

Life Cycle Assessment of CO₂ Capture by Zeolite 13X under Varying CO₂ Product Purity Targets

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INTRODUCTION

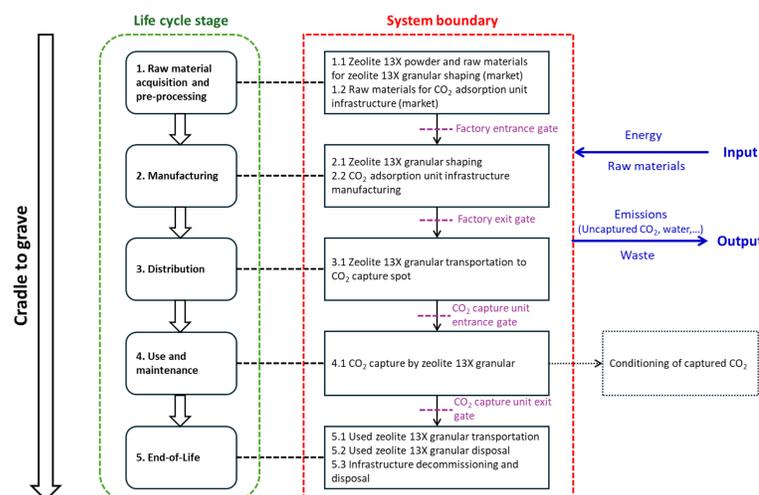
CO₂ capture is a key enabler for net-zero pathways. Compared with conventional amine scrubbing, adsorption-based capture offers the potential for lower regeneration energy, reduced solvent-related secondary pollution, and a high degree of material-process tunability [1].

As an industrial benchmark adsorbent, Zeolite 13X is widely used due to its robustness, low cost, and mature supply chain [2]. **However, its environmental performance remains insufficiently quantified, particularly under different CO₂ product purity constraints**, where separation difficulty and process configurations can change substantially. This gap limits a clear sustainability benchmark and hinders informed scale-up decisions. In this work, we conduct life cycle assessment (LCA) of CO₂ capture by Zeolite 13X across varying CO₂ purity targets and quantify the net CO₂-eq reduction rate to support decision-making on purity specifications and process selection.

METHOD

Protocol: ISO 14040/14044 [3, 4]
Function unit: 1 tonne CO₂
Software: Simapro 10.1

System boundary: cradle-to-grave
Database: ecoinvent 3.10
Life cycle impact assessment method: EF 3.1

