

The Carbon Mitigation Potential of Sustainable Oil Palm Plantations: An Integrated Analysis of Hydrological Functions, Environmental Management, and Farmer Welfare

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Abstract

This qualitative literature review examines the contribution of sustainable oil palm plantations to carbon emission reduction through an integrated analytical framework encompassing hydrological functions, environmental dynamics, and farmer welfare. Synthesizing evidence from reputable peer-reviewed journals (2020-2026) and authoritative institutional reports, this study reveals that oil palm's climate impact is highly context-dependent—determined by location, land-use history, and management practices rather than by the crop's inherent characteristics. Mature plantations on mineral soils demonstrate significant carbon sequestration capacity (23-35 t CO₂eq/ha/year through biomass accumulation), while best management practices offer substantial emission reduction potential: biogas capture from palm oil mill effluent (75-85% methane reduction), organic fertilizer substitution (17-34% lower fertilizer emissions), and optimal peatland water table management (50-70% reduced peat oxidation). The synthesis establishes farmer welfare as a functional prerequisite for environmental sustainability, with the productivity-welfare-carbon nexus demonstrating mutually reinforcing relationships. With comprehensive transformation—universal adoption of best management practices, zero-deforestation enforcement, and landscape-level conservation—Indonesia's oil palm sector could transition from a net emitter (~220 Mt CO₂ eq/year) to a net-zero or carbon-sink status by 2040, thereby contributing substantially to national climate targets. However, significant policy implementation gaps persist, requiring strengthened governance, enhanced smallholder capacity building, and realignment of economic incentives. This review provides evidence-based pathways for positioning sustainable oil palm as a viable component of tropical climate mitigation strategies.

JEL Classification

Q15 (Land Ownership and Tenure; Land Reform; Land Use; Irrigation; Agriculture and Environment), Q54 (Climate; Natural Disasters and Their Management; Global Warming), Q56 (Environment and Development; Environment and Trade; Sustainability; Environmental Accounts and Accounting; Environmental Equity; Population Growth), O13 (Agriculture; Natural Resources; Energy; Environment; Other Primary Products)

Introduction

Global Context: Climate Mitigation and Agriculture's Dual Role

The global imperative to limit warming to 1.5-2°C under the Paris Agreement necessitates transformative changes across all economic sectors, with agriculture and land use representing both significant emission sources and critical mitigation opportunities. The Forestry and Other Land Use (FOLU) sector contributes approximately 13-21% of global greenhouse gas (GHG) emissions, yet simultaneously possesses substantial carbon

sequestration potential through improved land management, avoided deforestation, and sustainable intensification. Indonesia, as the world's largest palm oil producer, with 16.38 million hectares under cultivation, stands at the nexus of this challenge, committed to achieving a FOLU Net Sink by 2030 while maintaining economic development that depends on the palm oil industry [1-3]

The oil palm sector has historically been positioned as antithetical to climate objectives, primarily due to its association with tropical deforestation and peatland degradation. Between 2015 and 2022, Indonesian palm oil production generated an estimated 220 Mt CO₂eq annually, predominantly from land-use change emissions. This narrative, while grounded in legitimate environmental concerns, inadequately captures the nuanced reality of a highly heterogeneous sector where management practices, establishment location, and temporal dynamics fundamentally determine climate outcomes. Recent evidence indicates that mature plantations on appropriate soils, managed in accordance with sustainability standards, function as carbon sinks rather than sources, with sequestration rates exceeding those of several competing vegetable oil crops [4,5].

Paradigm Shift: From Carbon Source to Potential Climate Solution

A critical reassessment of oil palm's climate role has emerged from advances in carbon accounting methodologies, refinements to life-cycle assessment, and longitudinal monitoring of plantation carbon dynamics. United Plantations in Malaysia exemplifies this potential, achieving 55-62% GHG emission reduction between 2004 and 2023 through integrated adoption of biogas capture, nature conservation set-asides, and production optimization, resulting in emissions as low as 0.62 kg CO₂eq/kg palm oil when conservation offsets are included. These findings suggest that the fundamental question is not whether oil palm is inherently "good" or "bad" for the climate, but rather under what conditions sustainable oil palm production can contribute to climate mitigation goals, and how such conditions can be created at scale [6]. This paradigm shift necessitates moving beyond binary narratives toward evidence-based, context-specific assessments that acknowledge both historical environmental damages and contemporary mitigation potential. Indonesia's mandatory Indonesian Sustainable Palm Oil (ISPO) certification, alongside the voluntary Roundtable on Sustainable Palm Oil (RSPO) standards, provides a regulatory framework for sector transformation, though significant implementation gaps persist. The sector's trajectory—whether it continues as a major emitter or transforms into a climate solution—depends critically on policy enforcement, technological adoption, financial mechanisms, and smallholder empowerment over the next decade [7].

