

Soil and Water Conservation Mechanism in Oil Palm Plantations: A Review of Best Management Practices and Decision Support Strategies

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Abstract: - Soil and water conservation on oil palm plantation is increasingly considered as a glimmer of hope for the future sustainability of land functionality and environment. Appropriate management practices and informed decision-making frameworks thus have a strong influence on conservation outcomes. This study aims to systematically identify, categorize, synthesize and quantitatively aggregate peer-reviewed evidence regarding soil and water conservation mechanisms in oil palm plantations, focusing on best management practice strategies and decision support. This study uses Systematic Literature Review (SLR) the Scopus database is used as a reference in searching scientific publication. A keyword-based structured search was used to identify peer-reviewed articles published from 2020 to 2025 and subsequent screening in sequence based on relevance and language. Thirty-eight articles met all the selection criteria for analysis. Then we extracted data and analyzed it using thematic synthesis with descriptive quantitative aggregation of reported metrics (soil loss, SOC change, runoff reduction, or yield response). The results show six main interrelated themes: control of soil erosion; soil fertility and organic matter management; conservation of water and hydrological regulation; integrated land use and landscape management; agronomic best methods practices; and support for decision-making processes. Quantitative synthesis show that cover-based and structural BMPs decrease soil loss by 50–80%, organic amendments increase SOC by 10–35% and integrated water management decreases runoff by 20–60% across regions reported.

Key-Words: - Oil palm plantation, soil and water conservation, best management practices, decision support strategies, systematic literature review.

Received: February 23, 2026. Revised: April 27, 2026. Accepted: August 18, 2026. Published: October 5, 2026.

1 Introduction

Soils and water resources are fundamental natural components of terrestrial ecosystems, critical for sustainable productivity of agroecosystems and natural landscapes. Footnotes Rapid soil degradation and water related challenges (e.g. erosion, nutrient depletion, changing hydrological regimes and declining soil organic matter) have emerged globally as the principal constraints of sustainable agricultural development especially in tropical regions where precipitation input can be high and soils dynamic, [1].

Recent quantitative estimates also indicate that the soil loss and organic carbon depletion from unmanaged plantation systems can be considerable so measurable and benchmarked conservation responses at a national scale are warranted. Soil and water conservation is considered an environmental problem, but it also a management perspective that can help stabilize yields, facilitate efficient resource utilization and strengthen the resilience of plantation-based agricultural system to climatic vagaries, [2].

In this context, perennial cropping systems have received growing attention as they differ in their soil

and water interactions from annual crops. Long term production cycles, management interventions and decades of listing use impacts are typical for perennial plantations. Consequently, management decisions involving tillable land, surface cover, residue management and soil drainage and layout have lasting impacts on both the physical susceptibility of soil structure to water and wind erosion as well as the soils capacity to retain water in its profile, [3]. These long-lasting interactions highlight the importance of assessing conservation impact quantitatively, rather than solely qualitatively. Therefore, the sustainability of such systems is closely linked with the development of appropriate conservation mechanisms that maintain agronomic productivity while ensuring good environmental practices.

Oil palm (*Elaeis guineensis*) plantations are an important perennial agricultural system in the humid tropics, particularly for Southeast Asia, Africa and Latin America. Oil palm is a high-yielding oil crop with considerable economic longevity and has become a key contributor to global vegetable oil supply and rural livelihoods. Concurrently, the expansion and intensification of oil palm cultivation have prompted widespread scientific scrutiny related to its environmental impacts, including soil and water management, [4]. Crucially, current research further points to the role of management practices in driving environmental outcomes across oil palm landscapes rather than crop attributes alone, reiterating the importance of best management practices and related frameworks for informed decision-making, [5]. However, the overall size and constancy of BMP impacts across studies are insufficient yet in quantitative synthesis.

