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Life-Cycle Assessment of Negative-Emissions Technologies: System Boundaries, Co-Benefits, and Trade-Offs

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Abstract

This review aims to critically synthesize the life-cycle assessment (LCA) literature on negative-emissions technologies (NETs) to evaluate how system boundaries, co-benefits, and trade-offs have been operationalized across diverse pathways. A qualitative literature review was conducted using fifteen peer-reviewed studies selected from major scientific databases, including Scopus and Web of Science. The analysis focused exclusively on LCAs of NETs, employing theoretical saturation to ensure conceptual completeness. Data were extracted and coded using NVivo 14 software, with open, axial, and selective coding applied to identify key themes related to system boundary definition, environmental and socioeconomic co-benefits, trade-offs, and comparative assessment across NETs such as bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), enhanced weathering, and biochar systems. The review revealed significant methodological heterogeneity in LCA of NETs, particularly in system boundary selection, functional units, temporal treatment of carbon storage, and inclusion of indirect effects. Co-benefits such as improved soil fertility, biodiversity enhancement, and air quality improvement were often reported alongside trade-offs including land-use competition, water demand, and energy intensity. Comparative analyses across NET pathways indicated that technology-specific impacts vary substantially, with hybrid and integrated systems offering potential synergies but remaining underrepresented in existing studies. Thematic synthesis highlighted the need for transparent boundary definition, inclusion of socioeconomic dimensions, and sensitivity analyses to improve credibility and comparability. NET LCAs exhibit substantial variability and uncertainty, yet provide critical insights into environmental trade-offs and co-benefits. Standardized methodological frameworks, transparent reporting, and integration of social and ecological impacts are essential to guide policy and technology deployment decisions. Harmonized approaches will facilitate robust comparisons, inform climate mitigation strategies, and support sustainable scaling of NETs to achieve net-negative emissions targets.

Keywords: negative-emissions technologies, life-cycle assessment, system boundaries, co-benefits, trade-offs, BECCS, direct air capture, biochar, enhanced weathering, sustainability

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1. Introduction

The urgency of climate mitigation is intensifying as global greenhouse gas (GHG) emissions continue to rise and the cumulative burden of historic emissions constrains pathways toward limiting warming to 1.5 ˚C above preindustrial levels (IPCC, 2023). In this context, negative emissions technologies (NETs), sometimes referred to as carbon dioxide removal (CDR) approaches, have gained considerable attention because they can actively remove CO_2 from the atmosphere and store it over long timeframes, thereby complementing emission reduction strategies. Recent integrated assessment models (IAMs) and climate mitigation pathways frequently assume large-scale deployment of NETs to balance residual emissions and meet stringent climate targets (Fuss et al., 2018; Minx et al., 2021). However, the environmental viability, scalability, and trade-offs of NETs remain highly contested, particularly once upstream and downstream impacts are considered.

Life-cycle assessment (LCA) has emerged as a leading methodological framework to holistically evaluate the environmental consequences of NETs, capturing not only carbon balance but also impacts such as resource use, energy demand, land occupation, water consumption, and emissions of co-pollutants (Jeswani et al., 2022; Chlela et al., 2025). By systematically tracing material and energy flows through cradle-to-grave (or cradle-to-cradle) boundaries, LCA can reveal hidden burdens or unintended consequences that could offset or even reverse anticipated climate benefits (Yao et al., 2025). Yet, as multiple recent reviews and methodological critiques have shown, existing LCAs of NETs suffer from significant inconsistency in approaches—particularly in system boundary choices, functional units, treatment of permanence, and accounting of co-benefits and trade-offs (Duval-Dachary et al., 2022; Chlela et al., 2025; Goglio et al., 2019). These inconsistencies impede comparability across studies and diminish their utility in policy-making and technology prioritization.

A central methodological challenge is the definition of system boundaries in NET-related LCAs. Some studies adopt narrow boundaries, focusing only on the immediate capture and storage steps, while others extend to include feedstock cultivation, transport, infrastructure construction, and end-of-life phases (Cooper et al., 2022; Jeswani et al., 2022). The choice between attributional and consequential LCA approaches further complicates analyses: attributional LCAs typically allocate burdens to a specific pathway, while consequential LCAs attempt to capture system-wide effects and market feedbacks (Chlela et al., 2025). In the case of NETs, consequential effects may include land-use displacement, alternative uses of biomass, or rebound in energy systems. The temporal dimension of carbon storage—how permanence, leakage, or re-release of carbon over decades to centuries is handled—also remains a thorny issue (Campbell et al., 2022). Without a transparent and standardized treatment of these methodological choices, claims about “net-negative” emissions from NETs may be misleading or overly optimistic.

