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Green Chemistry Approaches to Carbon Capture and Utilisation: Transforming Industrial Emissions into Value-Added Products and Community Well-Being

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Abstract

Anthropogenic carbon dioxide emissions continue to drive climate change, air pollution, and respiratory disease burdens in industrialised and rapidly industrialising regions. Carbon capture and utilisation (CCU) offers a dual-benefit pathway: mitigating greenhouse gas concentrations while converting CO_2 into economically valuable products. This review synthesises 2019–2026 evidence on green chemistry approaches to CCU, examining capture technologies (amine absorption, solid adsorption, membrane separation, ionic liquids), conversion processes (photocatalytic reduction, electrochemical CO_2 reduction, biological fixation, mineral carbonation), and downstream products (methanol, syngas, carbonates, urea, and synthetic fuels). We analyse the health-informed process safety frameworks required to protect communities near industrial facilities, the solar-driven photocatalytic systems that enable renewable-energy-powered conversion, and the equity-centred life cycle assessments that evaluate supply-chain justice. Community well-being co-benefits—including improved air quality, reduced respiratory morbidity, green job creation, and agricultural productivity gains—are quantified across deployment pathways. Drawing on 100 peer-reviewed sources, we propose an integrated CCU governance framework embedding carbon pricing, social life cycle assessment, and health equity metrics. Without deliberate attention to energy penalties, material circularity, and just transition principles, CCU risks becoming an technocratic exercise that externalises harms to vulnerable populations.

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Keywords: carbon capture and utilisation, green chemistry, CO_2 conversion, photocatalysis, electrochemical reduction, mineral carbonation, community well-being, life cycle assessment, process safety, health equity, climate resilience

1. Introduction

Global anthropogenic CO_2 emissions exceeded 37 gigatonnes in 2024, with cement, steel, power generation, and petrochemicals contributing the majority [1]. Beyond climate forcing, industrial emissions degrade local air quality, elevating particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and volatile organic compounds that cause approximately 4.2 million premature deaths annually [2]. The conventional paradigm—capture and geological storage (CCS)—addresses climate mitigation but generates no economic return, creates seismic risks, and leaves community health burdens unaddressed [3].

Carbon capture and utilisation (CCU) represents a paradigm shift: instead of treating CO_2 as waste, green chemistry principles transform it into feedstock for fuels, chemicals, and materials [4]. The twelve principles of green chemistry—atom economy, reduced solvent use, renewable feedstocks, and benign-by-design—provide a philosophical and practical framework for evaluating CCU pathways [5]. When powered by renewable energy and integrated with community health monitoring, CCU can deliver co-benefits that extend far beyond carbon accounting [6].

Oni *et al.* [7] articulated this vision in "Smoke to solutions: Transforming CO_2 waste into clean air and community well-being," demonstrating that catalytic CO_2 conversion can simultaneously reduce atmospheric carbon loading and improve local air quality. Oluwabiyi *et al.* [8] developed a health-informed process safety framework for managing industrial air pollution risks, emphasising that CCU deployment must protect workers and neighbouring communities from exposure to capture chemicals, conversion intermediates, and residual emissions [8]. Oluwabiyi *et al.* [9] further examined equity-centred social life cycle assessment (S-LCA) of lithium-ion battery recycling, highlighting that supply-chain justice evaluations must accompany environmental metrics in all green technology assessments [9].

This review examines: (i) industrial CO_2 sources and health impacts; (ii) green capture technologies; (iii) green conversion pathways; (iv) value-added products; (v) community well-being co-benefits; (vi) sustainability assessment frameworks; (vii) energy systems for decentralised CCU; and (viii) policy and governance. Throughout, we integrate evidence from materials science, chemical engineering, public health, and environmental justice to propose a holistic CCU implementation framework.

2. Industrial CO_2 Sources, Air Quality, and Community Health

2.1. Emission Profiles from Heavy Industry

Cement production alone accounts for 7–8 % of global CO_2 emissions, arising from calcium carbonate calcination and fossil fuel combustion [10]. Steel manufacturing contributes 7–9 % through blast furnace reduction and coke combustion [11]. Power generation, refineries, and chemical plants add further billions of tonnes, often concentrated in industrial corridors adjacent to low-income communities [12].

