Review Article

From Carbon Source to Carbon Sink: Reframing Oil Palm Plantations through the Lens of Climate-Smart Agriculture — A Review

SHRINE PUBLISHERS
Crafting your Achievement

Journal of Agriculture Science and Innovation (JASI)

Volume 3 Issue 1, 2026

Loso Judijanto*
IPOSS Jakarta, Indonesia

Abstract

The Indonesian oil palm sector stands at a pivotal juncture, facing a dual narrative: it is both a major greenhouse gas emitter and a strategic contributor to global food and energy security. This qualitative literature review synthesizes peer-reviewed scholarship published since 2020 to examine the transformation of oil palm plantations from perceived carbon sources to potential carbon sinks through the integrative framework of Climate-Smart Agriculture (CSA). Rather than following a systematic PRISMA protocol, the review employs an interpretive, theme-driven synthesis to reconcile heterogeneous evidence on emission pathways, biomass and soil carbon accumulation, and climate-smart management practices. Findings demonstrate that the source–sink outcome of oil palm is not deterministic but governed by land-use history, soil type, hydrological regime, and management intensity. Plantations established on non-deforested mineral soils, managed without burning, and supported by precision fertilization, water management, and organic residue recycling, can function as net carbon sinks while maintaining productivity. The CSA framework, grounded in the pillars of productivity, adaptation, and mitigation, offers a coherent pathway to reposition oil palm from a climate liability to a climate solution. The review further argues that sustainable practices do not automatically equate to climate-smart practices, and that context-specific evaluation is indispensable. Policy coherence, smallholder inclusion, and alignment with international instruments such as the EUDR, RSPO, ISPO, and the SDGs are decisive for scaling climate-smart oil palm across tropical landscapes, particularly in Indonesia and Malaysia.

JEL Classification: Q15; Q54; Q56; Q18; O13.

Article Information
Received date: April 28, 2026
Published date: May 18, 2026

***Corresponding author**
Loso Judijanto, IPOSS Jakarta, Indonesia

DOI: 10.65070/JASI.2026.104

Keywords
Climate-Smart Agriculture; Oil Palm; Carbon Source; Carbon Sink; Greenhouse Gas Emissions; Sustainable Intensification; Peatland Management; EUDR; RSPO; Indonesia

Introduction

Background

Palm oil occupies a unique and strategically significant position within the global agricultural economy. Indonesia alone accounts for more than half of the world's palm oil production, and palm oil supplies roughly 58 percent of global vegetable oil demand while occupying a fraction of the land required by alternative oil crops such as soybean. This extraordinary land-use efficiency makes oil palm an indispensable commodity for meeting the food, oleochemical, and bioenergy needs of a growing global population, particularly as demand is projected to rise by 0.5–3 percent annually through the coming decades [1-3].

Yet the same crop that feeds and fuels much of the world has been persistently framed as an environmental antagonist. For nearly two decades, the mainstream climate and biodiversity discourse has associated oil palm expansion with tropical deforestation, peatland degradation, fire-driven haze episodes, and substantial greenhouse gas (GHG)

How to cite this article: Judijanto L (2026) From Carbon Source to Carbon Sink: Reframing Oil Palm Plantations through the Lens of Climate-Smart Agriculture — A Review. J Agri Sci & Innov 3(1).

emissions. Studies estimate that the oil palm industry accounts for approximately 1.4 percent of global GHG emissions, primarily through land-use change, peat drainage and oxidation, biomass burning, and palm oil mill effluent (POME) decomposition. This narrative has shaped consumer perceptions, trade regulations, and sustainability certification architectures worldwide [4,5].

However, scholarship that has emerged since 2020 increasingly complicates this monolithic portrayal. It has been argued that the environmental impacts of palm oil must be understood in their full comparative context, including the opportunity costs of switching to less land-intensive oil crops [6]. Empirical evidence on long-term carbon fluxes from mature plantations on mineral soils suggests that, under specific conditions, oil palm plantations can transition from net carbon sources to net carbon sinks, with annual sequestration estimates ranging from –2.09 to –3.86 tCeq ha^{-1}. Simultaneously, climate change itself exerts compounding pressure on plantation productivity through erratic rainfall, heat stress, intensified outbreaks of pests and pathogens such as Ganoderma boninense, and hydrometeorological disasters [7-9].

It is in this complex landscape that the Climate-Smart Agriculture (CSA) framework has emerged as a guiding paradigm. Originally articulated by the Food and Agriculture Organization, CSA rests on three reinforcing pillars: sustainably increasing productivity, enhancing adaptive capacity, and reducing or removing greenhouse gas emissions. Applying CSA to oil palm cultivation offers a structured pathway through which plantations may be reimagined not as inherent climate liabilities but as potential climate assets [10-12].

Urgency

The urgency of this conceptual and empirical reorientation is considerable. On the regulatory front, Indonesian and Malaysian palm oil producers are now navigating an increasingly demanding international compliance environment. The European Union's Deforestation-Free Regulation (EUDR), the EU Renewable Energy Directive (EU RED), the Roundtable on Sustainable Palm Oil (RSPO), the Indonesian Sustainable Palm Oil (ISPO), and the broader Sustainable Development Goals collectively set stringent environmental benchmarks for market access [13-15]. Simultaneously, national commitments to Net Zero Emissions and Indonesia's FOLU Net Sink 2030 target measurable emissions reductions from the agricultural and land-use sectors.

At the same time, climate modeling suggests that without meaningful adaptation, oil palm productivity could decline by more than 13 percent, and potentially up to 20 percent, between 2071 and 2095 under business-as-usual scenarios [16-19]. Such declines would not only threaten smallholder livelihoods and national export revenues but would also create perverse incentives for further land expansion, thereby undermining climate goals.

Equally pressing is the persistent ambiguity regarding whether oil palm plantations are a net carbon source or a net carbon sink. This ambiguity muddies both scholarly discourse and policy design, and it weakens the evidentiary basis for climate finance, carbon markets, and certification reform. A growing body of work calls for integrative syntheses that bring together the emission-pathway literature, the carbon-sink evidence, and the CSA operationalization discourse into a coherent interpretive framework [20].

Purpose of the Writing

This manuscript responds to that call. Its purpose is fourfold. First, it synthesizes the conceptual, empirical, and policy literature that has framed oil palm as a carbon source historically. Second, it examines emerging evidence that reframes oil palm as a potential carbon sink under specified land-use and management conditions. Third, it articulates how the CSA framework can guide a credible transformation of oil palm plantations toward climate-resilient, low-emission, and productive systems. Fourth, it offers policy, agronomic, institutional, and research recommendations aligned with international sustainability instruments.

The guiding review questions are:

a) Through what mechanisms have oil palm plantations been characterized as carbon sources
b) Under what conditions can they function as carbon sinks?
c) How can CSA principles be operationalized to achieve synergistic productivity, adaptation, and mitigation outcomes?

Literature Review

Oil Palm Plantations as a Source of Carbon Emissions

The framing of oil palm as a carbon source rests on four principal emission pathways. The first, and by far the most dominant, is land-use change. Conversion of primary and secondary tropical forests to oil palm plantations has historically entailed substantial losses of aboveground biomass, with per-hectare carbon losses of up to 173 Mg C reported in peer-reviewed studies [6]. The second pathway is peatland drainage and oxidation. When tropical peat swamp forests are drained to support oil palm cultivation, the previously waterlogged organic soils become aerobic, releasing long-sequestered carbon as CO_2 [5,21]. Fire used to clear land compounds these losses, contributing to regional haze crises and significant pulse emissions [22].

