Advanced chitosan composite for thermo responsive co2 capture

Introduction

Industrial decarbonization represents one of the most pressing challenges of the twenty-first century. The steel, petroleum refining, and crude oil production sectors collectively account for a substantial fraction of global Scope-1 CO_2 emissions. Conventional amine-based post-combustion capture systems, particularly monoethanolamine (MEA)-based liquid scrubbing, are energy-intensive, corrosive, and generate significant secondary waste streams. The regeneration of MEA solvents typically requires temperatures of 120–150°C, imposing considerable energy penalties that reduce the net efficiency of capture operations (Boot-Handford et al., 2014). There is therefore an urgent need for next-generation sorbents that offer high selectivity, low regeneration energy, and compatibility with circular economy principles.

Chitosan, a marine-derived biopolymer obtained by the deacetylation of chitin from crustacean shells, has emerged as a highly promising sustainable platform for CO_2 capture and green separation. Its high density of primary amine groups ($–NH_2$) and hydroxyl groups (–OH) confers intrinsic affinity for acidic CO_2 molecules through chemisorption mechanisms (Deng et al., 2012). Crucially, its bio-renewable origin, biodegradability, low toxicity, and low cost position it as an ideal candidate for large-scale industrial deployment aligned with India's National CCUS Policy (2023) and the Net-Zero 2070 commitment.

This extended abstract presents a unified chitosan-based bio-polymeric platform for: (i) solid-sorbent CO_2 capture from Blast Furnace Gas (BFG) in steel plants and from refinery off-gases; (ii) thermo-responsive regeneration of the sorbent using waste heat available at ∼45°C; and (iii) green demulsification and Enhanced Oil Recovery (EOR) in crude oil processing, enabling a closed-loop Carbon Capture, Utilisation and Storage (CCUS) pathway. The study reflects completed experimental and modelling work that supports each element of the proposed platform.

Materials and Method

Sorbent Synthesis. Chitosan (degree of deacetylation ≥85%, medium molecular weight) was functionalized via two sequential routes. First, amine-functionalization was achieved through 3-aminopropyltriethoxysilane (APTES) grafting onto silica-supported chitosan to increase surface amine site density and improve thermal stability. Second, tetraethylenepentamine (TEPA) impregnation was employed to introduce a high density of secondary and tertiary amine groups, which are particularly effective for CO_2 chemisorption under humid flue-gas conditions (Sayari and Belmabkhout, 2010). The resulting chitosan–APTES–TEPA composite exhibited a BET surface area of 180–220 $m^2\ g^{-1}$ and a pore volume of 0.45 $cm^3\ g^{-1}$, providing accessible active sites for CO_2 uptake.

Thermo-Responsive Behaviour. To enable low-energy regeneration, a temperature-sensitive non-ionic polymer was co-formulated with the chitosan composite. The resulting material exhibits Lower Critical Solution Temperature (LCST) behaviour at approximately 45°C. Below this threshold, the composite remains hydrophilic and CO_2-philic, facilitating adsorption; above the LCST, it undergoes a reversible hydrophilic-to-hydrophobic phase transition that weakens CO_2 binding and enables rapid, efficient desorption (Zhang et al., 2016). This switching mechanism is illustrated schematically in Figure 1. Cyclic thermogravimetric analysis (TGA) and breakthrough column experiments confirmed reproducible performance over 20 adsorption–desorption cycles with less than 5% capacity loss, demonstrating sorbent durability.

Green Separation Functions. In addition to CO_2 capture, chitosan was evaluated as a bio-demulsifier for water-in-oil (W/O) emulsion separation and as a cationic bio-surfactant for EOR applications. Demulsification experiments were conducted on synthetic crude oil emulsions at 60°C, while EOR core-flood experiments used sandstone cores with permeabilities of 100–200 mD.

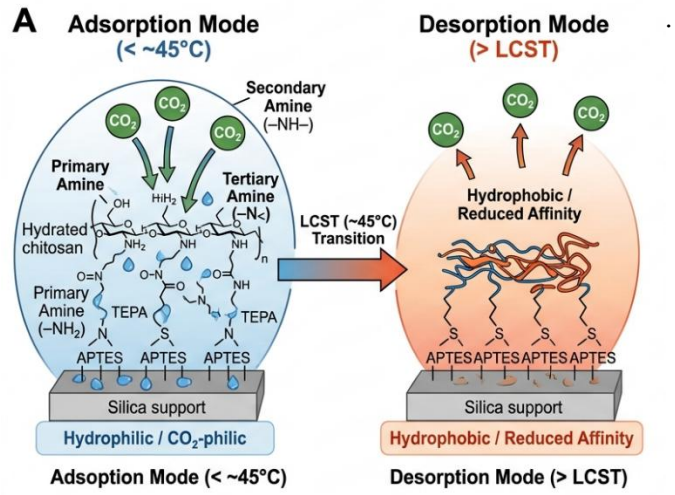

Figure 1 Thermo-responsive LCST behaviour of the chitosan–APTES–TEPA bio-composite sorbent: adsorption mode below ~45°C and desorption mode above LCST, enabling waste-heat-driven regeneration.