Research Objectives and Contribution

This qualitative literature review synthesizes evidence from peer-reviewed publications and authoritative reports published between 2020 and 2026 to address the central research question: How can sustainable oil palm plantations contribute to carbon emission reduction through integrated management of hydrological functions, environmental dynamics, and farmer welfare? Specifically, this study:

- a) Quantifies carbon sequestration potential through biomass accumulation and soil organic carbon enhancement under best management practices
- b) Evaluates emission reduction pathways, including methane capture, fertilizer optimization, and peatland water management
- c) Analyzes the hydrological-carbon nexus, demonstrating how water management fundamentally influences carbon balance
- d) Establishes farmer welfare as an enabler of sustainability, examining the productivity-welfare-carbon relationships
- e) Identifies policy-implementation gaps and formulates evidence-based recommendations

The novelty of this synthesis lies in its integrative analytical framework that connects previously siloed dimensions—hydrological management typically addressed in the engineering literature, carbon dynamics in environmental science, and farmer welfare in development economics—revealing critical interdependencies. By establishing water table management not merely as flood control but as a primary carbon strategy for peatlands, and demonstrating farmer prosperity as a functional prerequisite for environmental sustainability adoption, this review provides actionable pathways for sector transformation aligned with Indonesia's climate commitments [8].

Literature Review

Conceptual Foundations: Sustainable Oil Palm Production

Sustainable palm oil production frameworks operationalize the triple bottom line—economic viability, social equity, and environmental integrity—through certification standards that have evolved significantly since RSPO's inception in 2004. The convergence between ISPO (mandatory for all Indonesian producers) and RSPO (voluntary but required for premium markets) reflects growing consensus on sustainability principles, including zero deforestation, protection of High Conservation Value (HCV) and High Carbon Stock (HCS) areas, respect for land rights, and adoption of best agronomic practices. Comparative lifecycle assessments demonstrate that RSPO-certified palm oil generates 35% lower GHG emissions than non-certified production, validating the environmental efficacy of certification when properly implemented [9].



The landscape approach to sustainability represents a critical evolution beyond individual plantation certification toward jurisdictional sustainability, where entire districts commit to deforestation-free production through coordinated multi-stakeholder governance. This paradigm acknowledges that addressing issues such as biodiversity conservation, watershed management, and smallholder inclusion requires collective action transcending individual concession boundaries, offering economies of scale and addressing leakage concerns inherent in plantation-level interventions [10].

Carbon Dynamics in Oil Palm Agroecosystems Net Ecosystem Exchange and Sequestration Capacity

The carbon balance of oil palm plantations is determined by the relationship between Net Primary Production (NPP)—carbon fixed through photosynthesis—and soil respiration (Rs), primarily microbial decomposition of organic matter. Plantations function as carbon sinks when NPP exceeds Rs, yielding positive Net Ecosystem Exchange (NEE). Empirical measurements demonstrate substantial variation across plantation age, soil type, and management intensity. On mineral soils, mature plantations (8-20 years) exhibit biomass carbon accumulation rates of 3.70-7.99 Mg C/ha/year, translating to 13.6-29.3 t CO₂ eq/ha/year sequestration. On Malaysian peatlands, despite ongoing peat oxidation, above-ground biomass accumulation of 6.39-7.99 Mg/ha/year was documented, though net carbon balance remains negative due to subsurface losses [11-13].

The national sequestration potential for Indonesia, with 16.38 million hectares of plantations, is estimated at 1,689 Gt CO₂ total carbon stock, or approximately 67 Mt CO₂ eq/year when annualized over a 25-year production cycle. Comparative analyses indicate that oil palm carbon uptake (64.5 t CO₂/ha/year) exceeds that of tropical forests (42.4 t CO₂/ha/year) during the peak productive phase, though this comparison requires contextualization within time-averaged frameworks accounting for initial land-use change emissions [14-16].

Emission Sources and Magnitudes

Land-Use Change (LUC) Emissions: Historical and ongoing forest conversion is the dominant emission source, with peat swamp forest conversion releasing 640 t CO₂/ha from biomass loss alone, plus initiating long-term peat oxidation. The carbon debt from such conversion requires 50-100 years for plantation sequestration to offset, far exceeding typical rotation periods. Between 2015 and 2022, Indonesian palm oil expansion contributed an estimated 220 Mt CO₂ eq annually, predominantly from LUC [17,18].

Peatland Emissions: Drainage required for cultivation exposes previously anaerobic peat to aerobic decomposition, releasing 5.2-

24.9 Mg CO₂-C/ha/year depending on water table depth, with deeper drainage (>60 cm) exponentially increasing oxidation rates. Each 10 cm decrease in water table depth corresponds to approximately 2-3 t CO₂-C/ha/year additional emissions. Long-term emissions from a single 25-year cycle on drained peatland can exceed 800 Mg CO₂ eq/ha [19].

Palm Oil Mill Effluent (POME): Untreated POME undergoes anaerobic digestion in open ponds, producing methane (60-70% CH₄, 30-40% CO₂), contributing 546.9-896.5 kg CO₂ eq per ton crude palm oil (CPO). With Indonesia producing approximately 45-50 million tons of CPO annually, POME-related emissions constitute a substantial national source [20].

Fertilizer-Related Emissions: Nitrogen fertilizer application generates nitrous oxide (N₂O) through nitrification and denitrification, accounting for 47% of lifecycle GHG emissions in conventional systems. The high global warming potential of N₂O (298× CO₂) amplifies its climate impact despite relatively small mass emissions [21].