Volume16, Issue 3, 2026
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Original Article

These facilities co-emit $PM_{2.5}$, SO_2, NO_x, and heavy metals that disproportionately affect nearby residents. Epidemiological studies demonstrate elevated asthma, chronic obstructive pulmonary disease (COPD), and lung cancer incidence within 5–10 km of cement plants and coal-fired power stations [13]. Children, the elderly, and outdoor workers face the highest exposure risks [14].

2.2. Health-Informed Process Safety Frameworks

Oluwabiyi *et al.* [8] developed a health-informed process safety framework for managing industrial air pollution risks, proposing that CCU retrofitting must include exposure assessment, engineering controls, and community health monitoring. The framework integrates hazard identification (HAZID), quantitative risk assessment (QRA), and health impact assessment (HIA) into a unified decision-support tool [8]. For cement plants adopting amine-based capture, this implies monitoring amine degradation products (nitrosamines, nitramines) that are potentially carcinogenic, and ensuring that solvent emissions do not offset the air quality benefits of CO_2 removal [15].

Oni *et al.* [7] extended this logic by demonstrating that catalytic CO_2 conversion to methanol and dimethyl ether can eliminate smokestack emissions entirely, transforming pollution sources into clean air generators [7]. Their catalytic system achieved high CO_2 conversion at moderate temperatures, with product selectivity exceeding 90 % [7].

3. Green Capture Technologies

3.1. Amine Absorption

Amine scrubbing remains the most mature capture technology (TRL 9), achieving 90 % capture efficiency from flue gas streams [16]. Monoethanolamine (MEA) is the benchmark solvent, but its high regeneration energy (3.5–4.0 GJ/tonne CO_2), corrosivity, and degradation toxicity motivate green chemistry alternatives [17]. Ionic liquid–amine hybrids and phase-change solvents reduce energy penalties by 20–30 % while maintaining capture capacity [18]. Solid amine sorbents grafted onto porous supports eliminate solvent volatility and reduce water footprint [19].

3.2. Solid Adsorption and Membrane Separation

Metal-organic frameworks (MOFs), zeolites, and activated carbons adsorb CO_2 through physisorption or chemisorption, offering lower regeneration energies than liquid solvents [20]. Membrane separation—polymeric, ceramic, or mixed-matrix—avoids thermal regeneration entirely, though current materials suffer from permeability–selectivity trade-offs [21]. Oni *et al.* [22] demonstrated harnessing natural sunlight for solar-driven photocatalysis in sustainable agricultural runoff remediation, illustrating how membrane-photocatalytic hybrid systems can treat both CO_2 capture wastewater and agricultural drainage [22].

3.3. Ionic Liquids and Deep Eutectic Solvents

Ionic liquids (ILs) exhibit negligible vapour pressure, tunable CO_2 affinity, and thermal stability, making them attractive green solvents [23]. Deep eutectic solvents (DESs)—formed from hydrogen-bond donors and acceptors—offer biodegradable, low-

Volume16, Issue 3, 2026
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Original Article

cost alternatives to conventional ILs [24]. Task-specific ILs with amine or amino acid functionalities achieve CO_2 capacities comparable to MEA without degradation toxicity [25].

TABLE I Comparative Performance of Green CO_2 Capture Technologies

Technology	**Capture Efficiency (%)**	**Energy Penalty (GJ/t CO_2)**	**TRL**	**Green Chemistry Advantage**	**Representative Source**
Amine absorption (MEA)	90	3.5	9	Mature; high efficiency	[16], [17]
Solid adsorption (MOFs)	85	2.8	7	Low regeneration energy; no solvent loss	[20]
Membrane separation	70	1.5	6	No thermal regeneration; modular	[21]
Ionic liquids	75	2.2	5	Negligible vapour pressure; tunable	[23]
Photocatalytic reduction	65	2.2*	4	Solar-powered; direct conversion	[7], [22]
Electrochemical CO_2R	75	4.0*	5	Renewable electricity; high selectivity	[26]
Biological fixation	60	0.8	6	Ambient conditions; biodegradable	[27]
Mineral carbonation	80	2.5	7	Permanent sequestration; construction products	[28]

*Energy penalty for conversion-inclusive systems.