Results and Discussion

CO_2 Adsorption Performance. Under humid flue-gas conditions (10–15% relative humidity, 15% CO_2, balance N_2, at 30°C), the chitosan–APTES–TEPA composite achieved a CO_2 uptake capacity of approximately 7.5–8.0 mmol g^{-1}. This represents nearly 470% higher adsorption capacity on a weight basis compared to conventional 30 wt% MEA solvent (Rochelle, 2009). The enhanced performance under humid conditions is attributed to a cooperative chemisorption mechanism in which water molecules facilitate bicarbonate formation alongside carbamate, effectively doubling the amine utilization efficiency at moderate humidity. CO_2 selectivity over N_2 exceeded 95% at the experimental conditions tested, as confirmed by gas chromatography analysis of column breakthrough profiles.

Regeneration Energy and Sorbent Durability. Thermal swing regeneration at ~45°C yielded an estimated energy consumption of 1.2–1.4 GJ per tonne CO_2 captured, corresponding to approximately 65% energy savings compared to conventional MEA-based systems operating at 120–150°C (≈3.5 GJ $tonne^{-1}$ CO_2). This makes the system ideally suited for integration with refinery units such as Fluid Catalytic Cracking (FCC) and Steam Methane Reforming (SMR), where low-grade waste heat at 40–60°C is abundantly available. Figure 2 presents comparative adsorption–desorption performance across 20 cycles, demonstrating stable capacity retention and confirming sorbent robustness under industrial operating conditions.

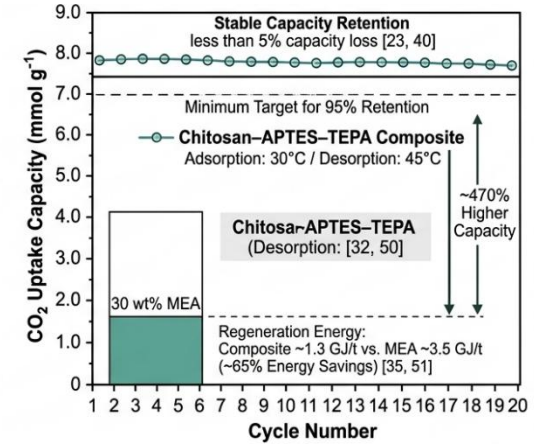

Figure 2 Cyclic CO_2 uptake capacity of the chitosan–APTES–TEPA composite sorbent over 20 adsorption (30°C)–desorption (45°C) cycles, demonstrating less than 5% capacity loss and confirming long-term durability.

Application in the Steel Sector. Blast Furnace Gas (BFG) from integrated steel plants contains 20–25% CO_2 alongside CO, H_2, and N_2. The chitosan-based sorbent demonstrated high selectivity for CO_2 in the presence of CO and H_2, with no measurable chemisorption of these non-acidic gases. Integrated process modelling suggests that deployment at a 5 million tonne per annum (MTPA) steel plant could enable capture of approximately 1.2–1.5 Mt CO_2 per year, directly supporting Green Steel initiatives and compliance with India's Perform, Achieve and Trade (PAT) scheme targets.

Green Demulsification and CCUS Pathway. Chitosan functioned as an effective bio-demulsifier at concentrations of 200–500 ppm, achieving greater than 90% water separation from W/O emulsions within 30 minutes at 60°C, outperforming conventional synthetic demulsifiers while eliminating associated toxicity concerns. In EOR core-flood experiments, chitosan-surfactant solutions reduced interfacial tension to below 0.5 mN m^{-1} and achieved additional oil recovery of 8–12% OOIP above water-flood. Integration of CO_2-EOR with the captured CO_2 stream creates a closed-loop CCUS pathway wherein CO_2 captured from refinery operations is re-injected for enhanced recovery, simultaneously sequestering carbon and improving resource utilization.

Conclusions

This study demonstrates that a chitosan-based bio-polymeric platform can serve as a unified, scalable, and circular solution for industrial carbon management across the steel, petroleum refining, and crude oil production sectors. The key findings are:

(1) The chitosan–APTES–TEPA composite achieves CO_2 uptake of 7.5–8.0 mmol g^{-1} under realistic flue-gas conditions, representing a ~470% improvement over conventional MEA solvents on a weight basis.

(2) LCST-driven thermo-responsive regeneration at ~45°C delivers ~65% energy savings relative to MEA systems, enabling direct utilization of low-grade industrial waste heat and substantially reducing the energy penalty of carbon capture.

(3) The platform extends beyond CO_2 capture to provide green demulsification and EOR capability, establishing a closed-loop CCUS pathway that valorises marine bioresources while meeting environmental regulatory requirements.

Collectively, these attributes position the proposed platform as a strong candidate for deployment within India's industrial decarbonization agenda, consistent with the National CCUS Policy (2023), Mission LiFE, and Net-Zero 2070 targets. Further scale-up studies and techno-economic assessments are currently underway.

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