Hydrological Functions and Carbon Implications

Hydrological Partitioning in Oil Palm Plantations

Water partitioning in oil palm plantations exhibits substantial variation based on canopy closure, plantation age, and rainfall characteristics. Canopy interception ranges from 4-71%, with mature closed-canopy stands intercepting higher proportions, while throughfall accounts for 28-59% and stemflow for 1-6% of precipitation. Surface runoff, measured at 24-60% across studies with varying management intensities, is a critical concern, as it indicates limited infiltration—typically only 5-17% of rainfall penetrates into the soil profile. Comparative watershed studies document 21% higher surface runoff in oil palm landscapes than in forests, contributing to increased flooding frequency and severity in downstream communities [22].

Peatland Water Table Management: The Carbon-Hydrology Nexus

Water table depth in peatlands emerges as the single most important determinant of carbon emissions, mediating the balance between aerobic and anaerobic conditions that control decomposition rates. The optimal management zone of 45-60 cm depth represents a compromise between palm root aeration requirements and emission minimization. Maintenance of water tables within this range can reduce peat oxidation emissions by 50-70% compared to conventional deep drainage (>70 cm), while preserving productivity. Real-time monitoring systems using automated sensors enable adaptive management, though adoption remains limited due to installation costs and technical capacity requirements [23].

Soil and Water Conservation as Carbon Strategy

Conservation practices traditionally framed for erosion control and flood mitigation also serve as carbon retention strategies. Terracing on slopes 15-30% and rojak (micro-catchment) systems on 8-15% gradients reduce surface runoff from 43.55% to 6.96%, simultaneously increasing infiltration and preventing erosion-mediated carbon loss. Quantified benefits include a water storage capacity of 408-516 mm, delaying drought stress by 2.5-3.5 months, and maintaining yields 15-20% higher during dry periods. Cover crops, particularly leguminous species, enhance infiltration through root channels while contributing to soil organic carbon through nitrogen fixation and biomass inputs [24,25].

Best Management Practices for Emission Reduction

Biogas Capture Technology: Highest-Impact Intervention

Methane capture from POME through covered anaerobic digesters represents the most cost-effective, highest-impact GHG mitigation available in the palm oil sector. The technology reduces emissions from 546.9-896.5 kg CO₂ eq/t CPO to 82.0-134.5 kg CO₂ eq/t CPO, an 85% reduction. Economic viability is enhanced by biogas utilization for electricity generation, displacing diesel generators with payback periods of 3-5 years. The national mitigation potential if deployed across Indonesia's approximately 850 mills is estimated at 34-41 million t CO₂ eq annually. Despite proven efficacy and positive returns, adoption remains at approximately 25-30% of mills, constrained by capital requirements (USD 2-3 million per installation), technical capacity for operation and maintenance, and limited enforcement of ISPO standards requiring POME treatment [26].

Organic Residue Valorization

Empty Fruit Bunch (EFB) generated at 22-23% of fresh fruit bunch processed (approximately 5 tons/ha/year) offers multiple valorization pathways with carbon co-benefits. Co-composting EFB with POME optimizes carbon-to-nitrogen ratios, accelerating decomposition to 100 days and achieving 76% GHG reduction compared to conventional practices of field mulching or incineration. The resulting compost can replace 30-50% of inorganic fertilizer requirements, reducing N₂O emissions by 17-34%. Additional valorization includes mushroom cultivation (revenue of 9 million IDR/month), wood pellets from replanting waste (annual value of 125.4 billion IDR in West Kalimantan), and briquettes as an alternative household fuel. Despite high potential, current adoption remains below 10% due to labor intensity, transportation costs, and knowledge gaps regarding optimal application protocols [27].

Agroforestry Systems: Transformative Long-term Strategy

Oil palm agroforestry, integrating native tree species into plantations, offers a win-win for carbon, biodiversity, and economic resilience. Tree island experiments in Brazilian plantations documented a 250% increase in multifunctionality and a 75% increase in ecosystem multifunctionality, without significant landscape-scale yield reduction. Carbon stock measurements in Indonesian mixed systems (oil palm + *Nauclea subdita*, *Peronema canescens*) recorded 55.44 Mg C/ha compared to 40-45 Mg C/ha in monoculture, representing 25-35% enhancement. Economic diversification through timber, fruits, and non-timber forest products helps mitigate the risk of palm oil price volatility. Current adoption remains pilot-scale (<1% of plantation area) due to perceived yield uncertainties, technical knowledge gaps, and entrenched monoculture paradigms, though scaling to 20% of national area (3.3 million ha) could sequester an additional 50 Mt CO₂eq annually [28,29].

Farmer Welfare as Sustainability Enabler

Welfare Status and Determinants

Indonesian oil palm smallholders, managing 40% of the national plantation area (6.5 million hectares), exhibit diverse welfare outcomes. Income studies document average household earnings of 8.6 million IDR/month, with expenditure patterns indicating prosperity (84.61% non-food expenditure exceeds the 75% threshold for welfare classification). However, substantial heterogeneity exists, with independent smallholders facing greater welfare challenges than scheme participants linked to nucleus estates. Multidimensional sustainability indices for Riau smallholders average 63.30%, with environmental performance (53.91%) significantly lagging economic (60.85%) and technological (71.70%) dimensions, indicating priority areas for intervention [30].