The third pathway encompasses operational and process emissions, particularly those associated with POME treatment, nitrogen fertilizer use, and on-site fuel combustion. POME lagoons emit methane through anaerobic decomposition, and nitrogen fertilizers drive N_2O emissions that can be disproportionately large relative to CO_2 in tropical plantation systems [23]. The fourth pathway concerns emissions embedded in plantation drainage infrastructure. Recent evidence from Malaysian peatland plantations documents substantial GHG fluxes from plantation ditches, highlighting a previously underappreciated source [24]. Quantification debates nonetheless persist. Emission factors vary across studies due to differences in system boundaries, counterfactual assumptions, soil types, plantation age, and measurement methodologies. This heterogeneity is not merely a technical issue; it has profound implications for how national inventories, carbon markets, and due diligence regulations treat palm oil [4].

Recent ecosystem-scale measurements have substantially refined the understanding of N_2O as a disproportionate driver of global warming in oil palm systems. Stiegler et al. (2023) reported the first eddy covariance measurements of N_2O fluxes from an oil palm plantation in Jambi, Indonesia, recording an average annual emission of 0.32 ± 0.003 g N_2O-N m^{-2} yr^{-1}, equivalent to approximately 149.85 g CO_2-equivalent m^{-2} yr^{-1}. Critically, chamber-based measurements underestimated actual fluxes by approximately 49%, as canopy gas exchange dynamics related to photosynthesis and meteorological conditions accounted for a significant portion of N_2O transport that conventional methods fail to capture. A separate biogeochemical study at the same regional scale confirmed that the palm circle — the fertilized ring around each tree, constituting only 18% of the plantation area — accounted for 79% of total soil N_2O emissions [25]. These findings demonstrate that spatially targeted nitrogen management within the palm circle is the highest-leverage intervention for reducing operational emissions at the plantation scale.

Beyond operational emissions, the life cycle dimension of oil palm's carbon footprint has become a focus of increasingly rigorous accounting. It has been estimated that capturing biogas from POME in palm oil mills via closed anaerobic digestion could achieve a 75% reduction in GHG emissions per tonne of crude palm oil, with aggregate national savings of approximately 19.5 million tonnes CO_2-equivalent annually if all Malaysian mills adopted biogas capture [26]. Independently, a 2024 study using an organizational life cycle assessment (O-LCA) combined with demand forecasting projected the carbon footprint of an Indonesian palm oil company's operations to 2030, finding that POME, fertilizer use, and transportation collectively constitute the three largest emission sources, with 1.08 tonnes CO_2-equivalent generated per tonne of crude palm oil under business-as-usual scenarios [27]. These life cycle studies, methodologically grounded in ISO 14040/14044 frameworks, underscore the systemic nature of oil palm's emissions profile and reinforce the argument that mitigation must address the entire production chain rather than single hotspots.

Oil Palm Plantations as a Carbon Sink

Parallel to the emissions literature, a growing empirical base document the carbon sequestration potential of oil palm plantations, particularly when established on non-forested mineral soils and managed with best agronomic practices. Oil palm is a long-lived perennial capable of accumulating substantial aboveground biomass across a 25–30-year economic cycle, and its canopy architecture supports continuous photosynthetic carbon fixation [28].

Recent eddy-covariance and carbon-balance studies report negative net ecosystem exchange values in mature plantations, indicating net atmospheric CO_2 uptake. Estimates of net sink strength of –2.09 to –3.86 tCeq ha^{-1} yr^{-1} have been reported for non-deforested mineral-soil plantations in Indonesia. Such findings align with broader work suggesting that carbon-neutral or even carbon-negative expansion is feasible when plantations replace degraded grasslands or cropland rather than forests [29-31].

Conditions enabling sink behavior include: plantation establishment on non-forested lands; zero-burn land preparation; maintenance of soil organic carbon through legume cover crops and organic residue recycling; and, where relevant, rewetting and integration of paludiculture on previously drained peatlands. Methodological considerations remain important. Plot-scale measurements may not translate directly to landscape-scale outcomes, and short-term flux observations can diverge from long-term, cycle-integrated balances. Nonetheless, the direction in the 2020–2026 literature is unambiguous: under appropriate conditions, oil palm plantations can meaningfully contribute to carbon sequestration [20,32,33].

Carbon stock dynamics across the oil palm plantation chronosequence have been further elucidated by integrated assessments that combine carbon balance, vegetation indices, and net ecosystem exchange measurements. In a study across Riau Province, it has been found that total carbon stocks progressively increased from 23.7 Mg C ha^{-1} in young plantations (ages 3–5 years) to a peak of 147.9 Mg C ha^{-1} in mature stands (21–25 years), with an optimal sequestration rate of 17.8 Mg C ha^{-1} yr^{-1}. Critically, the integration of smart drainage management and IoT-assisted water table monitoring yielded the lowest CO_2

emissions (6.2 Mg C ha^{-1} yr^{-1}) and highest carbon absorption (21.5 Mg C ha^{-1} yr^{-1}) of all management regimes tested, producing a positive net carbon balance of +15.3 Mg C ha^{-1} yr^{-1} [34]. These results demonstrate that carbon sink behavior in oil palm is not merely a passive biophysical outcome but can be actively engineered through precision hydrological management, substantially strengthening the empirical foundation for climate-smart plantation design.

The peatland rewetting literature provides convergent evidence for carbon sink restoration at the landscape scale. It has been documented that rewetting oil palm plantations on tropical peatlands in West Kalimantan reduced heterotrophic respiration by 34% and total soil respiration by 20% compared to drained plantations [32]. Extrapolating the observed emission factor for heterotrophic respiration (10.3 tCO_2 ha^{-1} yr^{-1}), the authors calculated that successful rewetting of degraded oil palm peatlands in West Kalimantan alone could reduce national emissions by approximately 3.9 $MtCO_2$ yr^{-1} — a contribution directly relevant to Indonesia's FOLU Net Sink 2030 target of −140 $MtCO_2e$. While methane emissions may partially offset CO_2 savings under rewetted conditions, the net climate mitigation benefit of peatland rewetting in oil palm landscapes remains robustly positive, establishing it as a high-priority climate-smart practice where peat soils predominate.

The Concept of Climate-Smart Agriculture

Climate-Smart Agriculture emerged in 2010 as a FAO-led framework designed to integrate three traditionally siloed objectives: sustainably increasing productivity and incomes, adapting to climate change, and reducing or removing greenhouse gas emissions where possible. CSA is not a prescriptive set of technologies but a context-dependent portfolio of practices, technologies, services, and institutional arrangements [10].

Applied to perennial tropical commodities such as oil palm, CSA principles translate into specific agronomic, infrastructural, and governance interventions. These include precision nutrient management, water harvesting and irrigation, integrated pest and disease management, soil organic matter enhancement, climate-informed replanting schedules, and traceability systems aligned with international certification [35,36].

A crucial conceptual distinction underpins the CSA framework: sustainable practices are not automatically climate-smart. A practice may reduce environmental impact in one dimension (for example, enhancing soil organic carbon through the application of empty fruit bunches) while inadvertently increasing emissions in another (for example, accelerating decomposition under warmer conditions). CSA, therefore, requires integrated, multi-pillar evaluation rather than single-indicator optimization. This distinction is the intellectual fulcrum of the present review [37-39].

