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Chitosan as a biomass-based bridge: integrating CO_2 capture and electrochemical upgrading

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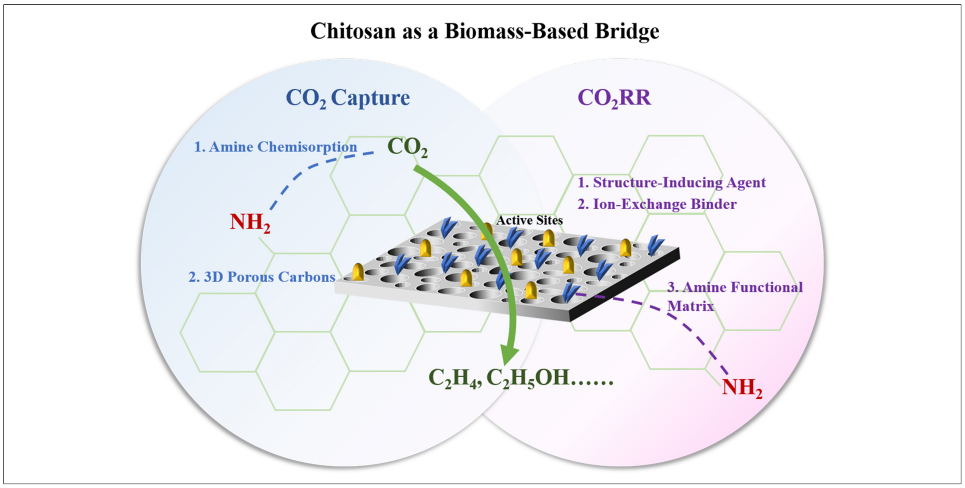

INTRODUCTION

Electrochemical CO_2 reduction reaction (CO_2RR) can convert waste CO_2 into fuels and chemicals. However, its industrial viability is limited by poor CO_2 solubility, sluggish mass diffusion, and low selectivity toward multi-carbon (C_{2+}) product[1,2]. It is urgently needed to design innovative electrode, which can enhance local CO_2 concentration, stabilize intermediates, and facilitate mass/electron transfer[2,3]. Chitosan is a natural polysaccharide rich in -NH_2 and -OH. Chitosan-derived amine-functionalized foams achieve efficient CO_2 capture via hydrogen bonding and acid–base interactions[4]. In CO_2RR, chitosan serves as a C/N source, a structure-inducing agent, and an ion-conductive binder[1-3,5]. Therefore, chitosan can act as a "biomass bridge" integrating upstream CO_2 capture with downstream electroreduction.

In this article, a brief summary of the key characteristics of chitosan-derived materials applied in CO_2 capture and CO_2RR is presented. Based on this, an integrated electrode is proposed: 3D macroporous chitosan foam is used as the CO_2 capture trap, chitosan-derived mesoporous material is used as the CO_2 enrichment

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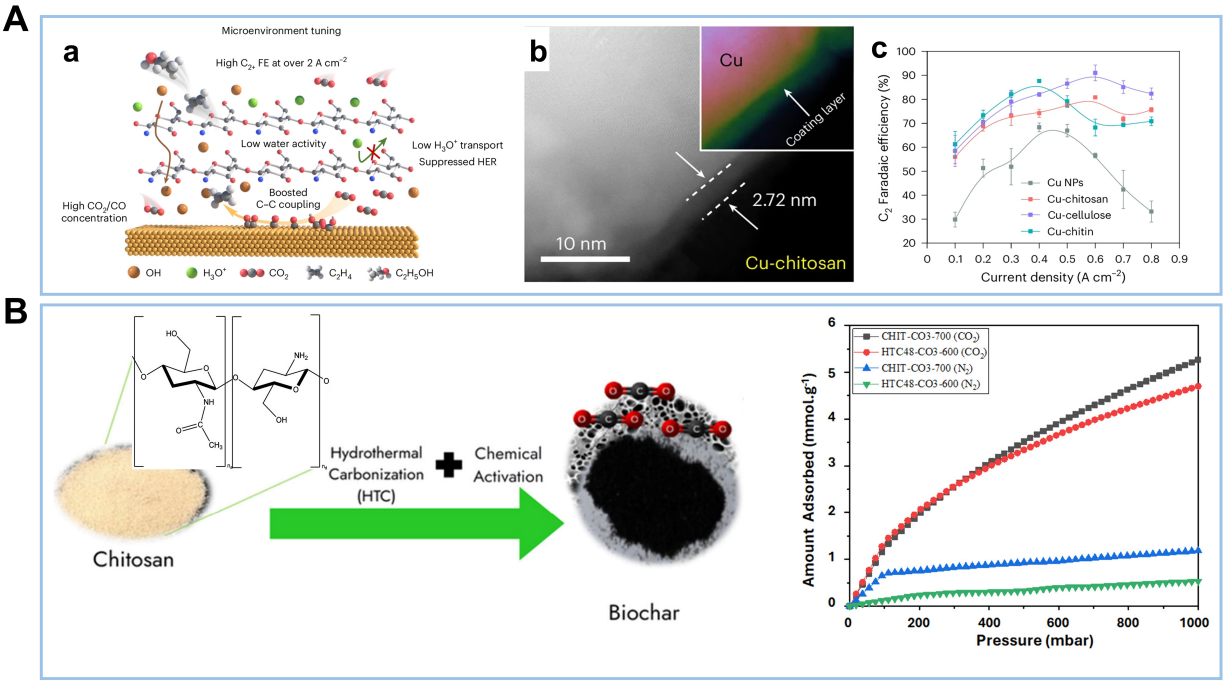