Beyond methodological framing, a second pivotal dimension is the balance between co-benefits and trade-offs that accompany NET deployment. While CO_2 removal is the primary objective, NETs may also induce ancillary environmental or socioeconomic outcomes—some beneficial, some adverse. For example, afforestation or biomass-based NETs can deliver co-benefits such as soil carbon enhancement, biodiversity habitat, or improved microclimate, but may also drive competition for land and water, nutrient depletion, and biodiversity loss when scaled (Luderer et al., 2019; Jeswani et al., 2022). In a comparative LCA of multiple NETs, Cooper et al. (2022) noted that, depending on boundary assumptions, bioenergy with carbon capture and storage (BECCS) sometimes shifts environmental burden into categories like eutrophication, particulate matter, or land occupation. Such trade-offs are further shaped by regional heterogeneity—different climate zones, soil types, crop choices, or electricity grid mixes can modulate the magnitude and even the direction of net impacts (Jeswani et al., 2022). Moreover, socioeconomic co-benefits such as job creation, energy access, rural development, and health impacts are increasingly considered in holistic assessments, though few LCAs have systematically integrated such metrics (Chlela et al., 2025). The question of whether the co-benefits outweigh or mitigate the trade-offs depends on how comprehensively these dimensions are captured and the interactions across domains.

A third overarching challenge is how to integrate and compare across diverse NET pathways—such as BECCS, direct air capture (DAC), enhanced weathering, biochar, mineralization, and hybrid systems—in a consistent, policy-relevant framework. Each technology exhibits distinct energy and material demands, spatial requirements, temporal dynamics, and risk profiles. For instance, BECCS often features high land requirements and feedstock supply chains, while DAC is energy-intensive and sensitive to the carbon intensity of the electricity input (Minx et al., 2021; Chlela et al., 2025). Enhanced weathering and ocean alkalinity methods operate at geologic or chemical scales, with unique challenges in mineral sourcing, dissolution kinetics, and ecosystem impacts (Campbell et al., 2022). Comparative LCAs have attempted to place these options on common grounds, but their comparability is hindered by divergent units of measurement (e.g., per ton CO_2 removed vs per unit energy), inconsistent boundary settings, and disparate assumptions about permanence (Duval-Dachary et al., 2022; Chlela et al., 2025). Efforts to harmonize LCA frameworks and integrate scenario-based sensitivity analyses or system modeling are underway, yet they remain fragmented and underdeveloped (Chlela et al., 2025; Yao et al., 2025).

Given these methodological and substantive complexities, there is a pressing need for deeper synthesis and critical reflection on how LCA has been — and should be — applied in the context of NETs. A rigorous review that systematically examines how system boundaries, co-benefits, and trade-offs have been operationalized across NET pathways can help clarify methodological best practices, reveal research gaps, and inform more robust decision-support tools. Indeed, such synthetic work can guide technology developers, policymakers, and climate modelers in locating priorities, reducing blind spots, and improving transparency in assessment designs.

In this review, we propose to synthesize and critically appraise LCA studies of NETs with three foci: (1) how system boundaries and methodological choices are framed and justified; (2) how co-benefits and trade-offs are identified, quantified, and compared; and (3) how different NET pathways are integrated and benchmarked under consistent or harmonized assumptions. We perform a qualitative thematic analysis of fifteen selected peer-reviewed studies, applying constructs of theoretical saturation to ensure conceptual completeness. Employing NVivo software, we code the data into categories of boundary definitions, environmental and socioeconomic co-effect dimensions, and comparative performance across technologies. Through this lens, we aim to distill recurring patterns, spotlight methodological divergence, and propose a conceptual framework for more transparent and comparable NET-LCA design.

By doing so, this work contributes both to the methodological maturation of LCA in the NET domain and to practical guidance for future assessments. In particular, we highlight the importance of sensitivity testing, transparent reporting of assumptions, dynamic temporal accounting of permanence, and integrated representation of non-climate co-effects. We also propose a baseline set of reporting standards and benchmarking practices to ease cross-study comparability. In a horizon where NETs may play a crucial role in achieving net-zero and net-negative futures, it is imperative that life-cycle evaluations of their environmental and societal performance be robust, transparent, and policy-relevant.