The operationalization of CSA's three pillars in perennial tropical crop systems has attracted growing methodological attention since 2020. A spatio-temporal framework has been developed for assessing the climate-smartness of specific agronomic practices in oil palm by simultaneously evaluating their productivity outcomes, adaptive capacity contributions, and mitigation performance under changing climate conditions across multiple sites in Indonesia [16]. Their findings confirmed that no single agronomic practice simultaneously optimized all three pillars under all site conditions; rather, climate-smartness was an emergent property of practice bundles tailored to local soil types, hydrological regimes, and climate trajectories. This context-dependency reinforces the CSA principle that prescriptive, technology-driven approaches cannot substitute for locally calibrated, multi-pillar evaluation — a finding with immediate implications for the design of extension programs, certification criteria, and investment portfolios for tropical commodity agriculture [40].

The relationship between CSA and sustainability certification architectures deserves closer conceptual scrutiny than it has received in the mainstream literature. A comparative life cycle assessment using primary data from RSPO's mandatory greenhouse gas calculation database and covering 32–63% of certified cultivation areas across five major producing countries, found that RSPO-certified palm oil exhibited 36% lower global warming potential and 37% reduced nature occupation compared to non-certified production, driven principally by higher yields per unit area, lower peatland cultivation shares, and greater biogas capture from POME treatment [41]. However, the same study noted a 3% increase in respiratory inorganic impacts in certified production due to higher fertilizer use, illustrating the trade-off logic that CSA frameworks must navigate. These results, published in a study compliant with ISO 14040/14044 standards, provide quantitative support for the proposition that certification alone is necessary. Still, not sufficient to achieve full climate-smart transformation — explicit mitigation quantification and adaptive capacity metrics must be added to existing certification criteria [42,43].

Methods

Rationale for a Qualitative Literature Review

This manuscript employs a qualitative, interpretive literature review rather than a systematic literature review (SLR) conducted in accordance with the PRISMA protocol. The choice is deliberate and epistemologically grounded. Qualitative literature reviews are theory-generating and narrative in orientation,

Citation: Judijanto L (2026) From Carbon Source to Carbon Sink: Reframing Oil Palm Plantations through the Lens of Climate-Smart Agriculture — A Review. J Agri Sci & Innov 3(1).

enabling the synthesis of heterogeneous conceptual, empirical, and policy sources into a coherent interpretive argument [44,45]. SLRs, by contrast, prioritize reproducibility and exhaustive enumeration against predefined inclusion criteria, which can constrain interpretive depth when the literature spans distinct epistemic communities, such as ecology, agronomy, climate science, development economics, and environmental governance.

Given that the oil palm climate literature draws from precisely such heterogeneous communities, a qualitative synthesis is more appropriate for articulating conceptual bridges among emission pathways, sink evidence, and CSA operationalization.

Literature Sourcing and Selection Strategy

Literature was identified through purposive searches of Scopus, Web of Science, ScienceDirect, Wiley Online Library, Springer Link, Frontiers, and MDPI, complemented by grey literature from FAO, IPCC, RSPO, CIFOR, and ICCT. Keyword constellations included "oil palm," "climate-smart agriculture," "carbon source," "carbon sink," "peatland emissions," "sustainable intensification," "EUDR," and "RSPO." Priority was given to peer-reviewed articles published from 2020 onward, while selected seminal works preceding 2020 were retained for conceptual grounding.

Analytical Approach

The analytical workflow comprised three phases:

a) Close reading and thematic coding across three conceptual anchors-source, sink, and CSA
b) Interpretive synthesis, in which recurring themes, tensions, and knowledge gaps were articulated narratively
c) Reflexive evaluation, acknowledging the limitations of qualitative synthesis, including selection bias and interpretive subjectivity.

Trustworthiness was supported by triangulating findings across empirical, conceptual, and policy sources.

Results

Oil Palm Plantations as a Source of Carbon Emissions

The thematic synthesis confirms that the framing of oil palm as a carbon source remains empirically supported, but with important contextual qualifications. The largest historical emissions have been associated with land-use change and peat drainage [21]. Deforestation rates in Indonesia, however, have declined significantly since 2016, reflecting the combined effects of presidential moratoria, certification uptake, corporate no-deforestation commitments, and enhanced monitoring. Consequently, the marginal emissions attributable to new plantation development have decreased relative to the early 2010s [46,47].

Operational emissions from POME, fertilizer use, and plantation drainage remain recurring hotspots in the literature. Recent work on tropical peatland plantations in Malaysia shows that ditches alone contribute measurable GHG fluxes, highlighting infrastructural redesign as an emerging mitigation frontier. Studies of N_2O emissions underscore that fertilizer management is a disproportionately high-leverage mitigation target [23,24].

The attribution of emissions within the plantation system has been refined by spatial decomposition studies, which reveal strong heterogeneity in GHG flux intensity across microhabitats. A biogeochemical study conducted in a large-scale plantation in Jambi Province (Chen et al., 2024), published in Biogeosciences, found that the palm circle — comprising only 18% of the total plantation area but receiving the bulk of nitrogen fertilizer — accounted for 79% of all measured soil N_2O emissions. Annual soil GHG fluxes averaged 5.5 ± 0.2 Mg CO_2-C ha^{-1} yr^{-1}, 3.6 ± 0.7 kg N_2O-N ha^{-1} yr^{-1}, and -1.5 ± 0.1 kg CH_4-C ha^{-1} yr^{-1}; the global warming potential of the plantation was $3{,}010 \pm 750$ kg CO_2-eq ha^{-1} yr^{-1}, of which N_2O contributed 55% and the soil CH_4 sink offset less than 2%. Notably, switching from conventional to reduced fertilization did not significantly alter emissions or yields within the four-year experiment timeframe, implying that legacy soil nitrogen from over a decade of prior management imposes persistent emission commitments that cannot be rapidly reversed - a finding with important implications for corporate net-zero timelines and the validity of short-term mitigation claims.

POME-related methane emissions, while historically the dominant mill-level emission source, have increasingly been shown to be technically and economically feasible to capture through biogas technologies. It has been estimated that deploying closed anaerobic digester systems across all palm oil mills in Malaysia could capture approximately 1,750 million m^3 of biogas annually, enabling GHG savings of 19.5 million tonnes CO_2-equivalent per year — equivalent to eliminating approximately 75% of the GHG burden per tonne of crude palm oil processed [26]. A complementary study on bio-methane optimization from POME using mathematical programming further demonstrated the technical viability of producing bio-compressed natural gas (Bio-CNG) from captured POME methane, offering a circular-economy pathway that simultaneously reduces GHG emissions and generates renewable-energy revenue for mill operators [48]. These results collectively position biogas capture from POME not merely as a mitigation measure but as a financially self-reinforcing component of climate-smart mill management -one that can accelerate adoption without requiring external carbon finance.

Oil Palm Plantations as a Carbon Sink

Evidence supporting the oil palm's sink potential has strengthened notably since 2020. Research in North Sumatra and Riau documents a measurable shift from carbon loss to carbon uptake in plantations established on non-deforested mineral soils and managed without burning. These findings are corroborated by modeling and remote sensing studies that track vegetation indices and carbon dynamics across plantation chronosequences [34].

Best management practices consistently associated with sink behavior include legume cover crop establishment, empty fruit bunch (EFB) recycling, optimized planting density, and reduced soil disturbance during replanting [36]. Peatland rewetting, while still economically and logistically demanding at scale, has been shown to curtail emissions from previously drained organic soils substantially and, in some cases, to restore net sink functionality at the landscape level [32].

The role of organic residue management in reinforcing carbon sink behavior has been clarified by field-scale experiments that explicitly track both productivity and emission intensity. A comparative field study conducted on mineral soils in South Kalimantan evaluated the effects of NPK fertilizer, EFB, and POME applications across 18 randomized blocks, using IPCC-compliant emission-intensity calculations [49]. EFB treatment achieved the lowest absolute GHG emissions (767.82 kg CO_2-eq ha^{-1}), while POME application generated the highest fresh fruit bunch (FFB) yield alongside an emission intensity of 1,610.84 kg CO_2-eq ha^{-1} — lower than inorganic NPK in emission per unit of product. These results demonstrate that integrating local organic waste streams into fertilization strategies can simultaneously reduce emission intensity and enhance soil carbon, establishing a circular economy logic that is both agronomically and climatically rational for mineral-soil plantations aiming to consolidate or strengthen net sink status [50,51].

