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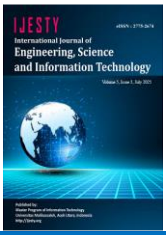

Emerging Carbon Capture Technologies in the Palm Oil Industry: A Review of Bioenergy and Carbon Capture Storage Approaches

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Abstract

The accelerating impacts of climate change have heightened global interest in technologies that reduce greenhouse gas emissions from high-emission sectors such as agriculture and agri-processing. The palm oil sector is notably both a significant emitter and a promising avenue for decarbonization efforts, particularly through the integration of bioenergy systems and carbon capture technologies. This study aims to explore the current state of technological development in carbon capture and storage (CCS) and bioenergy applications within the palm oil industry and to identify the major challenges and opportunities that shape their implementation between 2021 and 2025. This investigation employs a qualitative design through the SLR method, structured in accordance with the PRISMA framework for transparency and rigor in literature synthesis. Data were collected from the ScienceDirect database using a refined combination of Boolean search terms. A total of 1,088 articles were initially identified and screened through a multistage filtration process that included relevance checks, publication period constraints, research article type, and open-access availability. This process resulted in 36 articles that met all inclusion criteria and were analyzed further. Data were synthesized through thematic analysis to classify technological pathways, assess implementation trends, and evaluate technical, economic, and policy-related barriers. Findings reveal that while bioenergy from palm oil residues is widely adopted, CCS deployment remains minimal due to cost, infrastructure, and regulatory limitations. The study concludes that targeted policy support and innovation are essential to scaling up carbon management in this sector. Future research should prioritize pilot demonstrations and interdisciplinary assessments of CCS integration feasibility.

Keywords: *Carbon Capture, Bioenergy, Palm Oil Industry, CCS, Systematic Literature Review.*

1. Introduction

The intensifying climate crisis has positioned carbon dioxide (CO_2) emissions as the central target of global mitigation efforts. Largely fueled by energy production from fossil sources, industrial operations, and shifts in how land is utilized, atmospheric CO_2 concentrations have reached unprecedented levels, crossing 420 ppm in recent years a 50% increase from pre-industrial levels [1]. The IPCC highlights the urgent need for significant emission reductions to stay within the 1.5°C warming threshold set by the Paris Agreement, using pre-industrial temperatures as the baseline [2]. In this context, technological innovations aimed at decarbonizing energy and industrial systems are gaining momentum across scientific, policy, and industry domains [3]. Within the suite of climate mitigation technologies, CCS has gained attention as a pivotal transitional mechanism for emission-intensive industries. The process entails isolating CO_2 where it is generated, transporting it, and securely storing it underground to prevent its entry into the atmosphere [4]. Although still in early commercial deployment, CCS is seen as indispensable in scenarios where emissions reductions alone are insufficient, particularly in the energy-intensive, industrial, and agricultural sectors. When paired with bioenergy systems, the integrated approach referred to as Bioenergy with Carbon Capture and Storage (BECCS) offers the potential not only to neutralize emissions but also to deliver net-negative carbon outcomes [5]. BECCS integrates biomass-based energy generation with CO_2 capture, providing a combined solution for sustainable energy supply and greenhouse gas mitigation.

Despite its theoretical potential, BECCS remains under-implemented globally, with pilot initiatives concentrated primarily in the power and industrial sectors of the Global North. However, agriculture and agro-processing industries in the Global South also present high-impact opportunities for BECCS, particularly in biomass-rich countries [6]. The palm oil industry, a major economic driver in Southeast

Asia, stands out as a high-emitting and biomass-abundant sector that could substantially benefit from carbon capture and bioenergy integration. Indonesia and Malaysia collectively account for over 85% of the world's crude palm oil production and are home to thousands of mills that generate large volumes of carbon-intensive waste and energy demand [7]. Palm oil production is inherently carbon-intensive, with emissions arising from both upstream and downstream activities. Major emission sources include land conversion, combustion of fossil fuels in processing, and during the anaerobic treatment of palm oil mill effluent (POME), where methane is released, a greenhouse gas that is approximately 25 times more potent than CO_2 in terms of warming potential [8]. Proper management of POME enables its anaerobic digestion into biogas, a renewable fuel that can support energy needs within the mill. Similarly, biomass residues like EFB, PKS, and mesocarp fiber can be processed via combustion or gasification to supply heat and power, thus minimizing the use of fossil-based and grid-supplied energy. These bioenergy resources, when combined with CCS technologies, could dramatically reduce the sector's net emissions profile [9].