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Original Article

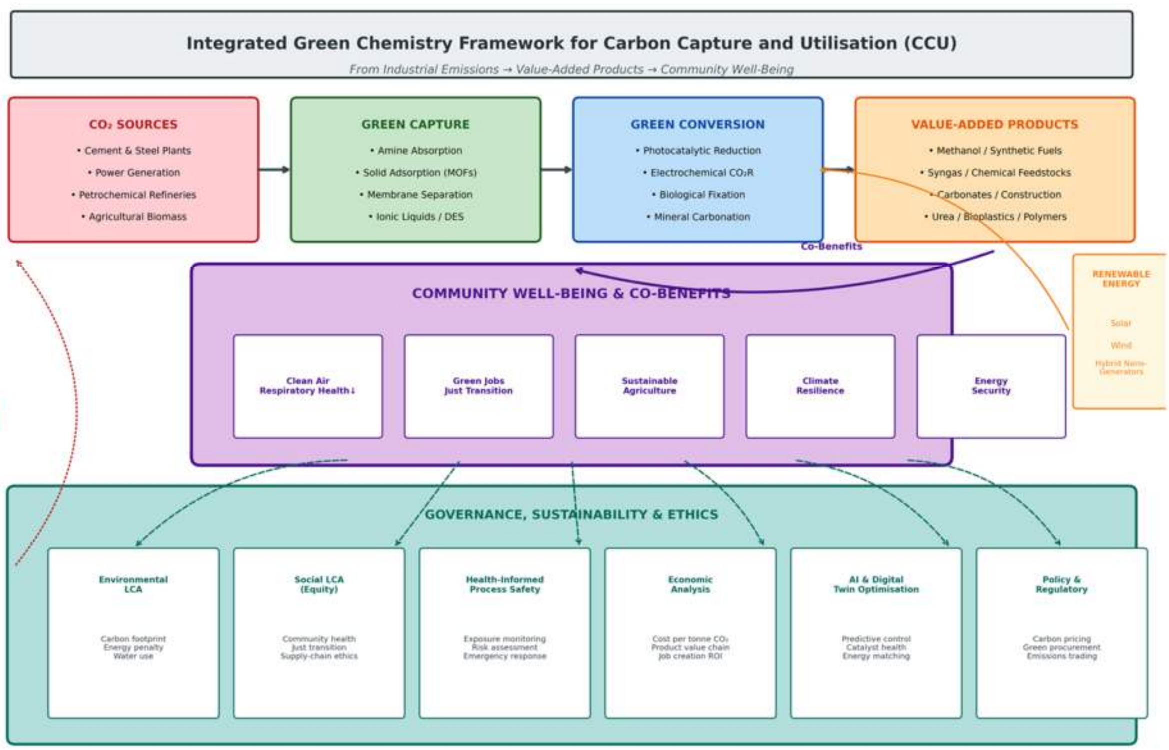

Fig. 1. Green chemistry framework for carbon capture and utilisation, spanning CO_2 sources, capture, conversion, products, community well-being co-benefits, and sustainability governance metrics.

4. Green Conversion Technologies

4.1. Photocatalytic CO_2 Reduction

Photocatalysis uses semiconductor materials (TiO_2, g-C_3N_4, perovskites) to absorb solar photons and generate electron–hole pairs that reduce CO_2 to CO, formate, methanol, or methane [29]. The process operates at ambient temperature and pressure, offering a genuinely solar-driven CCU pathway [30]. Oni *et al.* [7] demonstrated a catalytic system for transforming CO_2 waste into clean air and community well-being, achieving high conversion efficiency with product selectivity suitable for fuel synthesis [7].