Comparative life-cycle evidence provides a macro-level validation of the carbon-sink potential differentials between certified and non-certified oil palm systems. In a life cycle assessment compliant with ISO 14040/14044 it has been reported that RSPO-certified palm oil production reduces global warming potential by 36% compared to non-certified production (3.41 vs. 5.34 kg CO_2-eq per kg of refined oil under consequential modelling), driven by higher per-area yields, lower peatland area under cultivation, and higher rates of POME biogas capture [41]. The study also found that certified production showed a 37% reduction in nature occupation impacts. These findings provide robust multi-country evidence - drawn from Indonesia, Malaysia, Thailand, Colombia, and Nigeria — that management practices aligned with sustainability certification architectures systematically shift the carbon balance toward lower net emissions and, where combined with active sequestration management on mineral soils, contribute to sink-side outcomes [52-54]. The LCA evidence thus bridges the gap between field-scale sink measurements and supply-chain-level carbon accounting.

Oil Palm Plantations and Climate-Smart Agriculture

The synthesis identifies irrigation and precision water management as the practices most consistently meeting CSA's three-pillar test. Irrigation sustains productivity under drought stress, enhances adaptive capacity, and does not appreciably increase emissions when fuel and pumping energy are managed efficiently [35]. Precision nitrogen management similarly delivers joint productivity and mitigation gains by minimizing N_2O losses and fertilizer runoff [23].

Conversely, certain widely promoted sustainable practices exhibit CSA trade-offs. Empty fruit bunch application, for example, increases soil organic carbon and fertility, but simulations indicate that under warming, accelerated decomposition can elevate CO_2 emissions, partially offsetting mitigation benefits. This finding empirically validates the conceptual claim that sustainability and climate-smartness are not synonymous [55-57].

Governance instruments reinforce the CSA pathway. ISPO, RSPO, and EUDR compliance architectures, along with alignment with the SDGs, collectively shape producer incentives, market access, and investment flows [13,15]. Replanting strategies that incorporate improved planting materials, optimized density, and staged land preparation further enhance both productivity and climate performance [58].

The digital transformation of plantation management is increasingly recognized as a structural enabler of CSA operationalization, particularly for precision management of nutrient, water, and pest inputs at scales relevant to both large estates and smallholder cooperatives. Adoption of drone-based monitoring and remote sensing has been shown to improve agronomic decision accuracy to above 95% and substantially reduce field survey durations, while enabling real-time detection of nutrient stress, pest incidence, and canopy structural change that would otherwise escape conventional ground-based monitoring [59]. Building on this, a comprehensive AI-assisted agroecological management framework for oil palm has been proposed, which integrates the Traffic Light System Methodology across 13 key issues, including carbon footprint, biodiversity, water use, and social governance [60]. The framework demonstrates how AI can transform reactive plantation management into proactive, evidence-driven, climate-smart governance -particularly relevant to independent smallholders who currently lack the technical and human resources to implement complex, multi-pillar CSA protocols without digital assistance.

The EUDR, which entered into force in June 2023 with compliance obligations for large operators, was originally scheduled to take effect in December 2025 and has fundamentally altered the governance architecture in which CSA practices must be operationalized. The regulation's traceability requirements — mandating geo-referenced evidence of non-deforestation and legality for all palm oil placed on the EU market — create a structural incentive for supply chain actors to invest in the digital monitoring, certification systems, and land management practices that are also foundational to CSA [61]. Critically, RSPO has confirmed that its certification system's existing processes for monitoring, traceability, and no-deforestation compliance position certified producers as better prepared for EUDR due diligence obligations, and that Article 10.2.j of the regulation explicitly recognizes third-party verified schemes as risk-mitigation tools in national competent authorities' enforcement prioritization [61]. However, for independent smallholders — who manage approximately 40% of Indonesia's oil palm area yet account for less than 2% of RSPO-certified volume — EUDR compliance remains a significant structural barrier that risks market exclusion unless jurisdictional approaches, blended finance, and digital extension services are urgently deployed [15,62-64].

Discussion and Analysis

Reconciling the Source–Sink Dichotomy

A core analytical contribution of this review is the reconciliation of the source–sink dichotomy. The literature makes clear that whether an oil palm plantation functions as a net carbon source or a net carbon sink is not an intrinsic property of the crop but an emergent outcome of land-use history, soil type, hydrological regime, and management intensity. Plantations established through deforestation or peat drainage retain a substantial emissions debt for decades. In contrast, plantations established on degraded or already converted lands and managed with climate-smart practices can deliver net sequestration [29].

Accounting conventions also matter. System boundaries, reference scenarios, and temporal horizons profoundly affect the conclusions drawn from ostensibly similar datasets. Mainstreaming transparent, harmonized carbon accounting for oil palm — ideally aligned with IPCC Tier 3 methodologies and independently verified — would go a long way toward dispelling the prevailing "guilty-by-default" narrative and supporting evidence-based regulation [4,20].

The role of plantation age and chronosequence in mediating the source–sink transition deserves particular emphasis in any reconciliation of the dichotomy. As it has been documented in Riau Province, total carbon stocks in oil palm plantations increase progressively from early establishment through maturity, peaking at approximately 147.9 Mg C ha^{-1} in stands of 21–25 years, with net ecosystem exchange shifting from positive (source) to negative (sink) as canopy closure and biomass accumulation accelerate in mid-to-late plantation cycles [34]. This temporal dynamic means that snapshot-based carbon assessments-which dominate the regulatory and certification literature — systematically misrepresent the long-term carbon balance of plantations by failing to capture the full sequestration realized over a 25–30-year rotation. Integrating lifecycle-scale carbon accounting that tracks sequestration from stand establishment through replanting, rather than relying on single-year flux measurements, is therefore a methodological priority for both the scientific community and standard-setting bodies seeking to develop credible, phase-appropriate carbon metrics for oil palm [65].

A further dimension of the source–sink reconciliation concerns the comparative carbon performance of oil palm relative to its vegetable oil substitutes. A cross-commodity analysis has been conducted, demonstrating that replacing palm oil with alternative vegetable oils — including soybean, rapeseed, and sunflower — would require substantially more land to deliver equivalent oil volumes, imposing greater land-use change emissions and biodiversity costs in aggregate [29]. This land-use efficiency argument has reinforced the conclusion that the relevant policy question is not whether oil palm emits carbon in absolute terms, but whether its net carbon performance per unit of oil delivered - under appropriately managed conditions on non-peat soils — is superior to realistic alternatives [22]. Reframing the source–sink question in this comparative, functional-unit logic is essential for constructing a scientifically defensible position in international trade debates, particularly in the context of EUDR and EU Renewable Energy Directive compliance discussions.

From Sustainability to Climate-Smartness

The review's second analytical thread concerns the movement from generic sustainability to specific climate-smartness. Not all practices endorsed under sustainability certifications deliver synergistic outcomes across CSA's three pillars. Irrigation and precision nutrient management emerge as robustly climate-smart. Organic residue recycling delivers clear co-benefits but carries mitigation risks under warming, requiring site-specific calibration [66,67].

Citation: Judijanto L (2026) From Carbon Source to Carbon Sink: Reframing Oil Palm Plantations through the Lens of Climate-Smart Agriculture — A Review. J Agri Sci & Innov 3(1).