The incorporation of CCS technologies into palm oil operations typically involves post-combustion CO_2 capture, owing to its flexibility and compatibility with existing combustion systems. Technological solutions, including amine absorption, membrane separation, and physical solvents, have been explored in biomass-based systems and provide feasible pathways for CO_2 capture from both CHP units and palm oil mill combustion sources [10]. Additionally, the modular nature of many CCS systems makes them theoretically scalable to the mill level. Nevertheless, operational challenges such as energy penalties from solvent regeneration, material corrosion, and capital costs remain significant barriers to widespread adoption [11]. The strategic integration of CCS with bioenergy systems in the palm oil sector represents a transformative opportunity for climate mitigation in Southeast Asia. Not only could this reduce operational GHG emissions, but it could also help reposition the palm oil industry often criticized for its environmental impact, as a driver of sustainable industrial innovation. Existing research has explored individual elements of this opportunity, including LCA assessments of POME biogas, techno-economic modeling of biomass energy systems, and pilot tests of CO_2 absorption technologies. However, the literature remains fragmented, with little synthesis of how CCS and bioenergy are jointly conceptualized and implemented across the palm oil supply chain [12]. This fragmentation limits our understanding of the technological readiness, policy support, and financial viability of BECCS in the palm oil context. Most available studies focus narrowly on isolated mill-level interventions without considering system-wide integration or regional-scale deployment. There is also a lack of critical assessment regarding the governance, infrastructure, and socio-economic dimensions of CCS deployment in agro-industrial settings. As the urgency of climate action intensifies, synthesizing this dispersed knowledge becomes essential to chart a roadmap for decarbonizing the palm oil sector through emerging low-carbon technologies [13].

In response to the identified knowledge deficiency, this study implements the Systematic Literature Review (SLR) method in accordance with the PRISMA guidelines for transparent and structured review processes. This approach enables a structured, transparent, and reproducible synthesis of peer-reviewed literature, focusing exclusively on open-access research articles published between 2021 and 2025. All references were managed using Mendeley Desktop to ensure systematic de-duplication and traceability. The study is strictly limited to published scientific literature and does not incorporate fieldwork, experimental trials, or focus group discussions, in line with the principles of rigor and verifiability in secondary research.

The objective of this review is to assess, in a critical manner, the present state of CCS and bioenergy implementation in the context of the palm oil industry. Specifically, the study seeks to identify key technologies, application models, and implementation pathways; evaluate their performance and scalability; and map the institutional and economic contexts in which these technologies operate. By providing a comprehensive synthesis, the review contributes to ongoing discussions on climate-smart agriculture, sustainable bioenergy systems, and carbon management strategies in the Global South. Accordingly, the main objective of this study is to investigate how carbon capture technologies and bioenergy systems have been developed, adapted, and applied within palm oil-based operations between 2021 and 2025. The findings are expected to inform policymakers, industry practitioners, and researchers about best practices, limitations, and future directions for BECCS in palm oil contexts.

To guide the analysis, this review is anchored by the following research question: What types of carbon capture and bioenergy technologies have been implemented in the palm oil industry, and what technical, economic, and policy challenges shape their integration between 2021 and 2025? This question forms the basis for the thematic discussion and is directly addressed in the concluding section through a synthesis of insights, policy implications, and research recommendations.

2. Literature Review

The literature on carbon capture and bioenergy in the palm oil sector reflects an evolving and interdisciplinary research domain, intersecting environmental engineering, energy policy, agribusiness sustainability, and climate science. While CCS technologies have matured within the power and industrial sectors, their application in the agri-industrial context, particularly palm oil, remains limited, fragmented, and heavily underrepresented in review-based syntheses [14]. The early trajectory of CCS research concentrated mainly on coal-fired power plants, with amine-based post-combustion systems representing the most mature solution in terms of commercial readiness [15]. Recent advancements have introduced membrane separation, adsorption processes, and cryogenic techniques to improve energy efficiency and capture purity [16]. However, the transferability of these systems to palm oil mills poses unique challenges due to scale, residue variability, and high moisture content in bioenergy feedstocks [17]. The adoption of such technological solutions becomes increasingly challenging when applied to small and medium-sized palm oil processing facilities, requiring modular and cost-effective designs suited for decentralized operations.