Figure 1. (A) Cu-chitosan, Cu-cellulose and Cu-chitin electro-catalyze the transformation of CO_2 into C_{2+} products. Reproduced from Ref.[5], Copyright 2026, Springer Nature; (B) N-functionalized chitosan biochars have high CO_2 adsorption capacity. Reproduced from Ref.[6], Copyright 2025, ACS Publications. FE: Faradaic efficiency; HER: hydrogen evolution reaction; NPs: nanoparticles.

area and mass transfer pathway, and active sites close to this layer are used as the main interface for CO_2RR, resulting in product upgrading. This design concept provides new insights into creating CO_2-rich microenvironments for enhanced kinetics and selectivity. We hope this perspective can inspire further research into biomass-derived multifunctional materials for carbon capture and utilization, accelerating the transition toward a circular carbon economy.

CHITOSAN-DERIVED MATERIALS FOR CO_2RR OR CO_2 CAPTURE

Chitosan-derived electrocatalysts play multiple unifying roles through constructing rich mass transfer pathways and regulating the microenvironment of active sites, achieving efficient or highly selective generation of various products [Supplementary Table 1]. Firstly, chitosan is an excellent source of carbon and nitrogen. Upon pyrolysis, chitosan forms 3D porous carbon that stabilizes metal nanoparticles via strong metal–support interactions[1]. Its amino groups like pyridinic-N, can activate CO_2 to enhance CO_2RR performance[2]. Secondly, chitosan is a structure-inducing agent. It chelates metal ions and directs the growth of vertically aligned 3D structure on gas diffusion layers, which increases electrochemical surface area (ECSA), facilitates CO_2 diffusion, and protects the hydrophobic layer[3]. Finally, Chitosan is an ion-exchange binder. In the latest report, chitosan was coated on the surface of Cu NPs, reducing the oxidation rate of Cu, while its hydrophilic, ion-conductive nature can increase the local CO_2/CO concentration [Figure 1A][5].

Chitosan-based adsorbents exhibit efficient, reversible CO_2 capture ability due to high surface area, nitrogen functionality, and amine-rich surfaces [Supplementary Table 2]. On the one hand, chitosan can prepare 3D hierarchically porous adsorbents combined with other materials via hydrothermal treatment and carbonization[4]. It acts as a renewable C/N source, creating micro/mesopores during decomposition, and residual N-groups serve as basic adsorption sites, which make adsorbents possess excellent stability and