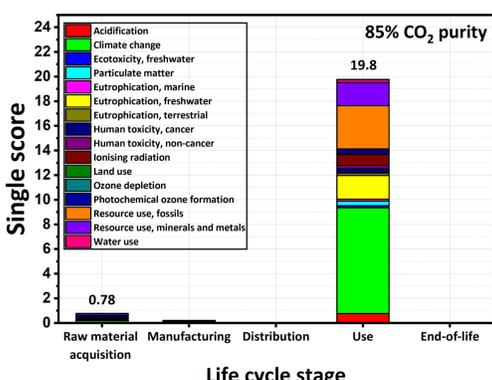
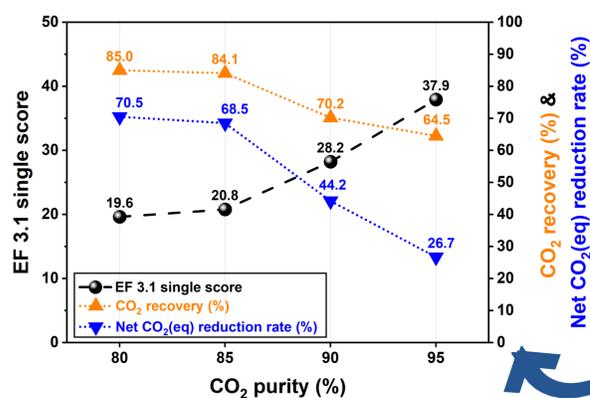
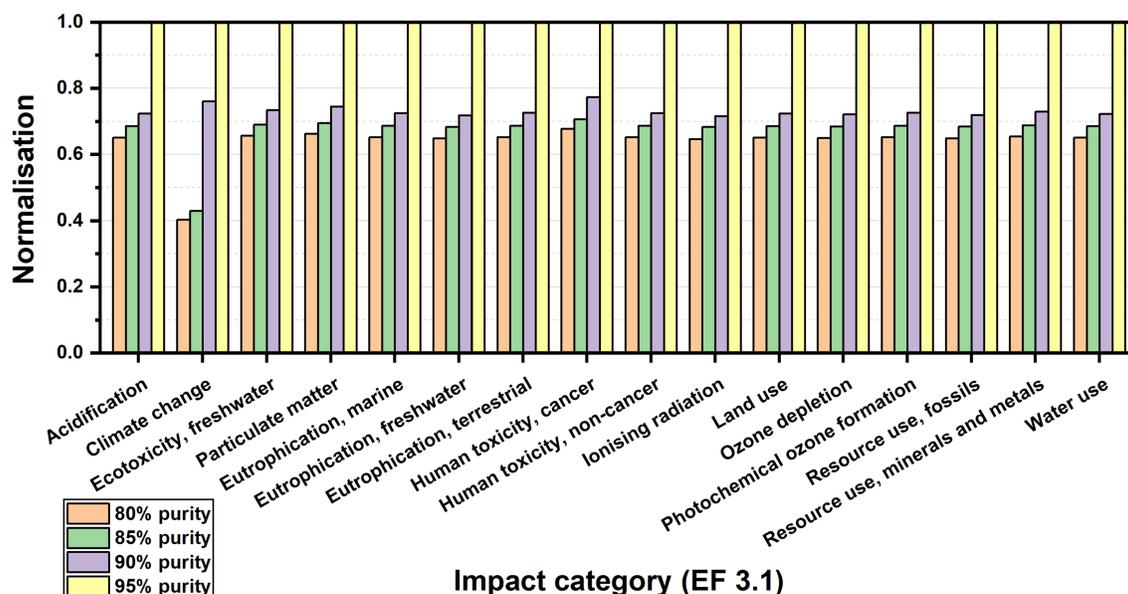


RESULTS

The key foreground data for inventory construction are provided below. The usage of zeolite 13X is determined by its productivity under a 5-year lifespan and 330 workdays per year, with other parameters sourced from our previous study [5].

CO ₂ Purity Target [%]	n° of experiment	Real CO ₂ Purity [%]	Recovery [%]	Energy [kWh/t _{CO2}]	Productivity [t _{CO2} /(day.m ³)]	Usage of Zeolite 13X [kg]
80	23	79.7	85.0	341.0	1.88	0.223
85	28	85.9	84.1	360.2	1.86	0.225
90	10	91.6	70.2	376.7	1.55	0.270
95	3	94.5	64.5	528.5	1.43	0.293

Normalized environmental profiles under four CO₂ purity constraints are illustrated right. All 16 impact categories increase as the purity target rises from 80% to 95%, with the 95% scenario exhibiting a higher environmental burden. This trend is attributed to the combined effects of reduced recovery, intensified energy consumption, and diminished productivity required to achieve higher purity levels.



Elevating CO₂ purity from 80% to 95% results in a decline in net CO₂(eq) reduction (from 70.5% to 26.7%) and a significant increase in the single score (from 19.6 to 37.9). This is primarily due to a trade-off where higher purity necessitates greater energy input and causes more CO₂ release owing to reduced recovery rates.

Taking the 85% purity target as an example, the use phase emerges as the predominant contributor to the single score, while the contributions from the other four stages are small. Specifically, Climate Change and Resource use, fossils are identified as the top two environmental hotspots within the use phase.

CONCLUSION

- Higher CO₂ product purity constraints may lead to more severe environmental impacts.
- The net CO₂(eq) reduction rate decreases as CO₂ product purity rises in 80-95% range.
- Sustainability optimization should prioritize the use phase, specifically targeting Climate Change and Fossil Resource Use.
- Techno-environmental trade-offs are driven by the nexus of purity, recovery, energy consumption, and productivity.