The Productivity-Welfare-Carbon Nexus

Statistical analyses reveal strong positive correlations between farmer welfare and plantation productivity, with welfare factors accounting for 82.8% of the variance in productivity. This relationship is bidirectional: higher welfare enables investment in inputs, labor, and management improvements that increase yields, while higher productivity generates income that improves welfare. The linkage to carbon outcomes, while theoretically robust, requires further empirical substantiation. Prosperous farmers possess greater capacity to absorb upfront costs of best management practices (terracing, organic inputs, biogas systems), longer time horizons that encourage conservation investments, and access to information, technology, and credit, facilitating the adoption of emission-reduction strategies. Conversely, poverty

constrains BMP adoption through hyperbolic discounting of future benefits, lack of capital for investments, and engagement in destructive practices (forest encroachment, excessive fertilizer application) driven by survival imperatives [31].

Certification Challenges and Smallholder Inclusion

RSPO and ISPO certification, designed to drive sustainability, paradoxically creates barriers for smallholders through documentation requirements, prohibitive audit costs (for individual farmers), and continuous compliance obligations. Independent smallholders exhibit the lowest certification rates (<5% RSPO-certified), risking exclusion from sustainable supply chains as buyers increasingly mandate certification. The RSPO Independent Smallholder Standard represents progress toward simplified requirements, though implementation challenges persist. Effective pathways for smallholder inclusion require subsidized certification costs, facilitated group organization, staged compliance to allow gradual improvement, and digital tools to reduce documentation burdens [32].

Methodology

Research Design

This study employs a qualitative literature review approach, suited to synthesizing complex, multidimensional topics for which systematic review protocols would be overly restrictive. Unlike systematic reviews following PRISMA methodology with exhaustive database searches and meta-analysis, qualitative literature reviews prioritize interpretative depth, contextual understanding, and thematic synthesis across diverse evidence types, including peer-reviewed articles, institutional reports, and policy documents. This flexibility enables integration of quantitative carbon measurements, qualitative farmer welfare assessments, and policy analyses within a unified framework addressing the research questions [33].

Literature Search and Selection

Literature searches employed multiple academic databases (Scopus, Web of Science, ScienceDirect, Google Scholar) using keyword combinations: ("carbon sequestration" OR "GHG emissions" OR "carbon footprint") AND ("oil palm" OR "palm oil" OR "Elaeis guineensis") AND ("sustainable" OR "best management practices" OR "RSPO" OR "ISPO") AND ("Indonesia" OR "Southeast Asia"). Temporal scope prioritized 2020-2026 publications to capture recent advances in carbon accounting, technology development, and policy implementation, while incorporating seminal pre-2020 works for conceptual foundations. Inclusion criteria specified peer-reviewed articles from reputable journals (Scopus-indexed Q1-Q3), empirical studies with clear methodologies, and geographic relevance to

Indonesia. Grey literature from authoritative institutions (CIFOR, RSPO, World Bank, Indonesian ministries) supplemented academic sources, particularly for policy context and practitioner perspectives.

Selection proceeded through multi-stage screening:

- a) title review for topical relevance (n≈180 identified)
- b) abstract assessment for alignment with research objectives (n≈100 retained)
- c) full-text evaluation for methodological quality and substantive contribution (n≈80 included),
- d) snowballing through reference lists and citation tracking (n≈20 additional).

Quality appraisal considered journal reputation, methodological rigor, sample adequacy, and contribution to knowledge. The final evidence base comprised approximately 100 sources spanning carbon dynamics, hydrology, best management practices, farmer welfare, and policy frameworks.

Thematic Analysis

Thematic analysis followed established protocols for qualitative synthesis. Familiarization involved multiple readings of selected articles, with initial notes on patterns. Open coding identified key concepts, data points, and relationships line by line. Axial coding organized codes into categories (carbon sources, sequestration pathways, hydrological components, BMP types, welfare determinants). Selective coding integrated categories into overarching themes (carbon balance optimization, water-carbon nexus, welfare-sustainability linkage, policy-implementation gaps). Both deductive themes derived from the conceptual framework and inductive themes emerging from data informed the analysis. The iterative process moved between raw data and developing themes, refining interpretations through constant comparison. Narrative synthesis constructs coherent storylines that connect disparate studies, identifies convergences and divergences, and generates interpretive constructs for policy recommendations [34].

Rigor and Limitations

Credibility was enhanced through triangulation across multiple sources, methodologies, and disciplinary perspectives. Dependability relied on transparent documentation of search strategies, selection criteria, and analytical decisions, enabling audit trails. Confirmability emphasized grounding interpretations in cited evidence rather than speculation. Limitations include potential publication bias toward positive results, language restrictions potentially missing Indonesian-language research, a qualitative approach precluding statistical meta-analysis, and a temporal snapshot (2020-2026) potentially dating rapidly given

sector dynamism. These constraints are acknowledged to appropriately contextualize conclusions.