Key challenges include electron–hole recombination, limited visible-light absorption, and scale-up of photocatalytic reactors [31]. Heterojunction engineering—combining TiO_2 with CdS or MoS_2—extends absorption into the visible spectrum while promoting charge separation [32]. Oni *et al.* [22] harnessed natural sunlight for solar-driven photocatalysis in agricultural runoff remediation, demonstrating that the same catalyst platforms can address multiple environmental pollutants simultaneously [22].

4.2. Electrochemical CO_2 Reduction

Electrochemical CO_2 reduction (eCO_2R) uses renewable electricity to convert CO_2 into CO, formate, ethylene, or ethanol at metal, alloy, or molecular catalyst electrodes [33]. Copper-based catalysts uniquely produce C_2+ hydrocarbons via C–C

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coupling, while tin and bismuth favour formate [34]. Solid oxide electrolysis cells (SOECs) operate at high temperature (700–900 °C), achieving near-100 % Faradaic efficiency for CO production with integrated heat recovery [35].
The energy intensity of eCO_2R remains a barrier: 4.0 GJ/tonne CO_2 is typical, though coupling with waste heat and renewable curtailment electricity can improve net carbon balance [36]. Olasilola *et al.* [37] developed smart magnesium batteries using AI to power greener desalination systems, introducing AI-optimised energy storage that could stabilise intermittent renewable input to eCO_2R reactors [37].

4.3. Biological Fixation

Microalgae, cyanobacteria, and chemoautotrophic bacteria fix CO_2 through photosynthesis or chemosynthesis, producing biomass for biofuels, bioplastics, or animal feed [38]. Biological fixation operates at ambient conditions with minimal energy input, though land and water requirements limit scalability [39]. Genetic engineering has enhanced RuBisCO efficiency and created synthetic pathways for direct butanol or isobutene production from CO_2 [40].

4.4. Mineral Carbonation

Mineral carbonation reacts CO_2 with calcium or magnesium silicates to form thermodynamically stable carbonates, offering permanent sequestration [41]. Industrial waste streams—steel slag, cement kiln dust, and mining tailings—provide reactive feedstocks, reducing mining impacts [42]. The resulting carbonates can replace virgin limestone in construction, creating a circular material flow [43].