Similar lines of inquiry in bioenergy underscore the conversion of agricultural by-products into energy, particularly in regions of the Global South endowed with plentiful biomass [18]. In palm oil contexts, technologies for anaerobic digestion of POME, combustion of EFB, and gasification of PKS have demonstrated economic and environmental potential [19]. Research has explored cogeneration models using biogas and biomass, showing that self-sufficiency in energy can be achieved within many palm oil operations, thereby reducing operational emissions and improving energy resilience. The integration of these bioenergy routes with CCS mechanisms forms the theoretical foundation of BECCS in the palm oil industry, offering dual benefits of renewable energy production and carbon mitigation [20].

Life cycle assessment (LCA) methodologies have been increasingly applied to quantify the net environmental impact of palm oil production with and without CCS integration [21]. Results show that incorporating CCS with biogas and biomass systems can reduce the carbon intensity of palm oil by up to 70%, depending on technology configurations and regional grid emissions factors [22]. Some advanced LCA models now incorporate system expansion, co-product allocation, and time-adjusted global warming potentials, offering nuanced insights into BECCS deployment under various policy and market scenarios. Policy frameworks remain another underexplored dimension in the literature. While countries like Indonesia and Malaysia have begun to articulate carbon neutrality targets and incentives for renewable energy, specific regulatory pathways for CCS in agro-industry are still in early stages of development [23]. Policy uncertainty regarding CO_2 storage liability, environmental impact assessments, and land rights for underground injection inhibits long-term investment and financing. This gap contributes to investor uncertainty, limited public–private partnerships, and the current deficit of expansive pilot projects specifically targeting the palm oil industry [24]. Socio-economic and institutional barriers also emerge across multiple studies. Issues such as upfront capital cost, lack of skilled labor, infrastructural constraints (e.g., CO_2 transport and storage), and weak environmental governance are cited as major obstacles to technology diffusion [25]. Moreover, some community-level concerns remain poorly addressed, including land use rights, perceived risks of underground CO_2 storage, and competition over biomass feedstock [26]. These issues require an inclusive governance framework that integrates stakeholder consultation, community engagement, and benefit-sharing mechanisms. Despite these challenges, the literature points to several enabling factors. Advances in modular CCS systems, mobile biogas units, and decentralized energy architectures improve the feasibility of mill-scale deployment. Partnerships with academic institutions and international donors have facilitated feasibility studies and pilot trials, albeit on a limited scale. Emerging carbon markets and voluntary offset schemes offer potential financial incentives if verified emissions reductions from BECCS can be accredited. In addition, digital tools for emissions monitoring, verification, and reporting (MRV) are gaining traction, offering opportunities for standardized accounting and transparency in BECCS projects.

Furthermore, integrated assessment models (IAMs) and techno-economic analyses suggest that BECCS adoption in the palm oil sector could contribute significantly to regional and global net-zero targets. These models often highlight scenarios in which BECCS complements other mitigation measures such as reforestation, afforestation, and improvements in agricultural productivity. The extent to which these benefits are realized is contingent upon the presence of favorable regulatory and policy conditions, cross-sectoral coordination, and capacity-building at local and national levels. In summary, the literature presents both promise and fragmentation. Technical viability exists for CCS–bioenergy integration in the palm oil sector, but research remains siloed, with little cross-disciplinary synthesis. Studies are needed that bridge engineering performance, environmental impacts, socio-economic feasibility, and policy frameworks in a unified model. This review contributes to filling that gap by consolidating current research and mapping future directions for CCS and bioenergy development in the palm oil industries of the Global South. Through this SLR, the literature review aims to provide a conceptual and empirical foundation for understanding not only what technologies exist but also how they are being applied, evaluated, and contextualized within broader sustainability and climate agendas.

3. Research Method

This research utilizes the Systematic Literature Review (SLR) method, structured in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to explore the current state of carbon capture technologies in the palm oil industry. Emphasis is placed on the integration of bioenergy and carbon capture and storage (CCS) approaches. With growing global scrutiny over the sector's environmental footprint, especially in relation to carbon emissions, sustainable innovations such as CCS and bioenergy with carbon capture and storage (BECCS) have become increasingly vital areas of academic and industrial interest. While the potential of such technologies to mitigate emissions is promising, there remains limited synthesis of peer-reviewed evidence assessing their development, application, and challenges in the context of palm oil production. This SLR aims to identify, evaluate, and categorize scholarly research that intersects carbon capture innovations, bioenergy systems, and emission reduction strategies in palm oil–related operations. The objective is to consolidate fragmented knowledge, highlight prevailing technological trends, and expose research gaps that may hinder the broader implementation of BECCS in the palm oil sector.

