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Sustainable AI–Enhanced Direct Air Capture (DAC): Transforming Air Recycling for Future Pollution Control

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Abstract: *Direct Air Capture (DAC) has emerged as a viable negative-emissions technology capable of extracting carbon dioxide (CO□) directly from ambient air. However, current DAC systems remain energy-intensive, financially demanding, and difficult to scale for urban environmental applications. Sustainable artificial intelligence (AI)—defined as efficient, low-energy computational systems—offers new pathways for optimizing DAC performance while reducing environmental burdens linked to algorithmic processes. This paper presents a comprehensive and original academic framework for integrating sustainable AI with DAC to support future air-recycling capacities and pollution-control strategies. Through an enhanced literature review, refined case study analyses, and expanded ethical reasoning, this study argues that AI-optimized DAC can significantly strengthen urban air-quality management, catalytic carbon recycling, and climate mitigation efforts. The paper concludes with policy-oriented recommendations to guide the responsible deployment of AI-enabled DAC systems within climate-neutral infrastructures.*

Keywords: sustainable artificial intelligence, direct air capture, air recycling, climate mitigation, pollution control

I. INTRODUCTION

Air pollution remains a critical global challenge, contributing to respiratory illness, ecosystem degradation, and climate change (World Health Organization, 2021). Conventional mitigation strategies—such as scrubbing systems, electrostatic precipitators, or point-source filtration—primarily address emissions at their origin and often fall short in offsetting accumulated atmospheric pollutants. Direct Air Capture (DAC), which removes CO_2 from open air regardless of emission source, has therefore become increasingly relevant to contemporary climate strategies (Keith et al., 2018). Yet despite its promise, DAC faces persistent barriers including high energy consumption, operational inflexibility, and limited large-scale adoption.

Sustainable artificial intelligence (AI) introduces a compelling solution to these challenges. Unlike traditional AI models that depend on high-energy cloud computation, sustainable AI prioritizes energy-efficient algorithms, low-carbon data architectures, and environmentally responsible processing (Strubell et al., 2020). Integrating these models into DAC systems enables intelligent airflow control, predictive sorbent-performance analytics, real-time energy optimization, and enhanced system reliability—ultimately transforming DAC from a resource-intensive technology into a more scalable air-recycling and pollution-control tool.

This paper provides a fully restructured, publication-level analysis of how sustainable AI can reshape DAC capabilities for future environmental governance.

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Objectives of the Study

General Objective

- To evaluate how sustainable AI can enhance DAC-supported air-recycling processes and strengthen future air-pollution mitigation systems.

Specific Objectives

- To analyze core principles of sustainable AI applicable to DAC performance optimization.
- To examine the role of AI-enabled DAC in advancing future air-pollution control frameworks.
- To identify ethical, technological, and scalability challenges associated with AI-governed air-recycling infrastructures.
- To recommend policy, governance, and engineering strategies that support environmentally responsible AI–DAC integration.

Key Definitions

Sustainable Artificial Intelligence

Sustainable AI refers to computational systems designed to reduce energy intensity, carbon footprint, and hardware waste through efficient algorithms, renewable-powered data centers, and lifecycle-conscious digital infrastructures (Jones, 2023).

Direct Air Capture (DAC)

DAC is an engineered process that draws ambient air into a system where chemical sorbents or solvents selectively bind CO_2. The sorbents are regenerated through thermal, vacuum, or electro -chemical processes, producing concentrated CO_2 suitable for storage or utilization (Goeppert et al., 2021).

Air Recycling

Air recycling involves reprocessing and reusing purified or captured air components—including CO_2, purified oxygen, or conditioned air streams—for industrial applications, indoor air management, and circular-carbon systems.

Air Pollution Control

Air pollution control comprises technological and policy-driven practices designed to reduce pollutants and maintain safe atmospheric conditions (NASEM, 2019).

Significance of the Study

Integrating sustainable AI with DAC expands the technological horizon of future air-pollution management. AI-equipped DAC systems enable real-time process regulation, predictive fault detection, energy-efficient regeneration cycles, and dynamic load balancing—key features for scalable air recycling. Additionally, AI-enhanced DAC supports global decarbonization objectives such as the Paris Agreement's net-zero targets by converting carbon removal into an active component of urban-environmental planning.

Research Gaps

- Despite significant advancements, several gaps persist
- Limited empirical validation of AI-driven DAC systems (Caldeira et al., 2023).
- Insufficient integration of sustainable AI principles in carbon-removal operations.
- Underdeveloped frameworks addressing ethical constraints of AI-based environmental monitoring.
- Lack of unified models linking DAC, sustainable AI, and urban air recycling.

Conceptual Framework

The conceptual framework proposed in this paper integrates three pillars:

1. DAC as the Core Carbon-Removal Mechanism

Responsible for extracting atmospheric CO_2 with engineered sorbent systems.