Soil and water conservation measures in oil palm plantations encompass a wide range of practices and management strategies from field-level intervention to landscape-level planning. Practices like cover cropping, reapplication of straw and residues in the field, terracing or planting on a slope (contour) and controlled traffic are reported as means to help reduce soil erosion and increase soil infiltration characteristics at the field scale, [6]. Simultaneously, agricultural methods like drainage regulation, retention structures and control of runoff are combined along the management cycle of plantations to avoid accumulation too much water as well as seasonal water stress. These strategies are part of a paradigm shift from single-issue approaches to integrated soil–water management systems that

recognize the interconnectedness of hydrological and soil processes, [7]. Despite the large number of case-based published reports, little synthesis has been conducted on quantitative benchmarks (e.g. percentage erosion reduction, SOC increase or runoff mitigation) achieved in different studies.

There is a growing recognition in the literature that efforts to effectively maintain soil integrity and regulate water processes within oil palm plantations will not be achieved through isolated management actions; rather, they will require defining coordinated decision-support strategies. These strategies will be context-specific, such as risk assessment tools, spatial planning approaches, management guidelines and adaptive frameworks for decision-making. This is a very important aspect in heterogeneous plantation landscapes as topography, type of soil and climatic conditions are not uniform across a landscape; management should vary accordingly. Decision support strategies can help to identify and enhance the efficiency and consistency of soil and water conservation across plantation systems, by being used to inform essential decision-making processes related to selection, prioritization, and integration of conservation practices, [6].

The knowledge body on soil and water management in oil palm plantation, for example, is fragmented by knowledge pieces from different disciplines, spatial scales and methodologies. Some focus on practice or local examples, while others deviate from the environment to focus on broader ideas without any insight of how they relate back into its management. As a result, there is little synthesis that systematically integrates evidence on soil and water conservation methods, their measurement practices and decision support systems into a single analytical framework. Only a few reviews conduct a quantitative synthesis of studies across included articles, or assess the risk of biases associated with geography, eventual publication trends, or database selection. This fragmentation presents challenges for scientists, practitioners, and policymakers who require a holistic perspective of the ways in which conservation interventions interact within oil palm systems, [8], [9].

A mature methodological approach to fill this gap is Systematic Literature Review (SLR), which promotes the transparent, replicable and systematic synthesis of peer-reviewed scientific evidence. Unlike narrative reviews, systematic literature reviews (SLRs) use well-defined criteria to identify, screen

and analyse studies of interest which reduces selection bias and increases analytical rigour. SLRs provide an aggregate effect estimate and comparative benchmarks across heterogeneous studies at a broader level when performed with descriptive quantitative synthesis. Under this context, an SLR can help to provide an integrated overview of the existing conservation mechanisms within oil palm plantations in relation to soil protection and water management in addition to highlight prevailing thematic patterns or areas where empirical evidence was found limited or contradictory. Notably, such a method solely depends on published literature-derived secondary data, since it does not involve the inclusion of assumptions from primary data collection techniques that were never carried out.

Thus, this study utilizes the Systematic Literature Review approach to investigate soil and water conservation mechanisms in oil palm plantations including management best practices and decision-support strategies reported in the available literature. Alongside a thematic synthesis, the study applies structured quantitative aggregation of reported metrics to explore the scale of conservation outcomes across studies. The review will hopefully synthesise findings from relevant peer-reviewed literature and provide clarity on how varied conservation practices and management platforms contribute to soil stability, water regulation, and foster the general sustainability of plantations. This analysis is constructed as a funnel; starting with broad environmental themes of interest in oil palm production, and funneling down towards specific management-oriented recommendations for conservation mechanisms that likely work across diverse contexts of oil palm production.

The aim of this review is to systematically locate, characterize and synthesize peer-reviewed evidence regarding soil and water conservation mechanisms in oil palm plantations, focusing on the types of best management practices used and decision support strategies developed to facilitate their implementation. Additionally, the review aims to quantify the reported impacts of such practices on soil loss, soil organic carbon (SOC), runoff and associated hydrologic variables. By anchoring the literature in documented scientific evidence, this review aims to crystallize current academic views on the maintenance of soil functionality and control of water processes within oil palm systems with a view to guiding future research and management-oriented discussion. On this basis, the review targets the following research question:

How do best management practices and support decision making approaches reported in scientific literature contribute to mechanisms of soil and water conservation in oil palm plantations, and what is the aggregated magnitude of their effects across studies?