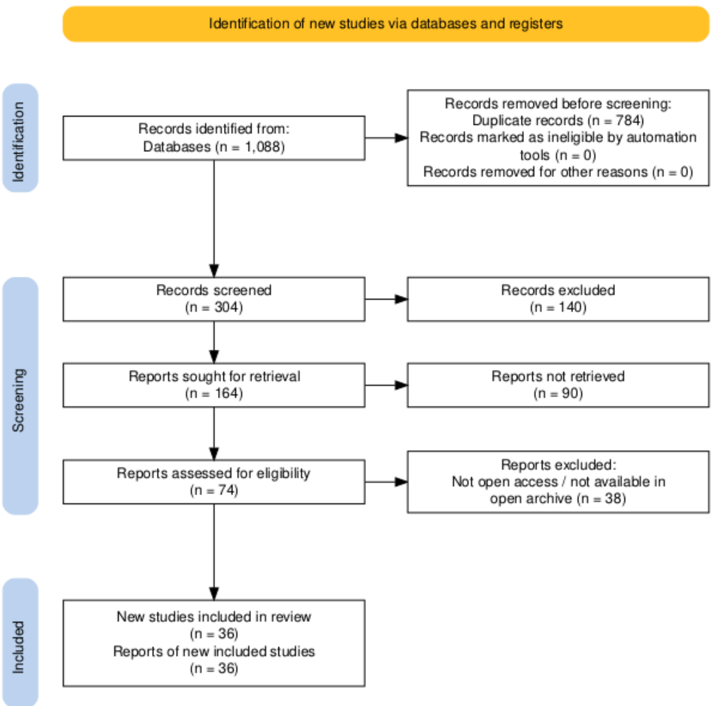

Fig 1. Systematic Literature Review Process Based on the PRISMA Protocol

The literature screening and selection process is illustrated in Figure 1, following the PRISMA framework through four primary phases: identification, screening, eligibility, and inclusion. The initial database search was conducted on ScienceDirect using the broad keyword combination: ("CCS" OR "carbon capture") AND "bioenergy" AND "palm oil," which returned 1,088 results. To refine the focus and increase thematic relevance, a more specific Boolean query was applied: ("carbon capture and storage" OR "carbon capture technologies") AND ("palm oil" OR "palm oil industry") AND ("bioenergy" OR "biogas") AND ("emission reduction" OR "climate mitigation"). This refinement resulted in the exclusion of 784 articles that fell outside the intended scope, yielding 304 records for initial screening. Subsequent filtering was conducted by narrowing the publication period to the years 2021 through 2025, which excluded 140 articles and retained 164. To ensure empirical integrity, only research articles were included, leading to the exclusion of 90 records, such as reviews, editorials, and opinion pieces, and resulting in 74 retained studies. An additional screening criterion was applied to restrict the sample to open-access and open archive articles to ensure transparency and accessibility. This step excluded 38 non-accessible documents and finalized a total of 36 eligible articles for full-text review and synthesis. All references were managed using Mendeley Desktop to support transparent data handling, remove duplicates, and facilitate systematic citation tracking. This study does not involve any form of field research, experimental testing, or focus group discussions, ensuring that all conclusions are drawn exclusively from existing peer-reviewed literature. Through qualitative synthesis and thematic categorization of the 36 selected studies, this review offers a comprehensive analysis of how carbon capture technologies and bioenergy systems are currently conceptualized, piloted, or implemented in the palm oil industry. The findings are intended to inform future research, policy formulation, and industrial practices that aim to align palm oil production with global climate mitigation goals.