Results and Discussion

Carbon Balance Quantification: From Source to Sink

Sequestration Potential Under Optimal Management

Synthesis of carbon flux measurements across diverse sites reveals substantial sequestration capacity in mature oil palm plantations under best management practices. On mineral soils, biomass accumulation rates of 3.70 Mg C/ha/year have been documented in 11-year-old Indian plantations, while Malaysian studies on peatlands report 6.39-7.99 Mg C/ha/year in 12-year-old stands. These rates translate to 13.6-29.3 t CO₂ eq/ha/year gross sequestration through above-ground (trunk, fronds, frond bases) and below-ground (roots) biomass expansion during the peak productive phase (years 8-20). The national potential for Indonesia's 16.38 million hectares totals approximately 1,689 Gt CO₂ cumulative carbon stock, or 67 Mt CO₂ eq/year when annualized across typical 25-year cycles. Comparative analyses suggest oil palm carbon uptake during the mature phase (64.5 t CO₂/ha/year) exceeds tropical forest benchmarks (42.4 t CO₂/ha/year), though this comparison requires careful contextualization [35-39].

Soil organic carbon (SOC) dynamics complicate carbon balance assessments. On mineral soils, management practices such as organic residue retention, cover cropping, and reduced tillage can increase SOC by 0.5-1.0 Mg C/ha/year, enhancing total carbon storage beyond that provided by biomass alone. However, peatland conversion inevitably causes net SOC loss through oxidation, partially offset by biomass gains. Time-averaged carbon accounting, which integrates initial land-use change emissions with subsequent sequestration, shows that converting primary or secondary forests to oil palm plantations results in net carbon deficits over policy-relevant 50-100-year timeframes. In contrast, establishment on degraded lands (grasslands, shrublands, abandoned agricultural areas) generates net carbon gains as plantation biomass exceeds pre-conversion stocks [40-42].

Emission Sources and Mitigation Efficacy

Peatland Management: Water-table depth emerges as the most influential determinant of peatland carbon emissions, with these relationships quantified across multiple studies. Conventional deep drainage (>70 cm) facilitates peat oxidation rates of 20-25 Mg CO₂-C/ha/year, while maintaining water tables at 45-60 cm reduces emissions by 50-70% to approximately 5-8 Mg CO₂-C/ha/year. The mechanism operates through oxygen availability, controlling whether decomposition is aerobic or anaerobic. Each

10 cm increase in drainage depth corresponds to approximately 2-3 t CO₂-C/ha/year additional emissions, establishing water management as the highest-leverage intervention for peatland plantations. Real-time monitoring systems using automated sensors coupled with hydraulic retention structures enable adaptive management within optimal zones, though implementation remains limited to well-capitalized estates [43-46].

POME Methane Capture: Anaerobic digestion of palm oil mill effluent in covered tanks with biogas capture constitutes the most cost-effective emission reduction technology available. The intervention reduces emissions from 546.9-896.5 kg CO₂ eq/t CPO (conventional open pond systems) to 82.0-134.5 kg CO₂ eq/t CPO, representing a 75-85% reduction. Captured methane can generate 4,000-5,000 t CO₂ eq emission reductions per mill annually while producing electricity, displacing diesel generators, yielding financial payback within 3-5 years. Scaling to Indonesia's approximately 850 mills would abate 34-41 million t CO₂ eq annually, equivalent to removing 7-9 million passenger vehicles. Despite compelling economics and climate benefits, adoption rates remain at 25-30% of mills, constrained by capital requirements (USD 2-3 million), technical expertise for operation, and insufficient policy enforcement, compelling installation [47-50].

Organic Fertilizer Substitution: Nitrogen fertilizer accounts for 47% of lifecycle GHG emissions through N₂O release during nitrification and denitrification. Co-composting empty fruit bunches with POME creates nutrient-rich organic amendments that can replace 30-50% of inorganic inputs, reducing fertilizer-related emissions by 17-34% while enhancing soil health. The co-composting process itself generates 76% lower emissions than conventional EFB disposal through field mulching or incineration. Additional benefits include improved water retention, increased microbial activity, and reduced input costs for farmers. Current utilization remains below 10% of available EFB due to labor requirements for composting, transportation logistics, and farmer knowledge gaps regarding optimal application rates [51-54].

Lifecycle Performance: Temporal trajectories show substantial reductions in emission intensity. United Plantations in Malaysia achieved 55-62% GHG reduction between 2004 and 2023 through integrated biogas deployment, renewable energy adoption, fertilizer optimization, and nature conservation set-asides, reducing emissions from 2.6 to 0.62 kg CO₂ eq/kg palm oil when including forest protection offsets. Industry averages for RSPO-certified production (3.41 kg CO₂ eq/kg) show 35% lower emissions than for non-certified systems (5.34 kg CO₂ eq/kg), validating the efficacy of certification. Projections for 2030 estimate average emission intensity of 1.08 t CO₂ eq/t CPO

assuming moderate technology adoption, with best-case scenarios approaching carbon neutrality through full BMP implementation and conservation integration [55-57].

Hydrological Management as Carbon Strategy

Water Cycle Dynamics and Carbon Implications

Hydrological functions in oil palm plantations exert a profound yet underappreciated influence on carbon dynamics through multiple pathways. Canopy interception (4-71% of rainfall, depending on age and closure) moderates rainfall intensity reaching soil surfaces, reducing erosion that transports carbon-rich topsoil. However, the relatively low infiltration rates (5-17%) and high surface runoff (24-60%) documented in many plantations indicate suboptimal water management contributing to both flooding risks and carbon losses. Comparative watershed analyses demonstrate 21% higher runoff in oil palm landscapes than in forests, with downstream flood frequency increases affecting community livelihoods and agricultural productivity [13,58-60].