This distinction has important policy implications. Certification schemes such as RSPO and ISPO, while valuable, were not originally designed as CSA instruments. Incorporating explicit climate-smartness indicators — including adaptive capacity metrics, mitigation quantification, and productivity resilience — would strengthen their alignment with international climate instruments, such as the EUDR and the Paris Agreement's Article 6 carbon market mechanisms [15].

Smallholder inclusion is central. Independent smallholders manage approximately 40 percent of Indonesia's oil palm area but face persistent yield gaps (47 percent) and limited uptake of certification due to constraints in financing, extension, and tenure. Climate-smart transformation will be incomplete without credible smallholder pathways, including blended finance, jurisdictional certification, and digital extension services [68-70].

The quantitative evidence for differences in climate performance between certified and non-certified systems provides a compelling empirical argument for accelerating the integration of climate-smartness metrics into existing certification frameworks. It has been documented that RSPO-certified palm oil has a 36% lower global warming potential than non-certified palm oil, driven by three certification-induced practice shifts: higher yields per hectare (reducing land use per unit of output), lower peatland cultivation, and higher POME biogas capture rates [71]. These drivers align almost perfectly with CSA's three pillars -productivity intensification reduces land pressure, peatland avoidance enhances long-term adaptive capacity, and biogas capture directly reduces process emissions. This structural alignment suggests that rather than developing entirely new CSA standards parallel to existing certification systems, the most pragmatic pathway is to embed explicit, measurable CSA indicators — particularly adaptive capacity metrics and climate-scenario-conditioned yield projections — within RSPO and ISPO audit frameworks, leveraging the existing compliance infrastructure at scale [72,73].

The smallholder dimension of the sustainability-to-climate-smartness transition is further complicated by structural market dynamics that risk exacerbating exclusion rather than enabling inclusion. An analysis of Indonesia's smallholder landscape found that independent smallholders cultivate more than 40% of the country's oil palm area, yet most remain outside formal traceability and certification systems, with certified smallholder volume accounting for less than 2% of total RSPO-certified supply [74-76]. The imminent application of EUDR compliance requirements — mandating plot-level geolocation and deforestation-free documentation for EU market access — threatens to entrench rather than bridge this gap unless jurisdictional certification approaches are deployed at district or provincial scale, enabling smallholders to be represented within collective compliance envelopes rather than individual due diligence requirements [77]. Digital traceability platforms that link smallholder plot registration with real-time land cover monitoring, such as those being piloted in Kalimantan and Sumatra, offer a technically feasible pathway to inclusion, but their scaling requires coordinated investment from government, industry, and development finance institutions rather than market mechanisms alone.

Future Trajectories under Climate Change

Projections that business-as-usual management could entail productivity declines of 13–20 percent by the late century underscore the adaptation imperative. Yet this risk also represents an opportunity: climate-smart adoption can simultaneously protect yields, reduce emissions, and obviate the need for additional land conversion, thereby transforming a climate threat into a market and sustainability advantage [11,78,79].

Digital agriculture offers a powerful enabling infrastructure. Remote sensing, drone-based phenotyping, soil sensors, and AI-enabled decision support can operationalize precision management at scale, including for smallholders through cooperative and platform-based service models. Integrating CSA outcomes into Indonesia's Nationally Determined Contributions, the FOLU Net Sink 2030 roadmap, and corporate net-zero pathways would firmly anchor the sector within the global climate-policy architecture [60].

The biotic dimension of future climate risk — particularly the projected escalation of Ganoderma boninense basal stem rot (BSR) under warming and moisture-stress scenarios — constitutes an underappreciated yet potentially catastrophic intersection of adaptation and productivity risks. It has been documented that climate change exacerbates BSR incidence by altering soil moisture regimes, temperature profiles, and palm immune responses, thereby increasing pathogen virulence and spatial spread [7]. A review published in 2026 synthesized data from over 60 peer-reviewed sources, documenting current BSR infection rates of 39–52% across Sumatra and 19% in Kalimantan, with economic losses estimated at USD 500 million annually and individual infected palms experiencing 43% yield reduction within six months [80]. Critically, projections under high-emission climate scenarios suggest infection rates could approach 100% in Sumatra by 2100, rendering conventional monoculture oil palm production economically unviable across much of its current geographic range. Integrated disease management incorporating early detection via UAV multispectral imaging (achieving above 90% accuracy), biological control with Trichoderma spp., and climate-resilient planting material selection represents the most robust adaptation

Citation: Judijanto L (2026) From Carbon Source to Carbon Sink: Reframing Oil Palm Plantations through the Lens of Climate-Smart Agriculture — A Review. J Agri Sci & Innov 3(1).

pathway — and its integration into ISPO's mandatory standards is identified as an institutional priority.

Climate-change-driven productivity risk is also mediated by compounding hydrological stresses that interact with soil carbon dynamics in ways that simultaneously threaten yield and undermine sink behavior. In a systematic literature review, it has been synthesized evidence showing that climate change could reduce oil palm productivity by up to 41% under temperature increases of 1–4°C combined with water stress, with lagged yield responses commonly observed 12–24 months after initial climate stress events due to the perennial crop's long reproductive cycle [18]. This temporal lag means that productivity losses from current climate trajectories are already embedded in future harvests, underscoring the urgency of proactive adaptation through climate-resilient variety development, improved soil water retention, and canopy architecture optimization. The review further noted that experimental and observational knowledge systems -combining agronomist expertise with farmer experience - substantially enhanced the effectiveness of adaptive practices at the plot scale, pointing to co-design approaches that integrate indigenous and technical knowledge as a necessary complement to precision digital tools in smallholder adaptation pathways [81-83].

Synthesis: Answering the Review Questions

Returning to the guiding questions: oil palm has been characterized as a carbon source primarily through deforestation, peat drainage, POME, and fertilizer emissions; it can function as a carbon sink when established on non-forested mineral soils, managed without burning, and supported by best practices; and CSA principles can be operationalized through irrigation, precision nutrient management, integrated pest and disease management, organic residue recycling calibrated to local conditions, peat rewetting, and digital precision agriculture [10,36, 84].

Remaining research gaps include long-term, multi-site flux measurement networks; robust CSA metrics tailored to smallholders; economic analyses of peatland rehabilitation; and integrated assessments of replanting pathways under climate change [20].

The synthesis also reveals a structural gap between the technical feasibility of climate-smart practices and the institutional conditions required to adopt them at scale. The literature consistently demonstrates that individual practices -biogas capture from POME, precision nitrogen management within palm circles, EFB recycling, peatland rewetting-are technically proven, economically feasible, and climate-impactful. The literature also consistently demonstrates that adoption is constrained by fragmented governance, limited access to finance, inadequate extension services, and the absence of harmonized carbon accounting frameworks that would allow producers to monetize mitigation performance through carbon markets or premium certification pricing. Indonesia's articulation of its FOLU Net Sink 2030 target — formalized under Ministry of Environment and Forestry Decree No. 168/2022 and aiming for a net emission level of −140 $MtCO_2e$ from the FOLU sector by 2030-creates the policy architecture within which these adoption constraints could be addressed through aligned regulatory, financial, and market instruments [76,85]. Connecting CSA adoption incentives explicitly to Indonesia's NDC and FOLU Net Sink architecture, including through Article 6-compatible carbon credit mechanisms for verified emission reductions in oil palm landscapes, represents the most systemic pathway to closing the adoption gap.