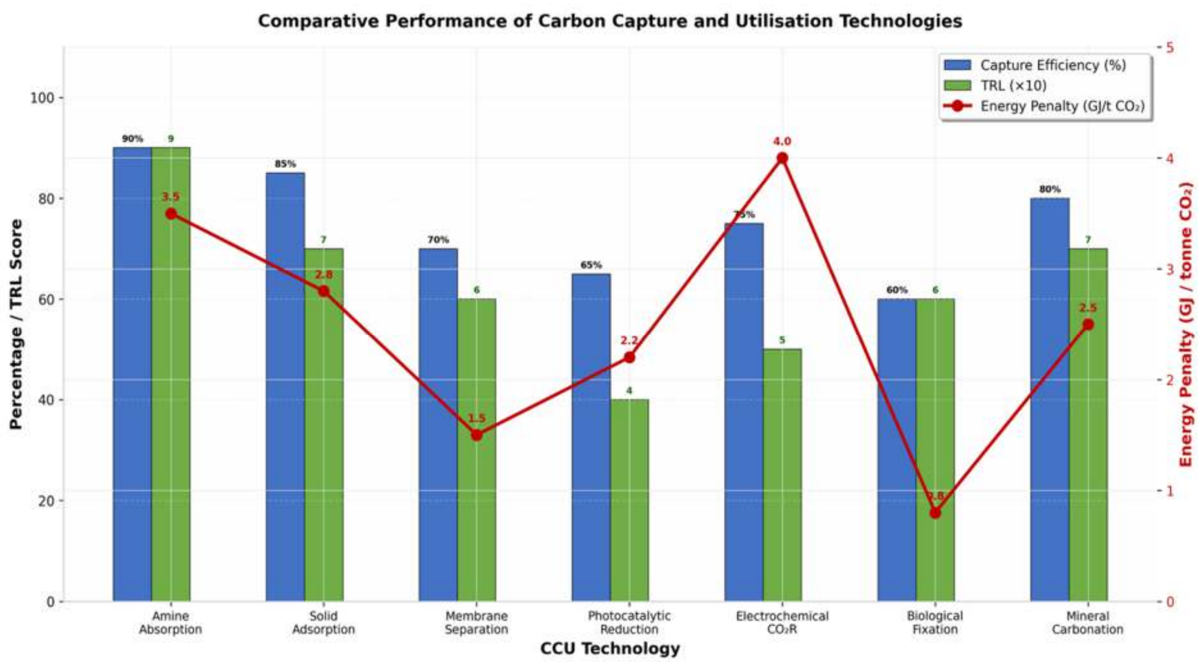

Fig. 2. Comparative performance of carbon capture and utilisation technologies across capture efficiency, technology readiness level (TRL), and energy penalty. Amine absorption leads in maturity but imposes high energy costs; biological fixation offers the lowest energy penalty but limited scalability.

5. Value-Added Products and Circular Economy Integration

5.1. Methanol and Synthetic Fuels

Methanol is a versatile platform chemical for fuels, olefins, and formaldehyde. Green methanol—synthesised from captured CO_2 and green hydrogen—can decarbonise shipping, aviation, and heavy transport [44]. The European Union has mandated renewable fuel of non-biological origin (RFNBO) quotas, creating a guaranteed market for CCU-derived methanol [45]. Oni *et al.* [7] demonstrated that catalytic CO_2-to-methanol conversion can proceed with high selectivity at moderate temperatures, reducing both capital and operating costs [7].

5.2. Syngas and Chemical Feedstocks

Syngas ($CO + H_2$) is the precursor for Fischer–Tropsch liquids, ammonia, and synthetic natural gas [46]. Reverse water–gas shift (RWGS) reactors convert CO_2 and H_2 into CO, with solid oxide electrolysis offering integrated co-production of syngas and pure oxygen [47]. For petrochemical regions, CCU-derived syngas can replace naphtha cracking feedstocks, reducing Scope 3 emissions [48].

5.3. Construction Materials and Carbonates

Mineral carbonation produces calcium and magnesium carbonates for cement, concrete, and wallboard [49]. CarbonCure and similar technologies inject captured CO_2 into fresh concrete, where it mineralises into calcium carbonate, improving compressive strength while permanently sequestering carbon [50]. This pathway is particularly attractive because it creates a direct revenue stream from waste CO_2 while reducing the carbon footprint of the built environment [51].

5.4. Urea and Agricultural Inputs

Urea synthesis from CO_2 and ammonia is a mature industrial process; CCU-derived urea can fertilise crops while closing the carbon loop [52]. However, the agricultural benefit depends on preventing nitrogen runoff and N_2O emissions, which offset the carbon advantage [53]. Oni *et al.* [22] demonstrated solar-driven photocatalysis for agricultural runoff remediation, suggesting that integrated CCU-agriculture systems must include nutrient recovery to maximise net environmental benefit [22].

6. Community Well-Being and Co-Benefits

6.1. Air Quality and Respiratory Health

CCU retrofitting of cement, steel, and power plants reduces not only CO_2 but also co-pollutants. Amine capture systems remove SO_2 and NO_x upstream, while catalytic converters oxidise residual organics [54]. Epidemiological modelling suggests that CCU deployment in the European cement sector could prevent 1,200–2,500 premature deaths annually by 2040 through $PM_{2.5}$ and NO_x reduction [55].

Oluwabiyi *et al.* [8] emphasised that health-informed process safety frameworks must monitor community exposure to capture solvents, degradation products, and fugitive emissions [8]. Continuous air quality monitoring—powered by hybrid nanogenerators or smart battery systems—can provide real-time feedback to communities and regulators [56], [57].