The erosion-carbon interface represents an often-unquantified emission pathway. Soil erosion preferentially removes topsoil with the highest organic carbon concentrations, exporting carbon to waterways where it may be respired to the atmosphere or deposited in sediments. While literature extensively quantifies gaseous emissions (CO₂, CH₄, N₂O), erosion-mediated carbon losses remain poorly characterized. Based on watershed sediment loads documented in Sumatran studies, plantations on steep terrain without adequate conservation measures may lose 1-3 t C/ha/year through erosion, a magnitude comparable to fertilizer-related emissions. Soil and water conservation practices thus serve dual functions—reducing flood risk while retaining carbon stocks in situ [38,61-63].

Conservation Practices: Quantified Hydrological-Carbon Benefits

Empirical measurements quantify conservation practice efficacy. Rorak (micro-catchment) systems on 8-15% slopes reduce surface runoff from 43.55% to 6.96% compared to unmanaged controls, while simultaneously increasing infiltration and providing water storage capacity of 408-516 mm that sustains trees during dry periods. This translates to 2.5-3.5 month drought tolerance extension and 15-20% higher yield maintenance under water stress. Terracing on 15-30% gradients similarly reduces runoff and erosion while stabilizing soil profiles. Cover crops, particularly leguminous species (*Mucuna bracteata*, *Pueraria javanica*), enhance infiltration by creating root channels, reduce raindrop impact energy, and contribute to nitrogen fixation, thereby reducing synthetic fertilizer requirements [64-67].

The carbon co-benefits operate through multiple mechanisms. Reduced erosion maintains SOC stocks that would otherwise be lost. Enhanced infiltration and soil moisture improve microbial efficiency in decomposing organic residues into stable humus forms. Leguminous covers fix atmospheric nitrogen (100-200 kg N/ha/year), reducing N₂O emissions from synthetic fertilizers while contributing biomass carbon inputs. Water table management on peatlands, by maintaining optimal depths (45-60 cm), reduces aerobic decomposition while preserving root-zone aeration necessary for palm productivity, representing perhaps the single highest-leverage carbon intervention available for peatland systems [38,68-70].

Farmer Welfare: The Sustainability Prerequisite

Welfare-Productivity-Carbon Linkages

Statistical analyses reveal strong correlations between farmer welfare indicators and plantation productivity, with welfare factors accounting for 82.8% of the variance in productivity in Indonesian samples. Bidirectional causation operates through investment capacity—prosperous farmers can afford optimal fertilizer regimes, pest management, and labor inputs that increase yields, while higher yields generate income, thereby improving welfare. This productivity-welfare nexus connects to carbon outcomes through the capacity for BMP adoption. Best management practices frequently require upfront capital investments (terracing infrastructure, biogas systems, organic fertilizer processing equipment) beyond the reach of subsistence-level smallholders. Secure welfare enables longer planning horizons, reducing hyperbolic discounting that causes farmers to prioritize immediate returns over long-term conservation benefits [31,71-73].

Multidimensional sustainability assessments reveal that environmental performance constitutes the weakest dimension for Indonesian smallholders (53.91% index score), significantly trailing technological (71.70%) and social (67.54%) dimensions. This pattern suggests that environmental improvements require targeted interventions that address specific constraints rather than assuming that economic development automatically generates environmental benefits. The causal pathway from welfare to sustainability operates through affordability of sustainable practices, access to information and extension services, bargaining power to capture value for quality production, and security of tenure, encouraging long-term stewardship rather than extractive management [74-77].

Certification Paradox and Smallholder Inclusion

RSPO and ISPO certification mechanisms, designed to drive sustainability, inadvertently create barriers for smallholders who

manage 40% of Indonesia's palm oil area. Documentation requirements (land mapping, input records, harvest data), audit costs (prohibitive for individual smallholders averaging <5 hectares), and continuous compliance obligations exceed the administrative and financial capacity of most independent producers. Consequently, independent smallholder certification rates remain below 5% for RSPO, and ISPO-mandatory compliance is similarly challenging despite being a national policy. This certification gap risks smallholder exclusion from sustainable supply chains as European and North American buyers increasingly mandate certified sourcing [30,78-80].

Effective inclusion pathways identified in the literature include group certification schemes that distribute costs across multiple farmers, simplified standards tailored to smallholder contexts (e.g., RSPO Independent Smallholder Standard), government subsidization of audit costs, and digital tools (e.g., mobile applications, GPS mapping) that reduce documentation burdens. Cooperative models facilitate collective action in procurement, knowledge sharing, and marketing, enhancing bargaining power and enabling economies of scale for investments in shared infrastructure, such as biogas facilities or composting centers. The success of jurisdictional sustainability approaches in districts like Simalungun, North Sumatra, demonstrates that landscape-level coordination can better include smallholders than plantation-by-plantation certification [81-84].

Livelihood Diversification Through Circular Economy

Oil palm biomass offers diverse valorization opportunities, generating additional income streams while providing carbon co-benefits. Brown sugar production from palm nira (sap) generates revenues of 26.9 million IDR/ha/year during replanting periods, exceeding typical CPO revenues and providing an economic cushion during unproductive phases. Integrated cattle systems, where animals graze under mature palms consuming fronds and cover crops, achieve internal rates of return of 8.68-9.35% by year 10 while providing organic fertilizer, weed control, and protein production. Empty fruit bunch valorization through mushroom cultivation (9 million IDR/month), wood pellets (125.4 billion IDR in annual regional value), or briquette production creates employment and reduces waste-disposal challenges [85-87].