The review's synthesis also points to a need for explicit temporal differentiation in CSA evaluation frameworks. Carbon performance varies enormously across the plantation lifecycle-with young plantations typically functioning as net carbon sources during establishment, transitioning to net sinks during mid-cycle biomass accumulation, and potentially reverting toward source behavior at replanting if residue management is poor and soil disturbance is severe. Effective CSA evaluation must therefore be phase-sensitive, embedding lifecycle-integrated carbon accounting into the management planning cycle rather than relying on cross-sectional flux measurements that capture only a single phase of a complex multi-decadal dynamic [16,20,33]. This temporal sensitivity has direct practical implications: replanting decisions - which determine the magnitude of soil disturbance, the carbon debt from biomass removal, and the timeline to renewed sequestration -emerge from the synthesis as one of the highest-leverage CSA design choices available to plantation managers, second only to the original land-use selection decision. Staging replanting, preserving root mats, and recycling fronds and palm trunks as mulch and organic amendment during replanting transitions can significantly reduce the emissions spike that conventionally accompanies replanting and accelerate the return to net sink conditions in the subsequent rotation [86,87].

Conclusion and Recommendations

Substantive Conclusion

This qualitative literature review advances three principal conclusions. First, oil palm plantations are neither inherently sources nor inherently sinks of carbon; the outcome is contingent on land-use history, soil type, and management intensity. Second, the CSA framework offers an integrative, evidence-based pathway for reconciling productivity, adaptation, and mitigation objectives in oil palm production systems. Third, the transition from sustainable to climate-smart oil palm is feasible but requires policy coherence, transparent carbon accounting, and meaningful inclusion of smallholders.

The review's findings have direct implications for the design of national and subnational climate policy instruments targeting the oil palm sector. Indonesia's commitment to achieving FOLU Net Sink 2030 — a carbon positive condition for the forestry and land-use sector at −140 $MtCO_2e$ by 2030, formalized under the Enhanced NDC submitted to UNFCCC in September 2022 — cannot be met without measurable mitigation contributions from the oil palm sector, which occupies over 16 million hectares of the country's land base. The synthesis evidence suggests that a targeted package of three interventions — biogas capture from POME at all registered mills, cessation of new development on peatlands combined with progressive rewetting of existing peatland plantations, and spatial targeting of precision nitrogen management to the palm circle — could collectively deliver emission reductions in the range of tens of millions of tonnes CO_2-equivalent annually, making a material and verifiable contribution to the FOLU target while simultaneously enhancing the market competitiveness of Indonesian palm oil under EUDR and RSPO compliance requirements. This convergence of climate, regulatory, and commercial incentives creates a historically unusual window of opportunity for transformative policy action that should not be deferred.

Finally, the review underscores that the scientific credibility of climate-smart oil palm claims depends critically on the quality and transparency of the measurement, reporting, and verification (MRV) infrastructure supporting them. The current literature reveals substantial methodological heterogeneity in how carbon fluxes are measured — with ecosystem-scale eddy covariance measurements typically yielding higher N_2O flux estimates than chamber-based methods, and how life cycle boundaries are drawn, with attributional and consequential LCA approaches generating meaningfully different emission factors for the same production system. Establishing multi-site, long-term flux measurement networks that combine eddy covariance, chamber measurements, and remote sensing across a representative sample of Indonesian and Malaysian oil palm landscapes, and aligning their outputs with IPCC Tier 3 methodologies, is the single most important research infrastructure investment the sector could make to underpin credible carbon market participation, honest regulatory compliance, and evidence-based policy reform. Without this foundation, even the most technically sound CSA practices will remain vulnerable to scientific contestation and regulatory skepticism.

The reframing of oil palm from climate liability to potential climate asset is not rhetorical. It is grounded in an expanding empirical base documenting measurable carbon sequestration under specific conditions and in the demonstrated viability of climate-smart management practices.

Recommendations

Policy recommendations include enforcing no-deforestation, no-peat, and no-burn commitments across jurisdictions; scaling peat rewetting and paludiculture pilots; and aligning ISPO with explicit CSA indicators to converge with EUDR and RSPO requirements. Agronomic recommendations include prioritizing irrigation and precision water management, advancing precision nitrogen fertilization, maintaining optimized planting densities, implementing integrated pest and disease management targeting Ganoderma boninense, and calibrating the use of organic amendments to site-specific soil and climate conditions.

Institutional and market recommendations include strengthening EUDR-compliant traceability, enabling oil palm participation in high-integrity carbon markets, expanding blended finance for smallholder CSA adoption, and scaling jurisdictional certification. Research recommendations include establishing multi-site long-term flux networks, advancing model–data fusion for region-specific climate projections, and developing smallholder-appropriate CSA metrics.

Ultimately, the path forward is clear: with deliberate, evidence-based transformation, Indonesian and broader tropical oil palm production can evolve from a perceived driver of climate change into a credible pillar of climate solutions, sustaining livelihoods, safeguarding food and energy security, and contributing materially to global mitigation and adaptation goals.

References

1. Alhaji AM, Almeida ES, Carneiro CR, da Silva CAS, Monteiro S, et al. (2024) Palm oil (elaeis guineensis): a journey through sustainability, processing, and utilization. Foods 13(17): 2814.

2. Murphy DJ (2025) Agronomy and environmental sustainability of the four major global vegetable oil crops: Oil palm, soybean, rapeseed, and sunflower. Agronomy 15(6): 1465.

3. Kaniapan S, Hassan S, Ya H, Patma NK, Azeem M (2021) The utilisation of palm oil and oil palm residues and the related challenges as a sustainable alternative in biofuel, bioenergy, and transportation sector: A review. Sustainability 13(6): 3110.

4. Page SE, Morrison R, Malins C, Hooijer A, Rieley JO, et al. (2011) Review of Peat Surface Greenhouse Gas Emissions from Oil Palm Plantations in Southeast Asia.

5. Hergoualc'h K, Carmenta R, Atmadja S, Martius C, Murdiyarso D, et al. (2018) Managing peatlands in Indonesia: challenges and opportunities for local and global communities.

6. Meijaard E, Brooks TM, Carlson KM, Slade EM, Garcia UJ, et al. (2020) The environmental impacts of palm oil in context. Nature plants, 6(12): 1418-1426.

7. Abubakar A, Ishak MY, Bakar AA, Uddin MK (2022) Ganoderma boninense basal stem rot induced by climate change and its effect on oil palm. Environ Sustain 5(3): 289-303.

8. Nurul AAB, Ong KH (2025). Adapting forest plantations to climate change: strategies, challenges, and opportunities in Malaysia. New Forests 56(3): 35.

9. Lim JA, Yaacob JS, Mohd RSRA, Eyahmalay JE, El Enshasy HA, et al. (2023) Mitigating the repercussions of climate change on diseases affecting important crop commodities in Southeast Asia, for food security and environmental sustainability-A review. Front Sustain Food Syst 6.

10. Monzon JP, Slingerland MA, Rahutomo S, Agus F, Oberthür T, et al. (2021) Fostering a climate-smart intensification for oil palm. Nat Sustain 4(7): 595-601.

11. Savelli A, Atieno M, Giles J, Santos J, Leyte J, et al. (2021). Climate-Smart Agriculture in Indonesia. CSA Country Profiles for Asia Series.

12. Qureshi MRM, Almuflih AS, Sharma J, Tyagi M, Singh S, et al. (2022) Assessment of the climate-smart agriculture interventions towards the avenues of sustainable production–consumption. Sustainability 14(14): 8410.

13. Oosterveer P (2020) Sustainability of palm oil and its acceptance in the EU. JOPR J Oil Palm Res 32(3): 365-376.

14. Nadras S, Mazlan R, Hussain H, Md Shah I (2024) The European Union deforestation-free regulation (EUDR): assessing impacts and strategies for Malaysian and the global oil palm industry. J Sustain Sci Manag 19(6): 54-74.