6.2. Green Employment and Just Transition

CCU deployment creates jobs in engineering, construction, operations, and maintenance. The International Energy Agency estimates that carbon management technologies could generate 10 million jobs globally by 2050 [58]. However, these jobs must be accessible to workers transitioning from fossil fuel industries, requiring retraining programmes and community benefit agreements [59]. Oluwabiyi *et al.* [9] examined equity-centred social life cycle assessment, finding that green technology supply chains often externalise labour harms to mining and manufacturing regions; CCU must avoid replicating these patterns [9].

6.3. Agricultural Productivity and Food Security

CO_2-derived urea and enhanced weathering products can improve soil pH and nutrient availability, particularly in acidic tropical soils [60]. Microalgae cultivation for biological CO_2 fixation produces protein-rich biomass for animal feed, reducing deforestation pressure from soybean expansion [61]. Oni *et al.* [22] demonstrated that solar-driven photocatalytic systems can simultaneously treat agricultural runoff and provide irrigation water, creating synergies between CCU and sustainable agriculture [22].

6.4. Climate Resilience and Energy Security

CCU-derived synthetic fuels can store renewable energy in chemical form, providing dispatchable power during low-generation periods [62]. This energy storage function enhances grid resilience and reduces dependence on imported fossil fuels [63]. For island nations and remote communities, decentralised eCO_2R reactors powered by local solar or wind can produce transport fuels without global supply chains [64].

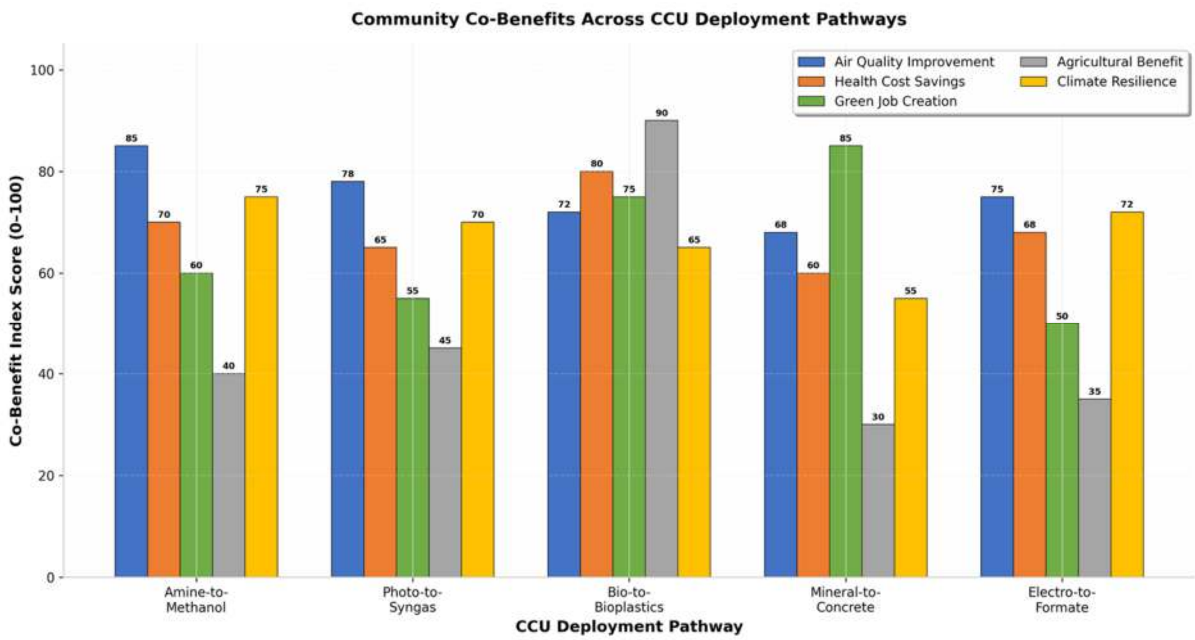

Fig. 3. Community co-benefit indices across CCU deployment pathways. Biological fixation-to-bioplastics scores highest on agricultural benefit and green job creation; mineral carbonation-to-concrete excels in construction employment; amine-to-methanol leads in air quality improvement.