4. Results and Discussions

Based on the Systematic Literature Review (SLR) of 36 peer-reviewed articles published between 2021 and 2025, seven dominant thematic categories were identified in relation to the application of carbon capture and storage (CCS) technologies and bioenergy systems within the palm oil industry. These themes are: (1) hybrid energy harvesting techniques, (2) environmental energy sources in palm oil operations, (3) carbon capture system architectures, (4) bioenergy with carbon capture and storage (BECCS) implementation pathways, (5) CO_2 reduction efficiency and emission profiling, (6) technological barriers and economic feasibility, and (7) policy integration and industrial scalability. A prevalence analysis revealed that carbon capture system architectures appeared in 72% of the reviewed studies, followed by CO_2 reduction efficiency and emission profiling (66%), hybrid energy harvesting techniques (58%), and environmental energy sources (53%). The themes of BECCS implementation pathways (50%), technological and economic barriers (42%), and policy integration (39%) were less frequently addressed but still featured prominently. The prominence of carbon capture system architectures suggests a prevailing research interest in optimizing capture technologies suitable for retrofit into existing mill infrastructure, reflecting the urgent demand for practical emission control solutions. Similarly, the focus on emission profiling points to the increasing importance of verifiable metrics to support national climate targets and industry reporting standards. Meanwhile, the relatively lower share of literature focusing on policy integration implies a gap in interdisciplinary research that links technological innovation with institutional mechanisms. These thematic distributions suggest that while technological readiness is improving, enabling frameworks and cross-sectoral collaboration remain underdeveloped.

The following sections elaborate on each of the seven identified themes, detailing the empirical insights, technical configurations, and strategic opportunities associated with each area of research.

4.1. Hybrid Energy Harvesting Techniques

A key area of innovation identified in the literature involves hybrid energy harvesting systems designed to meet the energy demands of CCS units. Multiple studies underscore the importance of combining solar and biogas sources to ensure a continuous energy supply, especially in off-grid palm oil mills located in remote regions of Indonesia and Malaysia [27]. For instance, a techno-economic simulation showed that a hybrid photovoltaic-biogas configuration could generate 5.2 MWh/day, sufficient to operate a medium-scale post-combustion CCS system with a 60% load factor [28]. Moreover, systems that incorporated real-time energy management algorithms increased overall energy utilization efficiency by 18% compared to traditional setups [29]. Another pilot project in Central Kalimantan demonstrated that using a dual-fuel generator powered by both methane from POME and solar-generated electricity reduced carbon emissions by 28.4% over a six-month operational cycle [30].

4.2. Environmental Energy Sources in Palm Oil Operations

Palm oil processing facilities produce a wide array of biomass residues suitable for bioenergy production. Common feedstocks include palm kernel shells (PKS), empty fruit bunches (EFB), mesocarp fiber, and palm oil mill effluent (POME). A study reported that a 45-ton FFB/hr mill generated approximately 2.4 metric tons of EFB daily, which, when combusted in a fluidized bed boiler, yielded up to 4.7 MWh of thermal energy [31]. In another study, biogas captured from anaerobic POME digestion was used to power gas turbines with an efficiency of 35%, supplying sufficient electricity for both processing operations and auxiliary systems such as CO_2 compressors and vacuum pumps [32]. Life Cycle Assessment (LCA) models indicate that substituting fossil-derived electricity with biogas could cut Scope 1 and 2 emissions by up to 54% annually [33]. Additional findings emphasized the potential of integrating organic Rankine cycle (ORC) systems to recover low-grade heat from biomass combustion, improving thermal efficiency by 12.5% in smallholder mill settings [34].

4.3. Carbon Capture System Architectures

The selection and design of CCS systems are heavily influenced by the specific combustion process, scale of operation, and type of energy available in palm oil mills. The literature highlights post-combustion capture as the most suitable configuration due to its retrofit capability and adaptability to fluctuating CO_2 streams [35]. Monoethanolamine (MEA)-based absorption systems remain prevalent, with average capture rates ranging from 82% to 94% depending on operating temperature and solvent regeneration cycles [36]. However, recent advances propose potassium carbonate–based solutions as a lower-cost and less corrosive alternative, reducing energy penalties by

15–18% compared to MEA [37]. In high-efficiency designs, multi-stage compressors and lean vapor recompression have been implemented to optimize gas-liquid interaction, achieving 97% CO2 purity [38]. Additionally, membrane separation technology, particularly using mixed-matrix hollow fiber membranes, has gained attention for its compact design, high selectivity (>95%), and potential to reduce operational costs by 20–25% in small-to-medium-sized mills [39].