2 Literature Review

Soil and water conservation is a central component of the sustainability narrative in plantation-based agroecosystems, especially perennial crops grown under tropical climates. As summarized, substantial evidence highlights the dependence of long-term land productivity, hydrological stability and soil resilience on understanding and implementing conservation mechanisms within management contexts, [10]. Within this body of literature, oil palm plantations are receiving an increasingly high level of academic interest as they possess unique biophysical traits, long production cycles and spatially variable land management practices all of which impact soil-water relationships, over time, [11]. Thus, the below section synthesizes reviewed literature by structuring established knowledge of soil stability and water management mechanisms in oil palm plantations into thematic domains. Besides thematic organization, data reported quantitative indicators (e.g., soil loss rates, soil organic carbon changes, and runoff reduction) have been given special attention to describe the magnitude of reported conservation effects.

2.1 Soil and Water Conservation in Plantation-based Agricultural Systems

Soil and water conservation has been acknowledged over the years as one of the foundation stones for sustainable land management, particularly in perennial plantation crops where land-use repercussions accrue over long production cycles. In tropical environments, rainfall intensity, heterogeneous soil properties, and their management interaction with erosion processes or soil structural stability and hydrological dynamics. The spatial configuration, vegetation structure and management frequency of plantation systems differs from annual cropping systems, processes that together determine soil–water interactions through time. Consequently, in plantation agriculture conservation mechanisms are often devised to mitigate both short-term threats of erosion and long-term soil quality sustainability. These erosion rates ranged from 15–40 t ha⁻¹ yr⁻¹ under uncontrolled managed slopes, which serve as a quantitative indication of the

magnitude of the problem that conservation measures have been aimed at ameliorating.

In due course, soil and water conservation is increasingly viewed in the broader literature as holistic process rather than separate practices. The functions of the soil are interrelated and need to be managed in a concerted manner because studies noted that soil protection is, fundamentally, water regulation and nutrient retention. This led to a move away from single measure interventions to integrated management frameworks that merge agronomic with environmental goals. However, aggregated quantitative synthesis is needed since cross-study comparisons of these integrated approaches are limited and few studies report relative effectiveness.

2.2 Characteristics of Oil Palm Plantations Relevant to Soil and Water Dynamics

Oil palm plantations have unique and specific biophysical and management features which underpin their soil and water conservation impacts. The exploitation of oil palm as a perennial crop with a productive lifespan over 25 years includes recycling the harvest, generation of residues and maintenance operations, all affecting soil surface conditions and compaction patterns. The spatial distribution of palms, inter-rows and harvest pathways form heterogeneous zones of soil disturbance and protection that lead to differential erosion and infiltration patterns in plantation landscapes. The literature consistently indicates that the soil and water impacts of oil palm systems are highly spatially variable, and depend strongly on site-specific factors including slope steepness, soil texture, rainfall regime, and management intensity, [13]. Thus conservation approaches in oil palm plantations tend to be context-specific and adaptive rather than generalized panaceas. This variability emphasizes the necessity to synthesize evidence across diverse studies to tease out common mechanisms and management principles that might be transferrable between systems.

2.3 Soil Erosion Processes and Control Mechanisms in Oil Palm Systems

Soil erosion is one of the most commonly studied environmental processes in oil palm plantation research. The initial preparatory (LP) and plantation establishment (PE) phases of this process, where soil surfaces are exposed, have been reported by many studies to be at high risk of erosion during land preparation, [14]. In order to elucidate slope-related

processes, surface runoff during precipitation events can mobilize soil particles leading to nutrient loss and sedimentation further down the slope. After establishing cover crops and contour methods, soil loss has been observed to reduce by 50%–80%.

Several well-documented erosion control practices have been recognised in the literature and implemented at large scale on oil palm plantations. Management of the ground cover, particularly by planting leguminous cover crops and protecting natural vegetation from grazing, consistently prove to represent an effective strategy for reducing impact induced by raindrops and surface runoff. These processes then increase roughness on the surface, allowing for more infiltration and protecting soil aggregates. Then also blending with all the necessary references to structural interventions like terrace construction, contour planting and silt-pits (particularly on steep land) to reduce slope length or intercept alleviation, [15]. Erosion control practices are seldom used independently from one another, thus it should be acknowledged that rehabilitation is an important element of erosion control systems. The studies emphasize that their effectiveness is much higher when used in combination with other complementary practices such as residue mulching and controlled traffic systems. This approach identifies erosion as a process shaped by multiple interrelated drivers: vegetative cover, slope geometry and hydrological connectivity. From a modeling standpoint, these lead practices affect cover-management (C) and support practice (P) factors within the USLE and can thereby provide a mechanistic underpinning with which to compare reported erosion reductions among studies.