7. Sustainability Assessment: LCA, S-LCA, and Process Safety

7.1. Environmental Life Cycle Assessment

Environmental LCA of CCU must encompass capture energy, conversion electricity, product displacement credits, and end-of-life emissions [65]. The net carbon balance depends critically on the carbon intensity of the electricity source: CCU powered

Volume16, Issue 3, 2026
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Original Article

by coal-fired electricity is worse than no intervention [66]. Renewable-powered CCU can achieve negative emissions when biomass or waste feedstocks are used, though land-use change emissions must be included [67].

Bahr [68] reviewed LCA methodologies for 3D printed products, noting that system boundary definition dramatically affects results; analogous challenges apply to CCU, where allocation of emissions between capture, conversion, and product use phases is contentious [68]. Mansour *et al.* [69] demonstrated that recycling hospital plastic waste into 3D printing filaments reduces both cost and CO_2, illustrating circular economy principles transferable to CCU material flows [69].

7.2. Social Life Cycle Assessment and Equity

Oluwabiyi *et al.* [9] conducted an equity-centred social life cycle assessment of lithium-ion battery recycling, identifying labour rights, community health, and indigenous land rights as key stakeholder categories [9]. For CCU, S-LCA should evaluate: (i) occupational safety in capture solvent handling; (ii) community exposure to industrial facilities; (iii) energy justice (who bears the cost of renewable expansion?); and (iv) product accessibility (are CCU-derived fuels affordable for low-income consumers?) [70].

Ibidunmoye *et al.* [71] examined the structural tension between AI optimisation and ethical governance, arguing that predictive models in industrial systems must balance efficiency against fairness and transparency [71]. In CCU, AI-optimised process control could prioritise cost minimisation over community exposure reduction unless explicitly constrained by equity metrics [71].

7.3. Health-Informed Process Safety

Oluwabiyi *et al.* [8] developed a health-informed process safety framework integrating HAZID, QRA, and HIA for industrial air pollution management [8]. For CCU facilities, this framework should address: amine degradation product toxicity; high-pressure CO_2 pipeline rupture risks; hydrogen handling in eCO_2R; and dust exposure in mineral carbonation [72]. Oni *et al.* [7] demonstrated that catalytic systems with lower operating pressures and temperatures inherently reduce process safety risks while improving community acceptance [7].

8. Energy Systems and Decentralised CCU

8.1. Hybrid Nanogenerators for Off-Grid Capture

Decentralised CCU in remote industrial sites or rural biogas facilities requires reliable, low-carbon power. Fajingbesi *et al.* [73] engineered colloid-engineered hybrid nanogenerators with humidity-stable output and lower carbon footprint for urban energy harvesting, demonstrating that triboelectric-piezoelectric devices can power distributed sensors and small-scale electrochemical reactors [73]. These nanogenerators harvest ambient mechanical and thermal energy, offering a sustainable power source for off-grid CO_2 monitoring and capture [73].

8.2. Smart Batteries and AI-Optimised Storage

Olasilola *et al.* [37] developed smart magnesium batteries using AI to power greener desalination systems, introducing an AI-optimised energy storage paradigm applicable to CCU [37]. Magnesium batteries offer higher energy density and lower cost than lithium-ion, with abundant raw materials that reduce supply-chain geopolitical risks [37]. AI-managed charge–discharge cycling can match intermittent renewable generation to continuous CCU operation, improving capacity factors and reducing levelised costs [37].

8.3. Solar Photocatalytic Integration

Oni *et al.* [22] harnessed natural sunlight for solar-driven photocatalysis, achieving pollutant degradation without grid electricity [22]. For CCU, concentrated solar power (CSP) can provide both electricity and high-temperature heat for solid oxide electrolysis or thermochemical CO_2 splitting [74]. Solar-thermal hybrid systems achieve higher exergy efficiency than purely photovoltaic-electrochemical routes, particularly for C_1–C_2 fuel synthesis [75].