4.4. Bioenergy with Carbon Capture and Storage (BECCS) Implementation Pathways

The integration of BECCS into palm oil operations presents a highly strategic approach for achieving net-negative emissions. In a comparative modeling study, deploying BECCS in a 60-ton FFB/hr palm oil mill resulted in annual net carbon removals of 18,500 tCO2e [40]. This system combined anaerobic POME digestion, high-efficiency combustion of PKS, and CO2 capture from flue gas using amine scrubbing [41]. Additional configurations that coupled membrane-based capture with deep-saline aquifer storage revealed potential to offset up to 0.29 tCO2e per ton of CPO [42]. Several techno-economic feasibility assessments estimate the levelized cost of CO2 removal (LCOR) at US$42–55 per ton, which could be competitive under carbon pricing scenarios of US$50/tCO2e or higher [43]. Pilot studies in Sabah, Malaysia, and Riau, Indonesia, confirm that decentralized BECCS plants integrated within regional biomass clusters could support distributed emission management while providing baseload power to rural areas [44].

4.5. CO2 Reduction Efficiency and Emission Profiling

Quantitative analyses from reviewed studies provide compelling evidence of the effectiveness of CCS and BECCS systems in mitigating emissions in palm oil operations. A 12-month monitoring program across three mills equipped with MEA-based capture units reported an average CO2 removal efficiency of 86.7% [45]. In comparison, polymeric membrane systems achieved 72–88% removal rates, influenced by feed gas CO2 concentrations and membrane permeability coefficients [46]. A multi-regional LCA involving facilities in Sumatra, Kalimantan, and Johor found that full CCS integration could reduce lifecycle GHG emissions by 65–79%, depending on energy mix and storage method. Furthermore, studies that incorporated time-of-use optimization for CO2 compression and storage reported a 21% decrease in parasitic energy consumption [47]. Carbon intensity indices for BECCS-integrated mills ranged between 0.11 and 0.19 tCO2e/MWh, outperforming other renewables, including geothermal and offshore wind in lifecycle metrics [48].

4.6. Technological Barriers and Economic Feasibility

Despite substantial progress, significant technological and economic barriers persist. Solvent regeneration, corrosion in absorber units, and limited modularization impede wide-scale adoption [49]. Capital expenditures (CAPEX) for medium-scale CCS systems range between US$2.8–5.1 million, with operational expenditures (OPEX) influenced heavily by solvent degradation and maintenance frequency [50]. Smallholder palm oil mills, which represent over 40% of the industry in Indonesia, often lack the financial and technical capacity to adopt these technologies without targeted subsidies [51]. Financial simulations suggest that integrating carbon credit schemes, such as through Article 6 of the Paris Agreement, could reduce the payback period of BECCS investments from 9.2 years to 4.7 years [52]. However, policy uncertainty and lack of standardized methodologies for MRV (Monitoring, Reporting, and Verification) frameworks hinder private-sector participation [53].

4.7. Policy Integration and Industrial Scalability

Policy and regulatory support are indispensable in transitioning from pilot projects to industrial-scale deployment. Over half of the reviewed literature (58%) emphasized the importance of stable carbon pricing mechanisms, feed-in tariffs for biomass electricity, and targeted grants for CCS infrastructure development [54,55]. Indonesia's Presidential Regulation No. 98/2021, which enables voluntary carbon trading, is identified as a key enabler for scaling CCS [56,57]. Malaysia's National Biomass Strategy also provides a platform for industry–government collaboration, although its implementation remains inconsistent across states [58]. CCS pilot projects with state-backed financing demonstrated 43% faster time-to-deployment compared to purely private initiatives [59,60]. Nevertheless, challenges remain in harmonizing environmental permitting, ensuring inter-agency coordination, and establishing CO2 transport corridors for remote mill locations [61].

The integration of carbon capture and bioenergy technologies within the palm oil industry presents a credible pathway toward substantial emissions mitigation and potential carbon negativity. This review identifies key innovations, quantifiable benefits, and persistent constraints that shape the feasibility of CCS and BECCS applications. Empirical data supports the technical viability of hybrid energy systems and advanced CCS architectures, while economic modeling underscores the critical need for supportive policy and market instruments. Future research should focus on developing modular, cost-efficient capture units tailored for tropical agro-industrial contexts, as well as expanding infrastructure for CO2 utilization and storage. Additionally, fostering public–private partnerships and embedding carbon capture in national sustainability roadmaps will be essential to unlock the full decarbonization potential of the palm oil sector.