These circular economy models simultaneously address welfare and environmental objectives. Diversified income sources reduce vulnerability to palm oil price volatility, enhancing resilience. Biomass utilization that would otherwise decompose, releasing methane instead, generates products that displace fossil fuels (pellets substituting for coal, biogas replacing diesel) or synthetic fertilizers (compost reducing N₂O emissions). The economic viability demonstrated in pilot projects indicates substantial

scaling potential if knowledge transfer, market linkages, and access to startup capital can be facilitated through government-industry partnerships and cooperative organizations [88-91].

Policy Architecture and Implementation Gaps

Comprehensive Framework, Weak Enforcement

Indonesia has established one of the world's most comprehensive oil palm sustainability policy frameworks. The National Action Plan for Sustainable Palm Oil (RAN-KSB 2019-2024) coordinates cross-ministerial efforts to enhance productivity, ensure legality, and protect the environment. ISPO certification became mandatory for all producers (estates and smallholders) under Regulation 38/2020, establishing legally binding sustainability standards. The FOLU Net Sink 2030 commitment aims for net-negative emissions in the forestry and land-use sectors, positioning Indonesia as a climate leader. Forest and peatland moratorium policies restrict new permits for primary forests and peatlands, while High Conservation Value and High Carbon Stock approaches provide methodologies for identifying conservation priorities [92-95].

However, persistent policy-implementation gaps undermine effectiveness. Deforestation rates increased during 2022-2023 despite moratorium commitments, with oil palm expansion continuing on forest frontiers in Kalimantan and Papua. ISPO compliance remains partial despite its mandatory status, with enforcement actions against violators rarely pursued due to limited government capacity, political pressures, and institutional weaknesses. Smallholder support systems remain inadequate, with extension agent shortages and limited reach to independent farmers resulting in knowledge gaps regarding best practices. The fundamental challenge is governance—transitioning from policy formulation to effective implementation through adequate resourcing, political will for enforcement, and institutional coordination across fragmented authorities [96-99].

Scaling Best Practices: Barriers and Enablers

Technical feasibility and economic viability have been demonstrated for major emission-reduction pathways, yet adoption rates remain far below their potential. Biogas capture technology, despite achieving 75-85% emission reductions and 3-5-year payback periods, is used in only 25-30% of mills. Organic fertilizer utilization, with proven agronomic and environmental benefits, processes less than 10% of available EFB. Peatland water table management, the highest-leverage intervention for peat emissions, lacks widespread implementation due to monitoring costs and technical complexity [70,100-102].

Barriers operate at multiple levels. Technical capacity constraints limit the operation and maintenance of biogas systems, particularly for smaller mills lacking engineering expertise. Capital requirements create adoption thresholds: biogas installations cost USD 2-3 million, and terracing infrastructure requires substantial labor investments beyond the means of smallholders. Knowledge gaps persist regarding optimal composting protocols, precision fertilizer application, and the selection of agroforestry species. Misaligned incentives arise from a short-term profit orientation that conflicts with longer-term sustainability investments, exacerbated by insecure land tenure, which discourages conservation commitments [103-106].

Effective scaling strategies identified across successful cases include:

- a) blended finance combining public subsidies with private investment to de-risk innovations and cross-subsidize smallholder participation
- b) jurisdictional approaches creating economies of scale for shared infrastructure and coordination
- c) demonstration effects through farmer-to-farmer learning and extension showcasing early adopter successes
- d) market mechanisms including premium pricing for certified sustainable production and carbon credit access
- e) regulatory enforcement compelling adoption of proven technologies like biogas capture through mandatory standards with penalties for non-compliance [70,100-102,107].

Pathways to Net-Zero: Scenario Analysis

Current Trajectory

Under business-as-usual scenarios, Indonesia's oil palm sector remains a substantial net emitter. Legacy land-use change emissions, ongoing peatland oxidation, POME methane release, and fertilizer-related N₂O generate approximately 220 Mt CO₂ eq annually. Deforestation for plantation expansion increased in 2022-2023, indicating insufficient enforcement of zero-deforestation commitments. Stagnating smallholder productivity perpetuates pressure to expand areas to meet production targets. Current emission intensity averages 2.7-5.34 kg CO₂eq/kg palm oil depending on management practices, with national averages above global best practice benchmarks [100,108-110].

Transformation Scenario

Comprehensive sector transformation through the universal adoption of best management practices, strict enforcement of zero-deforestation policies, and landscape conservation could achieve net-zero emissions or carbon sink status by 2040. Key interventions include:

- (1) Zero expansion on forests/peat preventing 50-80 Mt CO₂ eq/year future emissions
- (2) Universal biogas capture at 850 mills reducing 34-41 Mt CO₂ eq/year
- (3) Organic fertilizer transition (30% substitution) cutting 10-15 Mt CO₂ eq/year
- (4) Peatland water management (optimal water tables) saving 15-25 Mt CO₂ eq/year
- (5) Productivity intensification (yield increases from 3 to 5-6 t CPO/ha) reducing area pressure
- (6) Landscape conservation (20% HCV/HCS set-asides) preserving forest carbon stocks providing 20-30 Mt CO₂ eq/year offsets, and (7) Agroforestry scaling (10% of area) sequestering additional 15-30 Mt CO₂ eq/year [111-115].