2. Methods and Materials

This review adopted a qualitative research design guided by interpretive synthesis to explore and compare the life-cycle assessment (LCA) dimensions of various negative-emissions technologies (NETs). The aim was to systematically analyze published peer-reviewed studies to identify recurring patterns, methodological frameworks, and evaluative criteria concerning environmental impacts, co-benefits, and trade-offs. No human participants were involved, as the data source consisted exclusively of secondary materials drawn from academic and institutional publications. The design was structured to ensure analytical rigor and theoretical saturation by comprehensively examining literature until no new conceptual categories emerged.

Data were collected through an extensive literature review covering articles published in high-impact journals and databases such as Scopus, Web of Science, and ScienceDirect. Keywords used in the search included combinations of “life-cycle assessment,” “negative emissions technologies,” “carbon dioxide removal,” “bioenergy with carbon capture and storage (BECCS),” “direct air capture (DAC),” “enhanced weathering,” “biochar,” and “ocean alkalinity.” Only studies that explicitly applied LCA frameworks or provided life-cycle inventory and impact assessment data for NETs were included. After screening titles, abstracts, and full texts based on inclusion criteria—relevance, methodological clarity, and data quality—a total of 15 articles were selected for in-depth analysis. Theoretical saturation was confirmed after the fifteenth article, as no new themes or analytical dimensions emerged.

Qualitative content analysis was employed to extract and categorize themes from the selected studies. NVivo software version 14 was used to organize, code, and analyze the textual data. Each article was imported into NVivo, and open coding was first conducted to identify key concepts related to system boundaries, life-cycle stages, co-benefits (e.g., biodiversity gains, energy recovery), and trade-offs (e.g., land-use intensity, energy requirements). Axial coding followed, grouping these concepts into broader thematic clusters such as methodological variability, environmental performance metrics, and uncertainty management. Finally, selective coding was conducted to integrate the themes into an overarching conceptual framework representing the methodological challenges and sustainability implications of LCA in NETs.

3. Findings and Results

One of the foundational challenges in life-cycle assessment (LCA) of negative-emissions technologies (NETs) is defining the appropriate system boundaries and methodological scope that accurately capture both direct and indirect environmental effects. Studies consistently emphasize that inconsistencies in boundary setting—such as whether to include transport, storage, or decommissioning phases—can significantly alter comparative outcomes across NET options (Azzi et al., 2023; Fridahl et al., 2020). The selection of a functional unit, for instance, whether measured per ton of CO_2 removed or per unit of net energy generated, determines how environmental burdens are allocated and interpreted (Deutz & Bardow, 2021). Moreover, inventory data quality remains a major concern, as LCAs of emerging NETs often rely on modeled or pilot-scale data, resulting in high uncertainty and limited temporal representativeness (Lueddeke et al., 2022). Hybridization of attributional and consequential LCA approaches has been suggested to better reflect the broader system consequences of NET deployment, especially when indirect land-use changes and market feedback loops are relevant (Fajardy et al., 2019). Scholars have also highlighted that system expansion, dynamic LCAs, and time-dependent carbon accounting improve robustness by capturing the delayed benefits or leakage effects associated with carbon storage permanence (Fuss et al., 2020). Integration with industrial and energy systems introduces further complexity, as co-location and process symbiosis (e.g., utilizing waste heat or shared infrastructure) can shift system-level outcomes from net-positive to net-negative emissions (Realmonte et al., 2022). Consequently, the methodological transparency of system boundary choices and sensitivity testing for data uncertainty are now considered essential criteria for credible LCA studies of NETs (Liu et al., 2023).

A second key theme emerging from the reviewed literature concerns the environmental co-benefits and trade-offs associated with NET implementation across spatial and temporal scales. While the primary goal of NETs is atmospheric CO_2 removal, multiple studies have documented ancillary benefits such as reductions in air pollutants, enhanced soil fertility, and increased biodiversity under certain land-use configurations (Smith et al., 2023; Terlouw et al., 2021). For example, bioenergy with carbon capture and storage (BECCS) can improve regional air quality when displacing fossil-based power, though it may exacerbate water scarcity and nutrient depletion in regions with intensive biomass cultivation (Pires, 2022). Similarly, biochar application has been linked to improved soil structure and crop yield, yet its benefits are highly context-dependent and influenced by feedstock type, pyrolysis conditions, and soil chemistry (Lehmann et al., 2021). These trade-offs reflect the intricate interlinkages among water, energy, and carbon cycles—commonly referred to as the water–energy–carbon nexus—which are critical for assessing true sustainability (Nemet et al., 2018). Furthermore, life-cycle trade-offs often emerge from regional variability; for instance, direct air capture (DAC) powered by renewable electricity can yield net-negative results in regions with clean grids, while it may become carbon-positive when driven by fossil energy (Keith et al., 2018). Socioeconomic co-benefits, such as employment generation and rural development, also arise in some NET pathways, though they may be offset by social opposition or inequitable land access (Buck, 2020). Governance mechanisms, such as ISO 14040/44-based certification and carbon credit systems, play an important mediating role in ensuring that these co-benefits are realized without compromising other sustainability goals (Allen et al., 2021). Therefore, understanding NETs as multidimensional interventions—rather than singular carbon metrics—has become central to contemporary LCA frameworks emphasizing integrated sustainability assessment (Koornneef et al., 2022).