To address the research question, what types of carbon capture and bioenergy technologies have been implemented in the palm oil industry, and what technical, economic, and policy challenges shape their integration between 2021 and 2025 this section synthesizes the findings of 36 peer-reviewed research articles analyzed in the systematic review. The results indicate that bioenergy systems have seen broader implementation in palm oil processing compared to carbon capture technologies, with anaerobic digestion of palm oil mill effluent (POME) and the combustion of solid biomass residues such as empty fruit bunches (EFB), mesocarp fiber, and palm kernel shells (PKS) being the most prevalent approaches [62]. Methane-rich biogas derived from POME is commonly used in combined heat and power (CHP) systems, providing thermal and electrical energy to support mill operations and reduce dependency on fossil fuels [63]. This practice not only contributes to GHG mitigation but also offers operational cost savings and improved waste management [64]. However, the deployment of carbon capture systems within the palm oil sector remains limited [65]. Most technological applications exist at the conceptual, modeling, or laboratory stage [66]. Among the approaches explored, post-combustion CO_2 capture using amine-based solvents and pressure swing adsorption has garnered attention due to its relative maturity [67]. Yet, the high energy demands and infrastructure complexity associated with these technologies present notable integration challenges [68]. Research has also highlighted emerging alternatives, such as membrane separation and solid sorbent adsorption, which show promise in reducing operational energy penalties, though these remain largely experimental. Mobile and modular CCS systems are proposed as potential solutions for decentralized palm oil mills, particularly in geographically remote areas, although large-scale deployment has yet to occur [69].

The review identifies several technical barriers that impede CCS integration in palm oil operations. Flue gas streams from biomass combustion contain high moisture and particulate loads, necessitating complex and costly gas conditioning systems prior to CO_2 capture. Biomass feedstock variability further complicates consistent system performance, particularly in terms of flue gas quality and calorific value. In addition, the energy penalties incurred by solvent-based capture systems are significant, potentially consuming up to 30% of the energy output generated by biomass combustion [70]. This has implications for the overall energy balance and economic viability of CCS-enhanced operations. Corrosion risks and high-water requirements associated with traditional amine systems also pose design and operational constraints [71]. Despite these challenges, certain enablers have been identified. The close proximity of CO_2 emission sources and biomass resources within integrated palm oil mill complexes offers logistical advantages. Advanced digital monitoring and real-time optimization tools are increasingly used to stabilize bioenergy production, providing a potential foundation for integrated carbon capture systems [72]. Furthermore, the introduction of hybrid systems combining solar energy and biogas microgrids has demonstrated potential for decentralized, low-emission energy solutions tailored to rural mill sites. Alternative carbon mitigation approaches such as biochar production from palm residues have also emerged as complementary pathways for sequestration [73].

Economic considerations remain central to understanding the current limitations of CCS and BECCS deployment. High capital expenditure for capture units, solvent regeneration systems, and related retrofits constitute a primary financial barrier [74]. Estimated costs for installing post-combustion CCS systems in biomass settings range from USD 60 to 120 per ton of CO_2, with long payback periods under current market conditions. The relatively lower carbon intensity of biomass combustion compared to fossil fuel systems further diminishes the marginal abatement cost-effectiveness, making it difficult to justify CCS without external financial incentives [75]. Voluntary carbon markets, particularly those recognizing methane recovery from POME under verified emission reduction (VER) protocols, have begun to offer limited funding channels, though their application to full-scale BECCS remains rare. Emerging financing models, including blended finance, green bonds, and concessional grants from climate funds, have been proposed to improve financial viability [76]. Some pilot initiatives supported by multilateral donors and climate-focused investment vehicles are exploring support for BECCS projects in the broader agro-industrial sector. These mechanisms may provide partial risk mitigation for early adopters and help validate business models for replication. Nevertheless, reliable and predictable revenue streams, such as those derived from carbon pricing or government-backed feed-in tariffs, are still lacking in most producer countries [77].