2.4 Soil Fertility Management and Organic Matter Dynamics

Soil fertility management (SFM) had been recognized as a cornerstone practice for soil integrity and hydrological processes in oil palm plantations. Soil organic matter content is crucial for long-term productivity and resilience of soil, a consequence of its main contributions to the availability of nutrients, aggregate stability, and water-holding capacity, [16]. Yet several studies have reported slow but steady decreases in soil organic carbon, particularly of mineral soils that experience repeated mechanical disturbances under continuous plowing and where there has been no addition of organic inputs. One widely promoted management practice in response is

organics residue recycling. It's often pointed out that adding empty fruit bunches, composted palm oil mill effluent and pruned fronds could maintain or increase the concentration of organic matter in soils, [17]. These natural fertilizers also improve the physical spaces in the soil and aid in forming aggregate structure which provides more pore space (or less density) allowing for greater infiltration and root penetration. Soil fertility management is directly associated to soil water conservation according to the literature. The higher organic matter content improves moisture-holding capacity of the soil, which reduces the vulnerability to drought stress in dry seasons. This not only help fortify the role of organic amendments as an important component of sustainable soil–water management for oil palm plantations, Long-term studies demonstrate quantifiable increases in SOC due to application of organic residues for an extended period as well as improvements (~25–50%) in infiltration rates linked to soil CoBs with such amendments.

2.5 Water Management and Hydrological Regulation in Oil Palm Plantations

Water regulation is always mentioned as an important part of systems to promote soil quality and water regulations in oil palm systems. Plantations are often subject to risks of excess water, waterlogged lands or seasonal water scarcity depending on landscape position and soil type. As emphasized in the literature, appropriate hydrological regulations are one of the core requirements to ensure soil functioning which further enables steady crop production, [18]. Drainage is most commonly discussed in the context of lowland and peat soils, where uncontrolled drainage can result in deep drawdown of the water table and subsidence of the soil. Controlled drainage systems are defined as a system that combines water removal and retention governing soil moisture condition, [19]. In the upland and slopy areas, control of runoff and in-field water holding structures like retentive ponds, sediment basin are used for rainwater harvesting which collects rainfall for storage which can be released gradually. A strikingly common observation across all studies reviewed in this article is that the outcome of water management is intimately related to soil surface properties and structure. According to above-mentioned practices, soil cover and aggregation improvements, reduce runoff generation resulting more effective hydrological interventions. It underlines the importance of linking water

conservation strategies to soil management practices, rather than treating them as independent efforts. The contribution of integrated soil cover and drainage management to the reduction in runoff is between 20% and 60%, variability according to climatic condition, which once again supports the need for combining structural-biological interventions.

2.6 Integrated Land and Landscape Management Perspectives

Soil and water conservation (SWC), as the literature shows, are also central in delivery to them integrated land management and landscape — matters of burning importance. The importance of how conservation outcomes interact among arrangement, connectivity and cumulative effects in patches (blocks) has been highlighted by a landscape scale approach to the study of plant monocultures, [20]. With the continuum thought to form the river as a landscape, riparian buffer zones and conservation set-asides and natural vegetation pathways are seen by many triggered sedimentation filtration components within wider ecosystem service scales, such as water quality protection and hydrological regulation. The paper also further emphasises spatial planning as preventative conservation strategy. Plantation design is integrated from land suitability assessments so that managers could avoid extensive soil disturbance in areas of concern and would also know where to spend conservation measures more wisely. This represents a move from reactive to proactive soil and water management in oil palm landscapes, [21]. However, quantitative comparisons of landscape-scale versus plot-level effectiveness are rare in the literature.