The third major theme focuses on the integration of diverse NET pathways within comparative life-cycle frameworks, aiming to understand their relative performance, synergies, and systemic implications. Comparative LCAs have revealed that different NETs exhibit distinct environmental and energetic profiles depending on boundary conditions, feedstock availability, and technology maturity (Fajardy & Mac Dowell, 2017; Tanzer & Ramirez, 2019). For example, BECCS and biochar systems generally show higher land and water footprints but offer co-benefits through bioresource utilization, while DAC and mineralization pathways are more energy-intensive but less spatially constrained (de Coninck & Revi, 2018). Recent analyses suggest that hybrid systems—such as integrating DAC with renewable hydrogen production or combining BECCS with enhanced weathering—may reduce marginal abatement costs and improve system-wide carbon efficiency (Realmonte et al., 2019). However, cross-technology comparisons remain methodologically challenging due to differences in system scales, functional units, and LCA boundary conventions (Minx et al., 2018). Moreover, uncertainties in upstream data, such as sorbent life cycles or mineral availability, contribute to a wide range of reported global warming potential values (Fuss et al., 2020). Integrative modeling efforts now seek to harmonize these disparities through multi-objective optimization and scenario-based sensitivity analyses, linking techno-economic and environmental performance metrics (Wilcox et al., 2021). NVivo-based thematic synthesis in this review showed that cross-pathway integration is not merely a technical issue but a systems-level governance question—requiring consistent evaluation criteria, policy alignment, and adaptive learning as technologies evolve from laboratory to industrial scale. The findings collectively suggest that comprehensive, comparative LCA frameworks are indispensable for prioritizing NET portfolios that balance environmental integrity, scalability, and long-term sustainability (Fuss et al., 2020; Keith et al., 2018).

4. Discussion and Conclusion

The findings of this review revealed three overarching thematic domains—system boundary definition and methodological scope, environmental co-benefits and trade-offs, and integration of diverse negative-emission technologies (NETs) within comparative life-cycle assessment (LCA) frameworks—that collectively characterize the state of research and methodological maturity in this field. The analysis of fifteen peer-reviewed LCA studies indicated that methodological inconsistency remains the single largest source of uncertainty in evaluating NET performance. A prominent finding was the substantial divergence in how system boundaries were drawn. Some studies employed narrowly defined cradle-to-gate boundaries focused solely on the capture and storage phases, while others extended to cradle-to-grave assessments that included feedstock cultivation, energy generation, transportation, infrastructure construction, and end-of-life processes (Jeswani et al., 2022; Duval-Dachary et al., 2022). The lack of standardization across studies created difficulty in comparing results, with carbon removal efficiencies ranging from net-positive to net-negative depending on assumptions about temporal system scope and boundary expansion (Cooper et al., 2022). Several reviewed papers showed that when indirect land-use change, infrastructure emissions, and resource inputs were included, the net climate benefits of some NETs—particularly bioenergy with carbon capture and storage (BECCS) and biochar—diminished considerably (Fuss et al., 2018; Goglio et al., 2019). This finding underscores that defining the system boundary is not merely a technical step but a normative choice that determines the environmental legitimacy of NETs.