2. Sustainable AI as the Optimization Layer

Enhances sorbent selection, airflow modeling, energy distribution, and operational control.

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3. Air Recycling as the Application Layer

Uses captured or conditioned air for industrial reuse, indoor environmental management, or circular-carbon pathways.

Together, these layers create a system where carbon removal, air recycling, and sustainable computation reinforce one another.

II. LITERATURE REVIEW

Direct Air Capture Technologies

DAC methods generally fall under two categories:Solid sorbents, which offer modulardesigns and moderate-temperature regeneration.Liquid solvents, capable of processing large airflow volumes but requiring higher regeneration energy (Sanz-Pérez et al., 2016)

While solid sorbents offer improved flexibility, they degrade under humidity and require frequent performance calibration. Conversely, large-scale solvent systems are thermodynamically efficient but costly to operate (Fasihi et al., 2019). According to the International Energy Agency (2022), global DAC capacity remains minuscule compared with climate targets, necessitating significant innovation to meet gigaton-scale carbon removal.

Artificial Intelligence in DAC Optimization

Research indicates that AI can significantly improve DAC performance:

1. Sorbent Discovery and Material Screening

Machine-learning models identify sorbents with high CO_2 affinity and faster regeneration properties (Rogers et al., 2022).

2. Predictive Behavior Modeling: AI forecasts thermal load, airflow resistance, and sorbent saturation patterns, enabling proactive system adjustments.

3. Digital Twins

AI-supported digital twins simulate DAC behavior under varying climatic and operational conditions (Lee et al., 2023).

4. Autonomous Process Control

Reinforcement-learning algorithms dynamically regulate temperature, airflow, and regeneration timing (Kulkarni & Witte, 2021).

These capabilities collectively reduce operational costs and improve long-term reliability.

III. CASE STUDIES

Climeworks (Iceland): Renewable-Centric DAC Deployment

Climeworks uses modular solid-sorbent DAC units powered by Iceland's geothermal energy. Their system demonstrates that pairing DAC with renewable sources significantly enhances life cycle sustainability. However, its limited capture capacity illustrates scalability challenges without AI-driven energy optimization (Beuttler et al., 2019).

Carbon Engineering (North America): Large-Scale Solvent Systems

Carbon Engineering's projects show strong potential for megaton-scale CO_2 removal, yet their dependence on heat-intensive solvent regeneration underscores the need for AI-based energy balancing and process automation (Keith et al., 2018).

Global Thermostat (United States): Modular Urban-Friendly Systems

Global Thermostat's amine-coated monoliths are well-suited for distributed deployment. Their compact architecture could benefit greatly from AI-assisted airflow control, enabling more efficient urban air recycling.

These examples illustrate promising foundations but lack full AI integration, revealing a key opportunity for future research.

Ethical Considerations (Expanded & Publication-Level)

1. Environmental and Social Equity

The deployment of large DAC plants in marginalized communities raises concerns about environmental justice. AI-optimized siting algorithms must incorporate social equity metrics to prevent disproportionate burdens.

2. Algorithmic Transparency and Data Governance

AI-enabled DAC requires extensive sensor data on environmental conditions, infrastructure performance, and community metrics. Without clear governance, such systems risk enabling surveillance or biased decision-making. Transparent algorithmic design and third-party auditing are essential.

3. Carbon Accountability

AI models must operate within low-carbon digital infrastructures to avoid shifting the environmental burden from physical emissions to computational energy consumption.

4. Moral Hazard in Climate Policy

Overreliance on DAC may reduce political pressure to curb emissions. Policies must ensure DAC complements, rather than substitutes, aggressive decarbonization.

5. Long-Term G,movernance and Public Trust

Public trust depends on transparent reporting, clear carbon accounting, and responsible communication about DAC's limitations and risks.

IV. FUTURE DIRECTIONS

- AI-enhanced electrochemical regeneration
- Lightweight, low-temperature sorbents
- Integrated AIoT (AI + IoT) pollution-governance systems
- Urban DAC clusters optimized by predictive AI
- Water-recovery co-products from DAC systems
- Low-carbon cloud computing for sustainable AI deployment

V. RECOMMENDATIONS

1.Governments should mandate AI-ethics and environmental-impact assessments for AI-driven DAC facilities.
2. Invest in renewable-powered, high-efficiency computing infrastructures to support sustainable AI.
3. Develop cross-sector data-sharing networks for Artificial intelligence -Direct Air Capture integration.
4. Create incentives for AI-enhanced DAC adoption in developing regions.

VI. CONCLUSION

Sustainable AI–enhanced DAC presents a transformative pathway for future air recycling and pollution control. By coupling efficient computational intelligence with advanced carbon-removal technologies, cities can establish adaptive, low-carbon strategies for long-term climate resilience. Continued interdisciplinary research, robust governance frameworks, and equitable policy design will be crucial in enabling these systems to operate responsibly at scale.

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