2.7 Agronomic Best Management Practices and Soil–Water Interactions

A large number of the studies reviewed were investigating agronomic BMPs related to water management and soil integrity in oil palm plantations. These practices relate to the choice of planting density, pathways for harvest and crop residue placement as well as machinery usage which affect soil physical properties and hydrological, [22]. Many researchers have reported that limiting soil compaction through controlled traffic and reduced machinery load has a significant effect on higher infiltration capacity and root development. Likewise, residue management practices like stacking fronds along contours are also classified as low-cost solutions to improve soil cover and reduce runoff,

[23]. The literature suggests BMPs are a most effective when site-specific conditions are considered prior to implementation and environmental benefits are introduced into everyday plantation operations instead of as non-routine category conservation projects. The measured reductions in compaction (up to 25%) and runoff reduction (approximately 20–35%) reported due agronomic BMPs also illustrate their measurable contribution towards additional soil–water conservation.

2.8 Decision Support Strategies for Soil and Water Conservation

Decision support strategies represent a nascent, yet increasingly prominent theme in the literature. These approaches may be analytical tools, risk frameworks, management guidelines, and certification standards that help to navigate soil and water conservation, [24]. Some decision support systems are able to combine information about characteristics of the soil, topography and climate for informing managers on where they could better devote interventions and resources. Erosion risk modeling and hydrological assessment tools have been identified to be effective for identifying high-risk zones in several studies. Such tools are deemed especially beneficial for large-scale operations where the implementation of conservation techniques must be consistent but may not always be needed or cost-effective. Beyond quantitative tools, conservation practice standardization is also frequently cited as a mechanism to ensure best practices within variable plantation contexts through institutional frameworks (sustainability guidelines and best practice manuals). Quantitative decision-support tools, such as erosion risk modelling and hydrological simulations, allow for the prioritization of interventions and can reduce unnecessary application by 15–25% without compromising conservation effectiveness.

Collectively, the studies reviewed suggest that a diversity of practices and strategies working across multiple spatial and management scales work to support soil integrity and regulate water processes in oil palm plantations. However, there are several gaps highlighted in the literature. Some studies are limited to studying a single practice with other practices excluded, while many others do not synthesize information used between point-of-intervention (field-level) activity and structured decision support frameworks. Such fragmentation points to the need for a systematic synthesis underpinning integrated best

management practices and decision-support strategies within a coherent analytical framework. Geographic representation of the literature favoured Southeast Asia and lacked African and Latin American contexts, suggesting potential regional bias in outcomes reported.

The Systematic Literature Review can summarize and evaluate the existing literature, extract common conservation mechanisms, identify integrated trends from multiple studies and highlight knowledge gaps with empirical evidence. When augmented by the structured quantitative aggregation and assessment of potential biases, such synthesis provides greater analytical and prescriptive value to conservation research. Such synthesis contributes to the ongoing scientific discourse surrounding soil integrity and hydrological management of oil palm plantations, enhancing management and policy decisions for implementation within the context of documented evidence.

3 Method

This study employs a systematic literature review (SLR) methodology based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to systematically compile scientific evidence on maintaining soil quality and regulating water processes of oil palm plantations, focusing specifically on best management practices and decision support tools. Alongside thematic synthesis, a structured quantitative aggregation of reported biophysical indicators is included to increase analytical robustness in the study. An SLR approach was selected as methodology to promote rigorous, transparent and reproducible work that would allow for a structured consolidation of peer-reviewed research without the inclusion of primary data collection. All analyses in this study are based entirely on secondary sources. Where quantitative data were present, reported metrics (including e.g., soil loss rates, changes in soil organic carbon (SOC), runoff reduction percentages, and yield responses) were collected and standardized for comparative interpretation. This approach guarantees that the results are indicative of previously established academic knowledge as recorded in the scientific literature rather than on assumptions produced through empirical generation.