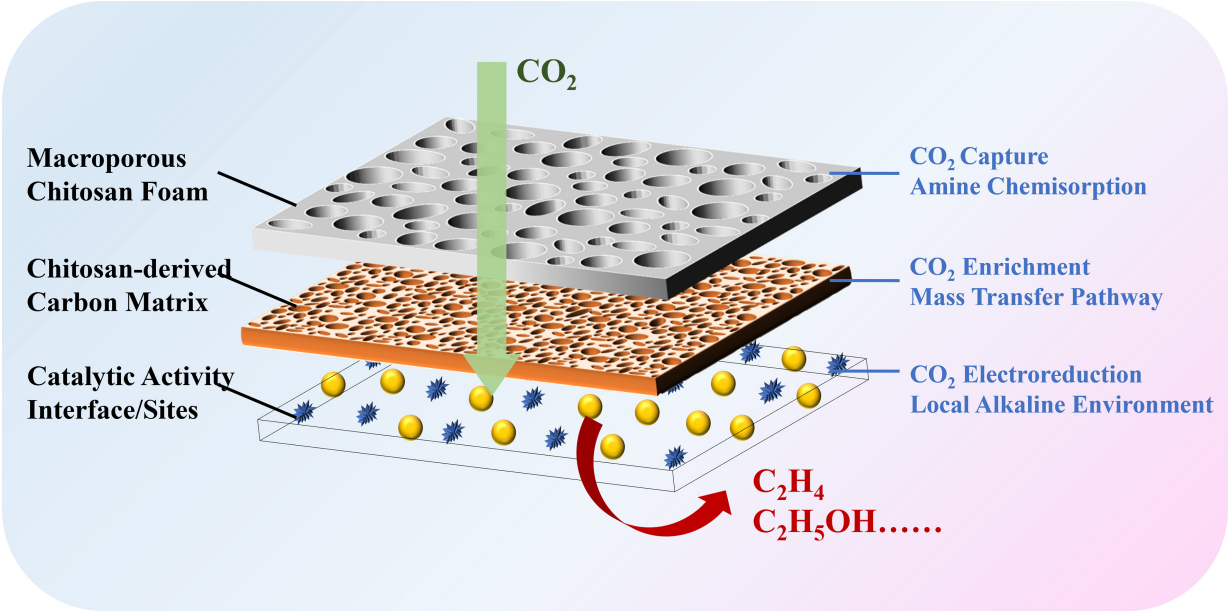

Figure 2. The integrated platform for CO_2 capture and CO_2RR upgrading. CO_2RR: CO_2 reduction reaction.

selectivity. On the other hand, amine-functionalized chitosan-based composites can further enhance CO_2 capture ability. In general, chitosan serves as a structural scaffold, provides initial amine sites, and acts as a matrix for additional amines [polyethylenimine (PEI), dopamine], boosting uptake via carbamate formation [Figure 1B][6].

FUTURE PERSPECTIVES: TOWARD INTEGRATED CO_2 CAPTURE AND CONVERSION

The above content reveals striking commonalities: chitosan is a renewable C/N source, a structural scaffold for hierarchical porosity, and a functional matrix with abundant amine groups. Thus, an integrated platform for CO_2 capture and CO_2RR upgrading can be constructed by fully leveraging the chelating ability, porous network formation and electron-donating amines of chitosan.

We propose a conceptual bifunctional gas diffusion electrode (GDE) with three hierarchical components [Figure 2]: (i) a macroporous chitosan foam or carbonized network for capturing CO_2 via amine-mediated chemisorption; (ii) a meso-/microporous N-doped carbon matrix for further concentrating CO_2; (iii) embedded metallic sites to transform CO_2 to C_{2+} products. This design eliminates separate capture/compression steps, feeding concentrated CO_2 directly to catalytic sites. In the actual operating device, the saturation state of capture layer and the continuous consumption of CO_2 at metallic active sites, both under the guidance of the electric field, facilitate the directional transport of CO_2.

In mechanism, the intrinsic properties of chitosan create a localized CO_2-rich microenvironment at catalytic interface. First of all, tunable porosity balances adsorption capacity with rapid diffusion, and chelation allows precise anchoring of metal active sites. Moreover, the amine groups bind CO_2 reversibly and generate a local alkaline environment upon quaternization, and nitrogen functionalities stabilize intermediates via hydrogen bonding, lowering asymmetric C–C coupling barriers, which suppresses hydrogen evolution reaction (HER) and steers selectivity toward C_{2+} products[2]. Comparing amine-functionalized electrodes, ionic-liquid/polymer-modified electrodes, or metal–organic framework (MOF)/covalent organic framework (COF)-derived capture–conversion materials, chitosan-derived electrodes have remarkable multifunctionality, low cost and environmental friendliness, and are expected to achieve cost reduction and efficiency improvement while integrating capture and conversion[7-9].

The integrated platform bypasses CO_2 solubility/diffusion limitations, shortens diffusion paths, opening a new paradigm for sustainable CO_2 valorization. However, there are several challenges and opportunities remaining:

1. The trade-off between capture capacity and catalytic activity needs optimization. The high amine loading may block active sites or alter hydrophilicity. Systematic studies on amine density, porosity, and performance are needed.

2. A thorough study is required for the long-term stability under the simultaneous capture/reduction conditions. For instance, when CO_2 chemisorption and cathodic potential act simultaneously, amine groups may undergo degradation. *In-situ* characterization methods [Raman, Fourier-transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS)] and solid-state ^{13}C nuclear magnetic resonance (NMR) techniques should be used to verify whether chitosan exists stably in the catalytic electrode[5,10].

3. The scalability to larger electrode areas and industrially relevant current densities (> 500 $mA \cdot cm^{-2}$) must be demonstrated, along with techno-economic and life-cycle assessments.

4. The design concept of the integrated platform should be extended to the utilization of other biomass polymers (such as cellulose, alginate) and other technical routes of CO_2 conversion (such as photocatalysis, thermal catalysis).

CONCLUSION

Chitosan is a multifunctional carbon-nitrogen framework rich in amino groups. It leads us to propose an integrated bifunctional GDE that combines efficient capture with direct electrochemical upgrading, which can build a CO_2-rich microenvironment with stabilized intermediates, enhancing kinetics and selectivity. While challenges in optimization, stability, and scale-up remain, this integrated platform represents a promising pathway toward sustainable CO_2 valorization and a circular carbon economy.

DECLARATIONS

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Authors' contributions

Manuscript preparation: Bi, J.
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Not applicable.

AI and AI-assisted tools statement

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Supplementary Materials

Supplementary Materials

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