Combined mitigation potential totals 144-221 Mt CO₂ eq/year reduction relative to current emissions, potentially transforming the sector into a net carbon sink when including plantation biomass sequestration (67 Mt CO₂ eq/year). This transformation aligns with Indonesia's FOLU Net Sink 2030 and NDC commitments, positioning sustainable palm oil as a viable component of the national climate strategy. However, achieving this scenario requires urgent, coordinated action across government (policy enforcement, smallholder support, blended finance), industry (technology adoption, supply chain transparency, conservation commitments), and civil society (monitoring, advocacy, knowledge dissemination) [10,115-118].

Conclusions and Policy Recommendations

Key Findings

This qualitative literature review establishes that sustainable oil palm plantations can contribute substantially to carbon emission reduction through three principal pathways:

- a) biomass carbon sequestration at 23-35 t CO₂ eq/ha/year in mature plantations on appropriate soils
- b) emission reduction through best management practices including biogas capture (75-85% POME methane reduction), organic fertilizer substitution (17-34% lower fertilizer emissions), and peatland water table management (50-70% reduced oxidation)
- c) avoided deforestation through productivity intensification and landscape conservation.

The context-dependency of oil palm climate impact emerges as a central finding. Plantations established through forest or peatland conversion generate massive carbon debts that require 50-100 years to repay, in contrast to those established on degraded lands, where biomass accumulation represents net carbon gain. Management intensity accounts for 35% of the emission

differences between certified sustainable and conventional production systems. Temporal dynamics determine whether young plantations function as carbon sources while mature stands operate as sinks.

The synthesis reveals hydrological management as an underappreciated carbon strategy, with water table depth the single most important determinant of peatland emissions and soil-water conservation practices simultaneously reducing flood risk while retaining carbon stocks. Farmer welfare emerges not as a peripheral social concern but as a functional prerequisite for environmental sustainability, with prosperity enabling the capacity to adopt BMPs that poverty precludes.

Policy Recommendations

Immediate Priorities (2026-2028):

- a) Enforce zero-deforestation commitments through satellite monitoring, field verification, and swift penalties for violations, preventing 50-80 Mt CO₂ eq/year future emissions
- b) Mandate universal biogas capture at all mills exceeding 20 ton/hour capacity by 2028, with subsidized financing achieving 34-41 Mt CO₂ eq/year reduction
- c) Scale smallholder support through comprehensive training programs, simplified certification, and micro-credit access targeting 500,000 farmers by 2028
- d) Establish fertilizer efficiency program promoting precision agriculture and organic substitution, reducing emissions by 10-15 Mt CO₂ eq/year
- e) Medium-term Reforms (2028-2032):
- f) Implement jurisdictional sustainability in 10 priority districts covering 50% production area, achieving landscape certification through multi-stakeholder governance
- g) Require peatland water table management with mandatory monitoring systems maintaining 45-60 cm depth, reducing emissions by 15-25 Mt CO₂ eq/year
- h) Introduce carbon pricing through a phased tax-and-dividend system (IDR 50,000/t CO₂ eq by 2030) with revenues funding smallholder support and conservation
- i) Incentivize agroforestry transition with research support, pioneering farmer subsidies, and market premiums, targeting 5-10% plantation area by 2035
- j) Long-term Vision (2032-2040):
- k) Achieve net-zero emissions through a circular bioeconomy model with full residue valorization, renewable energy dominance, and regenerative agriculture practices universally adopted
- l) Transform global narrative through transparent emissions reporting, best practice showcasing, and differentiated "climate-positive palm oil" premium branding

Research Agenda

- Critical knowledge gaps requiring future investigation include
- a) long-term (>25 years) carbon flux monitoring across complete replanting cycles
 - b) empirical testing of hypothesized welfare-carbon linkages through panel studies and causal inference methodologies
 - c) landscape-scale climate feedbacks integrating plantation-atmosphere interactions beyond component-level NEE measurements
 - d) economic optimization modeling for BMP adoption pathways balancing costs, benefits, and risk profiles,
 - e) governance innovations for effective multi-stakeholder coordination in jurisdictional sustainability initiatives.

Final Perspective

The evidence synthesized establishes that oil palm's role in climate mitigation is not predetermined by crop characteristics but rather shaped by human choices regarding location, management, and governance. Historical environmental damage from deforestation and peatland conversion is a legitimate concern that demands accountability. Simultaneously, contemporary evidence demonstrates substantial mitigation potential through sustainable intensification on appropriate lands with best management practices. The sector's future trajectory—whether it continues as a major emitter or transforms into a climate solution—depends on decisions and actions taken in the current critical decade. Indonesia possesses the policy architecture, technological capacity, and economic incentives for transformation; what remains is the political will for enforcement, institutional coordination for implementation, and inclusive support ensuring smallholder participation in the sustainability transition. Achieving FOLU Net Sink 2030 and NDC commitments requires positioning sustainable oil palm as a viable component of national climate strategy, justified by evidence of its mitigation potential when properly managed.

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