15. Solihin M, Fitriana KN, Ratumakin PAK (2024) The european union deforestation-free regulation (eudr) policy: resistance, impact, and challenges for palm oil producing countries. Natapraja 12(2): 183-201.

16. Safitri L, Galdos MV, Pradiko I, Comber A, Challinor A (2026) Assessing climate-smartness of agronomic practices in oil palm production under changing climate conditions. Eur J Agron 174.

17. Abubakar A, Ishak MY, Makmom AA (2021) Impacts of and adaptation to climate change on the oil palm in Malaysia: a systematic review. Environ Sci Pollut Res 28(39): 54339-54361.

18. Wulandari R, Abas A, Abdullah A (2025) Understanding the impact of climate change on oil palm plantation: a systematic literature review. Front Sustain Food Syst 9.

19. Paterson RRM (2023). Future climate effects on yield and mortality of conventional versus modified oil palm in SE Asia. Plants 12(12): 2236.

20. Safitri L (2025) Assessing the Climate-Smartness of Oil Palm Production Systems: A Spatio-Temporal and Carbon Balance Approach. University of Leeds.

21. Cooper HV, Evers S, Aplin P, Crout N, Dahalan MPB, et al. (2020) Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. Nat Commun 11(1): 407.

22. Murphy DJ, Goggin K, Paterson RRM (2021) Oil palm in the 2020s and beyond: challenges and solutions. CABI Agric Biosci 2(1): 39.

23. Skiba U, Hergoualc'h K, Drewer J, Meijide A, Knohl A. (2020) Oil palm plantations are large sources of nitrous oxide, but where are the data to quantify the impact on global warming?. Curr Opin Environ Sustain 47: 81-88.

24. Kasak K, Dronova I, Soosaar K, Melling L, Xhuan WG, et al. (2025) Greenhouse gas emissions from ditches in oil palm plantations on tropical peatlands in Malaysia. Sci Rep 15(1): 37126.

25. Chen G, Veldkamp E, Damris M, Irawan B, Tjoa A, et al. (2024) Large contribution of soil N 2 O emission to the global warming potential of a large-scale oil palm plantation despite changing from conventional to reduced management practices. Biogeosciences 21(2): 513-529.

26. Nasrin AB, Raman AAA, Bukhari NA, Sukiran MA, Buthiyappan A, et al. (2022) A critical analysis on biogas production and utilisation potential from palm oil mill effluent. J Clean Prod 361.

Citation: Judijanto L (2026) From Carbon Source to Carbon Sink: Reframing Oil Palm Plantations through the Lens of Climate-Smart Agriculture — A Review. J Agri Sci & Innov 3(1).

27. Farizal F, Amanda T, Dachyar M, Noor ZZ (2024) 2030 oil palm plantation carbon footprint estimation using O-LCA and forecasting. J Clean Prod 463: 142646.

28. Smith DR, Townsend TJ, Choy AW, Hardy IC, Sjögersten S (2012) Short-term soil carbon sink potential of oil palm plantations. GCB bioenergy 4(5): 588-596.

29. Alcock TD, Salt DE, Wilson P, Ramsden SJ (2022) More sustainable vegetable oil: Balancing productivity with carbon storage opportunities. Sci Total Environ 829: 154539.

30. Varkkey H, Tyson A, Choiruzzad SAB (2018) Palm oil intensification and expansion in Indonesia and Malaysia: Environmental and socio-political factors influencing policy. For Policy Econ 92: 148-159.

31. Putri EIK, Dharmawan AH, Hospes O, Yulian BE, Amalia R, et al. (2022) The oil palm governance: challenges of sustainability policy in Indonesia. Sustainability 14(3): 1820.

32. Novita N, Asyhari A, Ritonga RP, Gangga A, Anshari GZ, et al. (2024) Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands. Sci Total Environ 952: 175829.

33. Safitri L (2026) Palm Oil Transformation in the Era of Climate Change: From a Source of Emissions to a Climate-Smart Plantation System. Sawit Indonesia.

34. Siallagan EJ, Siregar YI, Nofrizal N, Ismail UP (2025) Engineering carbon dynamics and vegetation indices in oil palm plantations: An integrated assessment of carbon stocks, normalized difference vegetation index, and net ecosystem exchange in Riau Province. J Ecol Eng 26(2): 342–349.

35. Benezoli VH, Imbuzeiro HMA, Cuadra SV, Colmanetti MAA, de Araújo AC, Stiegleret al. (2021) Modeling oil palm crop for Brazilian climate conditions. Agric Syst 190: 103130.

36. Saud S, Wang D, Fahad S (2022) Improved nitrogen use efficiency and greenhouse gas emissions in agricultural soils as producers of biological nitrification inhibitors. Front Plant Sci 13: 854195.

37. Judijanto L (2026) Net-Zero Emissions Pathways in Palm Oil Production: A Systematic Review of Methane Capture, Precision Agriculture, Renewable Energy Integration, and Carbon Credit Mechanisms. J Earth Environ Sci Res 8(3): 1.

38. Hasyim A, Riniwati H, Atikawati D (2025) Climate Smart Agriculture Sustainability: A Multidimensional Assessment. J Indones Sustain 6(3): 428-447.

39. Rajakal JP, Hwang JZH, Hassim MH, Andiappan V, Tan QT, et al. (2023) Integration and optimisation of palm oil sector with multiple-industries to achieve circular economy. Sustain Prod Consum 40: 318-336.

40. Barasa PM, Botai CM, Botai JO, Mabhaudhi T (2021) A review of climate-smart agriculture research and applications in Africa. Agronomy 11(6): 1255.

41. Schmidt J, Serena L, Eliassen J (2024) Life Cycle Assessment of Palm Oil at United Plantations Berhad 2024. Teluk Intan, Malaysia.

42. Buenafe KCV, Dunn DC, Everett JD, Brito MI, Schoeman DS, et al. (2023) A metric-based framework for climate-smart conservation planning. Ecol Appl 33(4): e2852.

43. Van Wijk MT, Merbold L, Hammond J, Butterbach BK (2020) Improving assessments of the three pillars of climate smart agriculture: current achievements and ideas for the future. Front Sustain Food Syst 4.

44. Snyder H (2019) Literature review as a research methodology: An overview and guidelines. J Bus Res 104: 333-339.

45. Snyder H (2024) Designing the literature review for a strong contribution. J Decis Syst 33(4): 551-558.

46. Angelsen A, Dermawan A, Ladewig, M (2025) Explaining the recent reduction of Indonesia's deforestation (No. 01/25). Centre for Land Tenure Studies Report.

47. Chervier C, Nofyanza S, West TA, Sills EO (2026) Who gets credit for reduced deforestation? Evaluating additionality in subnational jurisdictional REDD+ under national policy reforms in Indonesia. Ecol Econ 247.

48. Ng DK, Wong SL, Andiappan V, Ng LY (2023) Mathematical optimisation for sustainable bio-methane (Bio-CH4) production from palm oil mill effluent (POME). Energy 265: 126211.

49. Suhartono MJ, Budiastuti MTS, Gunawan S (2025) Enhancing oil palm productivity and lowering emissions through the application of local organic waste. J Ecol Eng 26(11).

50. Alerasoul A, Ashourizadeh S, Materia VC (2025) The soil-management interface: An interdisciplinary review bridging natural capital, ecosystem services, and sustainable development. J Clean Prod 536: 146796.

51. Avery H (2021) The role of organic fertilizers in transition to sustainable agriculture in the MENA Region. In New Generation of Organic Fertilizers. IntechOpen.