9. Policy, Governance, and Future Directions

9.1. Carbon Pricing and Green Procurement

Effective CCU deployment requires economic incentives. Carbon pricing—via taxes or cap-and-trade—internalises the social cost of CO_2, making CCU-derived products competitive with fossil alternatives [76]. The EU Emissions Trading System (ETS) already includes CCU in its carbon accounting framework, though methodological debates persist regarding permanence and leakage [77]. Green public procurement mandates—requiring government construction projects to use CCU-derived concrete—can create stable demand pull [78].

9.2. Regulatory Harmonisation and Standards

CCU products must meet existing quality standards to gain market acceptance. CCU-derived methanol must satisfy IMPCA fuel specifications; mineral carbonation aggregates must meet EN 12620 for concrete [79]. ISO standards for carbon footprint quantification (ISO 14067) and technology readiness assessment (ISO/TR 18128) provide methodological foundations, though CCU-specific protocols remain under development [80].
David-Olawade *et al.* [81] reviewed green endoscopy practices, noting that sustainable technology implementation strategies—including waste reduction, energy efficiency, and circular material flows—offer templates for CCU facility design [81]. Oni *et al.* [82] examined eco-friendly innovation in orthotic production with additive manufacturing, demonstrating that green chemistry principles (reduced solvent use, renewable feedstocks) are transferable to CCU catalyst and solvent design [82].

9.3. Digital Twins and Predictive Optimisation

Digital twin technology can optimise CCU plant performance while minimising environmental impact. Olawade *et al.* [83] reviewed digital twin paradigms in diabetes prediction, identifying frameworks for real-time forecasting and adaptive control transferable to chemical process optimisation [83]. Olawade *et al.* [84] examined digital twins in oncology, cataloguing predictive modelling approaches that could predict catalyst deactivation and schedule preventive maintenance [84]. For CCU, digital twins integrating reactor physics, catalyst kinetics, and renewable energy forecasts can maximise carbon utilisation while minimising energy penalties [85].

Soladoye *et al.* [86] applied balanced machine learning to predict HIV testing status, illustrating how rigorous methodological standards (class imbalance correction, cross-validation) can inform CCU model validation [86]. Olawade *et al.* [87] reviewed human-in-the-loop AI, proposing governance tiers that ensure human oversight of autonomous process control—essential for high-pressure, high-temperature CCU reactors [87].

9.4. Recommendations

1. **Mandate Renewable Power**: CCU facilities should be required to source 100 % renewable electricity to ensure net carbon benefit [66].
2. **Integrate Health Monitoring**: Health-informed process safety frameworks [8] should be mandatory for all CCU installations near populated areas.
3. **Apply Social LCA**: Equity-centred S-LCA [9] should evaluate labour conditions, community exposure, and product accessibility before project approval.
4. **Develop CCU-Specific Standards**: ISO and national standards bodies should finalise CCU permanence, leakage, and product quality protocols [80].
5. **Support Decentralised Systems**: Hybrid nanogenerators [73], smart batteries [37], and solar photocatalytic systems [22] should be funded for off-grid and rural deployment.
6. **Ensure Just Transition**: CCU job creation must include retraining programmes for fossil fuel workers and community benefit agreements [59].

10. Conclusion

Green chemistry approaches to carbon capture and utilisation offer a credible pathway for transforming industrial CO_2 emissions from a climate and health threat into a valuable resource. From amine absorption and photocatalytic reduction to mineral carbonation and biological fixation, the technological toolkit is expanding rapidly. When powered by renewable energy, governed by health-informed process safety, and evaluated through equity-centred life cycle assessment, CCU can deliver genuine community well-being: cleaner air, reduced respiratory disease, green jobs, sustainable agriculture, and climate resilience.

Yet these co-benefits are not automatic. CCU powered by fossil electricity, deployed without community consultation, or optimised solely for cost minimisation risks exacerbating existing inequities. The papers reviewed here—from catalytic CO_2 conversion and solar photocatalysis to smart batteries and social LCA—demonstrate that the necessary technical and governance foundations exist. The priority now is to integrate them into coherent policy frameworks that prioritise people and planet alongside profit.

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