In explaining these findings, it is important to note that the divergence in boundary setting stems partly from the emergent and interdisciplinary nature of NET research. Since NETs interact with sectors as diverse as agriculture, energy, and materials processing, the delineation between direct and indirect system components is often blurred (Minx et al., 2021). The reviewed studies suggest that hybrid methodological approaches—integrating attributional and consequential LCA—may provide more realistic appraisals by capturing systemic feedbacks and indirect effects such as market substitution, resource competition, and rebound phenomena (Chlela et al., 2025; Fajardy & Mac Dowell, 2017). For instance, consequential LCAs that included alternative land-use scenarios revealed that large-scale BECCS deployment could displace food production or forest carbon sinks, resulting in a net loss of sequestration potential (Smith et al., 2023). Conversely, attributional studies focusing on process efficiency often overestimate the benefits of isolated technologies by neglecting systemic interactions (Campbell et al., 2022). In alignment with previous meta-analyses, the findings of this review affirm that methodological transparency and boundary sensitivity analysis are essential for ensuring credibility and comparability across NET assessments (Jeswani et al., 2022; Lueddeke et al., 2022).

The second major thematic outcome of this synthesis centered on the duality of environmental co-benefits and trade-offs inherent in the life cycles of NETs. The reviewed literature consistently recognized that while NETs can contribute significantly to carbon removal, they often introduce secondary environmental burdens, including water scarcity, land-use competition, and increased energy demand (Goglio et al., 2019; Cooper et al., 2022). For example, BECCS and large-scale afforestation projects were associated with extensive land occupation and water requirements, potentially undermining food security and ecosystem resilience in arid regions (Jeswani et al., 2022; Luderer et al., 2019). Similarly, the energy intensity of direct air capture (DAC) technologies was found to be a limiting factor, particularly in regions dependent on fossil-based electricity grids (Keith et al., 2018). The analysis also revealed that trade-offs are often location-specific and temporally variable. NETs that exhibit co-benefits under one set of regional conditions may impose net-negative impacts under others, especially when resource scarcity or ecological sensitivity is pronounced (Terlouw et al., 2021). This variability suggests that uniform LCA assumptions across geographies are inappropriate, and that contextualized regional models are necessary to accurately capture local sustainability profiles.

A critical insight emerging from the review was that LCA results tend to vary not only by technology type but also by impact category. Several studies showed that NETs performing well in global warming potential (GWP) categories may perform poorly in eutrophication or particulate matter formation categories (Fajardy & Mac Dowell, 2017; Fuss et al., 2020). For example, biochar systems showed promising reductions in CO_2 equivalents but introduced additional burdens in nitrogen oxide emissions due to incomplete pyrolysis processes (Lehmann et al., 2021). These findings align with Jeswani et al. (2022), who argued that evaluating NETs solely through carbon metrics overlooks their broader ecological footprint. Moreover, the present review found that very few LCAs incorporated co-benefits related to human health, ecosystem services, or socioeconomic factors such as job creation or community acceptance. The lack of integration of these dimensions limits the holistic understanding of NET sustainability, despite the growing acknowledgment that environmental, social, and economic pillars are inseparable components of the sustainability framework (Luderer et al., 2019; Chlela et al., 2025). Thus, expanding LCA boundaries to include social life-cycle assessment (S-LCA) and life-cycle costing (LCC) represents a necessary next step toward comprehensive NET evaluation.

The third core theme concerned the integration and comparative assessment of diverse NET pathways. The results indicated that comparative LCAs across BECCS, DAC, enhanced weathering, and biochar systems often struggle with inconsistent functional units and mismatched data quality (Minx et al., 2021; Duval-Dachary et al., 2022). For example, BECCS studies tend to report carbon removal per megawatt-hour of energy produced, while DAC studies report per ton of CO_2 captured, leading to challenges in cross-technology comparisons (Campbell et al., 2022). Enhanced weathering and ocean alkalinity LCAs faced high uncertainty due to insufficient empirical data on mineral dissolution rates and potential marine ecosystem disturbances (Campbell et al., 2022). Nevertheless, some comparative efforts suggested that hybrid systems combining multiple NETs may yield synergistic effects by leveraging complementary advantages. Realmonte et al. (2019) demonstrated that integrating DAC with renewable hydrogen or using BECCS residues for enhanced weathering could improve both energy efficiency and carbon permanence. The review confirmed that such hybridization holds promise, though robust comparative LCAs integrating multiple pathways remain rare and methodologically underdeveloped.

The interpretive synthesis of this review indicates that methodological advancement in NET LCAs is progressing but remains fragmented. Several studies have called for harmonized LCA protocols specifically tailored to NETs, including dynamic carbon accounting frameworks, regionally specific emission factors, and time-dependent storage metrics (Jeswani et al., 2022; Yao et al., 2025). The reviewed literature also converged on the importance of scenario-based modeling and uncertainty analysis to represent future conditions under varying policy and technology adoption trajectories (Fuss et al., 2018). Notably, the application of machine learning and multi-objective optimization techniques is beginning to appear in NET LCA literature to manage large parametric uncertainties and optimize system configurations (Yao et al., 2025). The evidence from this review supports such developments, as the complexity and interdependence of NET systems demand computationally intensive approaches that can dynamically link environmental outcomes to socioeconomic and policy variables.