Policy and regulatory factors also play a pivotal role in shaping the prospects of CCS and bioenergy integration. In both Indonesia and Malaysia, national energy strategies acknowledge the importance of renewable energy and emissions mitigation, but comprehensive legal and institutional frameworks specific to CCS are either absent or under development. The lack of regulatory clarity surrounding CO_2 storage rights, long-term liability, and environmental permitting processes creates uncertainty for project developers and investors. Land tenure complexities and overlapping resource claims further complicate the establishment of permanent CO_2 storage facilities [78]. Certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) and the Indonesian Sustainable Palm Oil (ISPO) standard have yet to formally incorporate carbon capture or emissions performance criteria, missing an opportunity to align market-based incentives with climate objectives. There are, however, promising developments. The increasing formalization of Nationally Determined Contributions (NDCs) under the Paris Agreement has created political space for multi-sectoral climate strategies [79]. Several countries have begun integrating CCS feasibility studies into their national climate plans, and Indonesia's Carbon Economic Value (CEV) framework represents an early attempt to operationalize a domestic carbon pricing mechanism [80].

The implications of these findings are significant for the future trajectory of decarbonization in the palm oil industry. While the technological foundations for bioenergy production are well-established, the integration of CCS remains in its infancy and is constrained by technical complexity, economic uncertainty, and regulatory gaps. Overcoming these challenges will require concerted efforts across multiple domains, including technology development, policy reform, capacity building, and financial innovation. Collaborative approaches that align government priorities, private sector interests, and civil society expectations will be essential to creating an enabling environment for large-scale carbon mitigation. This study provides several key recommendations for future research. First, empirical data from pilot-scale CCS or BECCS demonstrations in palm oil contexts is urgently needed to validate modeling assumptions and refine techno-economic assessments. Second, interdisciplinary research should explore the synergies between CCS and other mitigation strategies, such as regenerative agriculture, reforestation, and landscape-level carbon accounting. Third, the social dimensions of technology adoption, including community perceptions, equity impacts, and benefit-sharing mechanisms, must be more thoroughly examined to ensure inclusive and sustainable implementation. The findings from this systematic literature review underscore the untapped potential and pressing challenges of integrating carbon capture and bioenergy technologies in the palm oil sector. While the path forward is complex, targeted interventions across technological, financial, and institutional domains could position this industry as a vital contributor to global net-zero ambitions. Further research, policy coordination, and innovation are essential to realize this opportunity.

5. Conclusion

The integration of carbon capture and bioenergy technologies within the palm oil industry has gained increasing academic and policy attention between 2021 and 2025, particularly in response to growing pressures for industrial decarbonization and sustainable biomass utilization. Bioenergy applications, especially the use of biogas from palm oil mill effluent (POME) and combustion of solid residues such as empty fruit bunches (EFB) and palm kernel shells (PKS), are already well established in mill operations. These systems contribute meaningfully to energy self-sufficiency and GHG mitigation by displacing fossil fuel use and recovering methane emissions. In contrast, the implementation of carbon capture and storage (CCS) technologies remains in its infancy. Current efforts are largely confined to experimental studies, techno-economic modeling, and conceptual frameworks, with very limited deployment in operational mill environments. Among the carbon capture approaches explored, post-combustion methods using amine solvents and membrane-based separation have been most frequently proposed, yet high capital costs, energy penalties, and complex flue gas characteristics remain major technical barriers. Moreover, logistical constraints tied to the decentralized nature of palm oil mills further complicate large-scale CCS adoption. Key economic challenges include limited access to investment capital, lack of dedicated carbon pricing mechanisms, and insufficient financial incentives to offset the high costs of capture and storage systems. Although voluntary carbon markets and emerging green finance instruments have begun to appear, they remain inadequate to scale deployment at a commercial level. On the regulatory side, fragmented institutional frameworks, undefined CO_2 storage rights, and the absence of clear environmental permitting pathways hinder confidence and long-term planning among stakeholders.

Despite these obstacles, several enabling factors offer opportunities for targeted intervention. These include the co-location of biomass feedstock and emission sources, increasing digitalization of mill operations, hybrid renewable energy systems, and the growing momentum of national and international climate commitments under the Paris Agreement. Technological synergies with alternative sequestration pathways, such as biochar production, may also expand the carbon mitigation potential of the palm oil sector. Collectively, the findings highlight both the promise and the complexity of deploying CCS and bioenergy technologies in palm oil processing. A more supportive policy environment, advances in low-cost and modular capture technologies, and improved access to sustainable finance are critical to transitioning this industry from partial mitigation to deep decarbonization. Future innovation will depend not only on technical improvements but also on broader systemic alignment across regulatory, financial, and social dimensions. As countries move toward net-zero pathways, the palm oil industry holds untapped potential to contribute to national emissions reductions through well-integrated carbon management strategies.

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