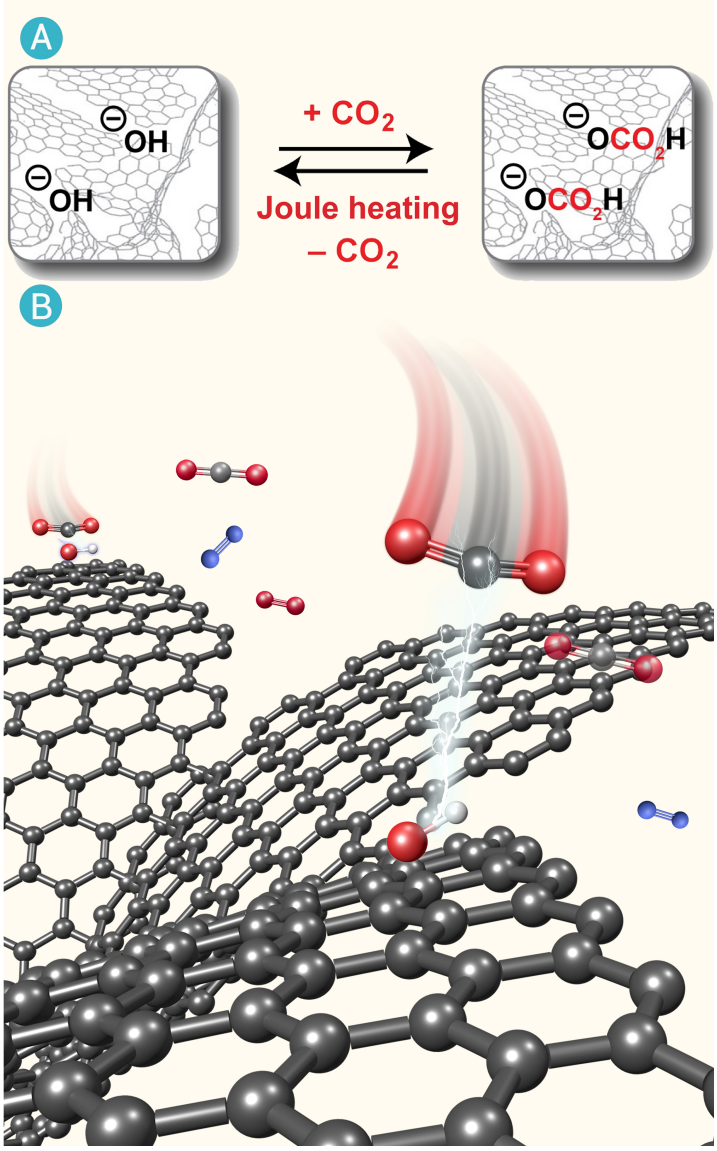

Figure 1. Schematic diagram of adsorption mechanism (A) Proposed mechanism for CO_2 capture by positively (hydroxide) charged-sorbent. (B) Scheme of supported OH^- capturing CO_2.

According to the International Energy Agency, the global CO_2 capture rate should increase from 1.6 Gt per year by 2030 to 7.6 Gt per year by 2050, where 2.4 Gt of CO_2 is removed directly from the atmosphere through DAC and other technologies. The Chinese Academy of Environmental Planning recommended that China should aim to meet an annual target of CO_2 captured by DAC technologies of 0.2–0.3 Gt by 2060. Though several promising materials and processes exist for DAC, there remains no proven DAC concept that is economically scalable. There is thus a need to explore approaches that can use renewable electricity for regeneration to allow for cost-effective scaling of DAC.

Hydroxide-based materials are among the most promising sorbents for DAC. Keith et al., described a techno-economic analysis for capturing CO_2 from the atmosphere in an industrial plant, where all the major components were drawn from well-established commercial concepts and could thus be assessed critically. Their design continuously captures ~1 Mt-CO_2 per year using an aqueous KOH sorbent coupled to a calcium caustic recovery loop.[3] However, an energetically costly regeneration step at 900ºC is required, as is the use of natural gas. A related approach uses calcium hydroxide as the sorbent, but again with a high temperature regeneration required at 900ºC.[4] The high temperatures required for the regeneration of these sorbents can be attributed to the substantial lattice energy of the generated carbonate compounds. An alternative approach, one that significantly reduces the regeneration temperature, is to disperse hydroxide species within a polymer matrix or a porous support material such as metal-organic frameworks. However, these materials currently suffer from limitations in terms of their long-term stability and relatively high material costs, which presents challenges for large-scale deployment.

In 2024, Li et al., made a breakthrough in developing a new sorbent for DAC.[5] This adsorbent material utilizes a battery-like charging process to accumulate large amounts of reactive hydroxide ions in the pores of the low-cost activated carbon. The activated carbon cloth acts like an electrode in a battery, and hydroxide ions accumulate in the tiny pores of the charcoal, with these ions then serving as the active sites in adsorption processes (Figure 1). These electrically conductive sorbents with tuneable structures are termed "charged-sorbents".

Compared to aqueous basic solutions used in other DAC processes, solid sorbents offer the possibility of low energy input (2~3 GJ/t CO_2), low operating costs, and a broad applicability across a wide range of scales. The charged sorbent rapidly captures carbon dioxide from the air by forming (bi-) carbonate. In contrast to conventional bulk carbonates, the reverse desorption process of the charged adsorbents does not need to overcome high lattice energy barriers and can, therefore, be completed at relatively low temperatures (90–100°C). Of further merit is the favourable electrical and thermal conductivities of the adsorbent, which are sufficiently high such that Joule heating desorption can be carried out directly, offering the opportunity to employ renewable energy sources to drive the desorption. This significantly improves the techno-economic argument and credibility for this as a

viable DAC technology. The relatively low costs of the constituent material and electrolyte also point to the potential readiness for commercialization. Beyond its use in DAC, the authors' demonstration of readily tuneable charged-sorbent materials, where the electrolyte and electrode can be rationally selected and designed, should lead to a family of new materials with applications in various energy-efficient gas separation technologies and energy conversion processes.

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AUTHOR CONTRIBUTIONS

X.F., and Z.S. co-wrote the draft. X.S. helped draw the figure. Z.S. supervised and revised the manuscript. A.R. helped polish the language. All authors contributed to the article and approved the submitted version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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