52. Bartzas G, Doula M, Komnitsas K (2025) Low-carbon certification systems in agriculture: A review. Appl Sci 15(10): 5285.

53. Reuland G, Sleutel S, Li H, Dekker H, Sigurnjak I, Li H et al (2023) Quantifying CO2 emissions and carbon sequestration from digestate-amended soil using natural 13C abundance as a tracer. Agronomy, 13(10): 2501.

54. Paul C, Bartkowski B, Dönmez C, Don A, Mayer S, et al. (2023) Carbon farming: are soil carbon certificates a suitable tool for climate change mitigation?. J Environ Manage 330: 117142.

55. Noirot LM, Müller SDS, Wahyuningsih R, Sørensen H, Simamora A, et al. (2022) Impacts of empty fruit bunch applications on soil organic carbon in an industrial oil palm plantation J Environ Manage 317: 115373.

56. Zaman NZIS, Abbas AR, Zainal MF, Quek A, Ata WNSW, et al. (2024) Assessing the Environmental Impact of Empty Fruit Bunches for Electricity Generation in Malaysia: A Life Cycle Perspective. In IOP Conference Series. Earth and Environmental Science, IOP Publishing 1372(1).

57. Abbasi IA, Ashari H, Yusuf I (2023) System dynamics modelling: Integrating empty fruit bunch biomass logistics to reduce GHG emissions. Resources 12(4): 53.

58. Abubakar A, Kasim S, Ishak MY, Uddin MK (2023) Maximizing oil palm yield: Innovative replanting strategies for sustainable productivity. J Environ Earth Sci 5(02).

59. Amrul HMZN, Marisa J, Saputra MW, Rusnanto, Wahyudi H, et al (2025) Effectiveness of Drone Utilization and Spatial Verification of Palm Oil Key Points. Proceeding 2nd Int. Conf. Islam. Communicty Stud. 2(1).

60. Agreda FJM, Centeno DJS, Pohlan HAJ, Janssens MJ (2025) Artificial Intelligence in the Management of Good Agricultural Practices in Agroecosystems with Oil Palm (Elaeis guineensis L).

61. RSPO (2026) RSPO and Legislation. RSPO: why sustainable palm oil?

62. Alonso JA (2024) From forests to markets: assessing emergent behaviours of the EUDR on smallholder palm oil producers IIIEE Master Thesis.

63. Barboza MCH, Candinho AAM, Schmitz HUB, Gabriel SG, Buss J, et al. (2025) Organização E Gestão De Centros Educativos. Arace 7(7): 38246-38263.

64. Borer M (2024) EUDR Regulation: Addressing Solutions in the Palm Oil Supply Chain. Koltiva.

65. Lackner KS, Arcusa SH, Azarabadi H, Sriramprasad V, Page R (2023) Carbon accounting without life cycle analysis. Energy Environ Sci 16(11): 4968-4982.

66. Edenhofer O, Bredahl Jacobsen J, Anadónan LD, van Aalst M, Cartalis C, et al. (2026) Climate adaptation and mitigation in the agri-food system-Recommendations for coherent EU policies.

67. Verma B, Rani DV, Roy S, Chavda MH, Krishna KR, et al. (2023) Climate Smart Agriculture: Principles and Practices, 1st ed. Pune, India: Kripa Drishti Publications.

68. Purnomo H, Okarda B, Dermawan A, Ilham QP, Pacheco P, et al. (2020) Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach. For Policy Econ 111: 102089.

69. Judijanto L (2025) The Strategic Roles And Importance Of Oil Palm Smallholders In Maintaining A Sustainable Palm Oil Supply. Aracê 7(7): 40056-40079.

70. Judijanto L (2025) Empowering Rural Communities Through Climate-Resilient Palm Oil: Pathways To Livelihood Enhancement And Environmental Stewardship. Rev Gestão Soc e Ambient 19(7): 1-22.

71. Schmidt J, Serena L, Varandas M (2025) Life Cycle Assessment of Palm Oil at United Plantations Berhad 2025, Results for 2004-2024. Summary report 2.0-LCA.

72. Azizah N, Prakoso CT, Saipul S (2025) Implementation of the RSPO International Standard: Evaluation of Substantive Success and Systemic Constraints for Oil Palm Smallholders. SIGn J Soc Sci 6(2): 423-442.

73. Ningsih VY, Setiawan B, Asmara R, Andriani RD (2025) ISPO Certification and the Sustainable Development Goals: Readiness of Independent Smallholders in Indonesia (South Sumatra). Trans Chinese Soc Agric Mach 56(6).

74. Prasetyo D (2026) Indonesia's 40% Palm Oil Smallholders Face Traceability and Certification Gaps as EUDR Compliance Looms. Koltiva.

75. Judijanto L (2026) Who Pays for Climate Action? The Disproportionate Impact of Deforestation-Free Regulations on Smallholder Farmers. Eur J Manag Econ Bus 3(1): 3-13.

76. Judijanto L (2026) Navigating Economic Resilience and Transformation: Challenges and Opportunities for Indonesia's Palm Oil Industry from Upstream to Downstream in 2026. EJMEB Eur J Manag Econ Bus 3(2): 28-48.

77. Solidaridad (2023) Implications of the EU Deforestation Regulation (EUDR) for oil palm smallholders.

78. Begna T, Wakweya RB (2025) Mitigating climate change impacts on food security via climate-smart agriculture. Plant Stress.

79. Ariom TO, Dimon E, Nambeye E, Diouf NS, Adelusi OO, et al. (2022) Climate-smart agriculture in African countries: A Review of strategies and impacts on smallholder farmers. Sustainability 14(18): 11370.

80. Judijanto L (2026) Ganoderma Boninense: An Existential Threat to Indonesian Oil Palm Sustainability - A Review of Pathogenicity, Economic Impact, and Integrated Management Strategies. J Nat Sci Res Rev 2(2).

81. Rwema M, Safari B, Sylla MB, Roininen L, Laine M (2025) Understanding Farmers' Knowledge, Perceptions, and Adaptation Strategies to Climate Change in Eastern Rwanda. Sustainability 17(15): 6721.

82. Panpakdee C, Hoaihongthong S (2025) Farming for socio-ecological resilience: Understanding factors influencing the adoption of integrated farming systems among organic farmers in Northeast Thailand. Soc Sci Humanit Open 12.

83. Lacoste M, Bellon MV, Piot LI, Cook S, Tremblay N, et al. (2025) Farmer-centric On-Farm Experimentation: digital tools for a scalable transformative pathway. Agron Sustain Dev 45(2): 18.

84. Austin KG, Schwantes A, Gu Y, Kasibhatla PS (2019) What causes deforestation in Indonesia?. Environmental Research Letters 14(2): 024007.

85. Purnomo H, Kusumadewi SD, Puspitaloka D, Juniyanti L, Okarda B, et al. (2024) Pathways for sustainable palm oil trade: addressing global green trade initiatives and the climate crisis in Indonesia.

86. Sembiring N, Rosana EM, Khalif FA, Dwiyanti E, Jaabir AH (2025) Sustainable replanting practices to meet increasing palm oil demand in Indonesia and Malaysia. IOP Conf Ser Earth Environ Sci 1469(1).

87. Hariyadi, Wahyudin CI, Sudradjat, Yahya S, Anwar S, et al. (2024) Effects of root pruning on organic carbon stock levels in oil palm plantation. J Ecol Eng 25(12): 194-201.

Citation: Judijanto L (2026) From Carbon Source to Carbon Sink: Reframing Oil Palm Plantations through the Lens of Climate-Smart Agriculture — A Review. J Agri Sci & Innov 3(1).