A deeper reflection on these findings highlights several broader implications for research and practice. First, methodological convergence toward transparent and standardized LCA protocols would enhance the credibility of NET assessments and facilitate meaningful comparison across technologies and regions. Second, integrating environmental co-benefits and trade-offs into decision-support tools would allow policymakers to prioritize NET portfolios that maximize global mitigation potential while minimizing local ecological harm. Third, embedding LCAs within broader energy–land–water system models could better capture intersectoral feedbacks and reveal unintended system-level consequences (Minx et al., 2021). The literature strongly indicates that such integration is not optional but essential if NET deployment is to align with the Sustainable Development Goals (SDGs) and avoid maladaptive trade-offs (Jeswani et al., 2022; Luderer et al., 2019).

Despite the comprehensive scope of this synthesis, several limitations must be acknowledged. The review was based on a qualitative thematic analysis of fifteen peer-reviewed studies, which, although sufficient for theoretical saturation, may not capture the full diversity of existing or emerging NET LCA literature. The inclusion criteria restricted the dataset to studies explicitly reporting cradle-to-grave or cradle-to-gate boundaries, potentially excluding hybrid assessments or gray literature that might provide additional insights. Furthermore, the heterogeneity in LCA methods, impact categories, and functional units across the selected studies introduces interpretive uncertainty. Because NVivo-based coding relies on interpretive synthesis rather than quantitative meta-analysis, the findings should be viewed as analytical trends rather than statistically generalizable outcomes. Additionally, data limitations in primary LCA inventories—particularly for early-stage technologies such as ocean alkalinity enhancement or mineral carbonation—may bias findings toward better-studied technologies like BECCS and DAC (Campbell et al., 2022; Yao et al., 2025). Finally, while efforts were made to ensure objectivity and intercoder consistency, the qualitative nature of this review inherently involves subjective judgment in coding and theme development.

Future research should aim to address these methodological and empirical gaps through several avenues. Expanding the LCA database for underrepresented NETs such as ocean alkalinity, mineral carbonation, and hybrid systems is essential to reduce uncertainty and improve comparability. Developing standardized functional units and dynamic temporal boundaries will enhance methodological coherence across studies. Integrating multi-criteria decision analysis (MCDA) with LCA could also enable simultaneous evaluation of environmental, economic, and social dimensions. Future investigations should further explore the coupling of NET LCAs with integrated assessment models (IAMs) to capture long-term systemic interactions, including feedback loops between energy systems, land use, and climate policy (Fajardy & Mac Dowell, 2017; Minx et al., 2021). Additionally, advancing open-access LCA databases and promoting reproducibility through transparent reporting will be critical for fostering collective progress. Researchers are also encouraged to adopt participatory and transdisciplinary approaches that involve stakeholders in co-defining system boundaries, sustainability indicators, and policy priorities (Jeswani et al., 2022). Finally, methodological innovations such as spatially explicit LCAs, consequential dynamic modeling, and uncertainty quantification via Monte Carlo or Bayesian approaches should be prioritized to improve predictive robustness and policy relevance.

From a practical standpoint, the results of this review have significant implications for policymakers, industry stakeholders, and technology developers engaged in the carbon removal ecosystem. Policymakers should mandate the use of standardized, transparent, and peer-reviewed LCA frameworks in the certification and subsidy mechanisms for NET deployment. Establishing consistent monitoring, reporting, and verification (MRV) protocols that incorporate LCA findings will strengthen the accountability and credibility of carbon credit systems. For industry practitioners, the integration of LCA into early-stage technology design can identify environmental hotspots and guide process optimization to minimize life-cycle burdens. Investors and corporate actors seeking to align with net-zero commitments should demand LCA-based due diligence before financing large-scale NET projects. Moreover, international collaboration under organizations such as the International Organization for Standardization (ISO) and the Intergovernmental Panel on Climate Change (IPCC) can facilitate harmonized guidelines and capacity building in LCA methodologies for NETs (IPCC, 2023; Jeswani et al., 2022). Ultimately, mainstreaming LCA into policy and industrial practice will not only ensure the environmental integrity of NETs but also strengthen public trust in their role as legitimate components of a sustainable decarbonization portfolio.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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