Strategic prioritization of carbon capture and utilization pathways for Saudi Arabia's circular carbon economy

As global leader in fossil fuel production, Saudi Arabia must balance economic growth with its decarbonization activities. This study assesses various CO_2 utilization pathways aligned with Saudi Vision 2030 and the Circular Carbon Economy, using a multi-criteria decision analysis framework to rank options by maturity, scalability, cost, sequestration potential, and policy fit. Among 9 assessed pathways, CCU for construction materials, such as concrete curing and carbonated aggregates rank highest due to their high technology readiness level (TRL 8–9), economic scalability, and potential for permanent CO_2 sequestration. It is estimated that around 4.7 Mt CO_2/y can be utilized in existing concrete plants across the Kingdom by 2030 with retrofitting costs of around $0.5M to 1.5M per site. Our analysis highlights that CO_2-derived fuels like synthetic methane and sustainable aviation fuels offer long-term decarbonization potential, especially when combined with DAC or biogenic CO_2 for net-negative emissions. However, they face challenges such as high energy demand, infrastructure needs, and abatement costs of $430–$650 per tonne of CO_2. Chemical conversion routes (e.g., formic acid, DMC, polyols, cyclic carbonates) have moderate maturity (TRL 4–6) and require substantial R&D investment. Though aligned with Vision 2030, their high costs and carbon leakage risks limit short-term viability. Algae-based utilization offers up to 2 tCO_2 sequestered per tonne of biomass but remains in early stages. Despite these challenges, Saudi Arabia has the potential to lead regionally in CCU by leveraging its industrial base, low-cost renewables, and policy momentum to advance impactful circular carbon solutions.