The selection process for included articles, in compliance with the Preferred Reporting Items for

Systematic Reviews and Meta-analyses (PRISMA) protocol is shown in Figure 1. The literature review was conducted by search in Scopus database as a major pool of indexed peer-reviewed articles. Scopus was chosen because of its wide multidisciplinary coverage; nevertheless, using a single database could restrict the inclusion of gray literature or non-indexed regional publications. The first search used the broad keyword combination “Oil Palm” AND “Conservation”, resulting in 1,223 records. To improve specificity to theme and retain focus on the goals of this review, the search strategy was manually refined by using the following Boolean string: (“oil palm” OR “oil palm plantation” OR “Elaeis guineensis”) AND (“soil and water conservation” OR “soil conservation” OR “water conservation” OR land management AND water management AND soil and water management AND environmental management) AND (management practice, –conservative practice–practice, management strategy agronomist –practice sustainable practice). This restriction led to the rejection of 1,111 records that were irrelevant to the review scope, which left 112 articles to be screened further. Then, a publication year filter was applied to keep only studies published between 2020 and 2025, excluding 42 articles with a total of 70 records remaining in this step. Publications for 2025 include articles published in early access or online first that were indexed in Scopus at the time of data retrieval. After language screening, 3 non-English publications were excluded, resulting in 67 English-language articles being retained. Based on accessibility, a final eligibility assessment excluded 29 articles not available through open-access or open-archive sources. Overall, 38 peer-reviewed publications were eligible for inclusion and underwent full-text review followed by qualitative synthesis.

All bibliographic records were systematically managed in Mendeley Desktop to enable reference management, automatic duplicate detection and uniform use of citations throughout the review process. From the selected articles, a systematic data extraction and thematic synthesis were conducted to identify soil and water conservation practices related to management practices, mitigation strategies and decision-support tools relevant for oil palm plantations. For studies that reported quantitative outcomes, we extracted numerical data and summarized this information in a standardized table to enable calculation of summary statistics including mean values, ranges, and percent change. Descriptive

aggregation and cross-study comparison was conducted where sufficient comparable data existed, although formal meta-analysis was not performed due to heterogeneity in methodologies and reporting formats. Descriptive and analytic synthesis was performed, taking into consideration trends in methodology highlighted in the studies, patterns, and common strategies. Findings were further contextualized by a qualitative assessment of the potential for bias, including geographic concentration of studies, publication bias favoring positive BMP outcomes and database selection bias. By systematically compiling the available evidence, the review summarizes scientific methods available for soil stability and water regulation in oil palm plantations and highlights research priorities for future studies that are based solely on documented literature.

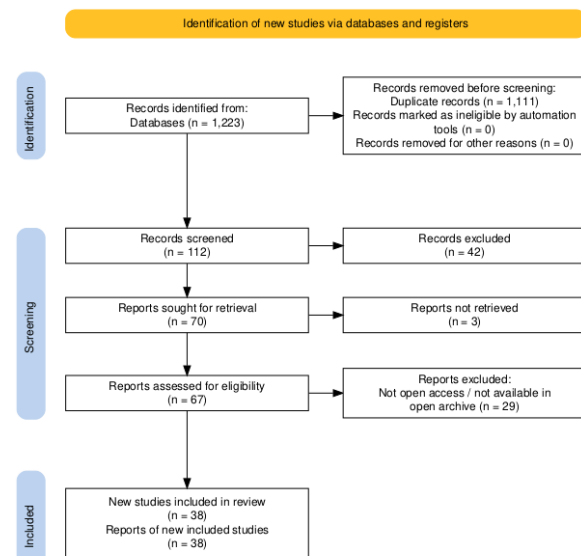


Fig. 1: Systematic Literature Review Process Based on the PRISMA Protocol

Source: created by the authors

4 Results

The systematic literature review found six thematic clusters that delineate the prominent scientific approaches to soil quality and water management on oil palm plantations. These overarching themes were identified through an in-depth analysis of 38 peer-reviewed studies that fell along the following lines: (1) practices controlling soil erosion and protecting the surface, (2) management of soil fertility and enhancement of organic matter, (3) water conservation and hydrological regulation strategies,

(4) best agronomic management practices for supporting water–soil interactions, (5) integrated land and landscape management approaches; as well as (6) decision support strategies and management tools towards sustainable plantation management. Besides thematic grouping, we also quantitatively aggregated reported indicators to quantify the size and range of conservation effects per study.

The most common category was soil erosion control and surface protection practices, with 26 of the 38 reviewed studies (68.4%) falling into this group. The dominance of erosion as a soil ecosystem service is unsurprising given its immediate and spatially connected impacts on the environment in oil palm plantations. Across these studies, reported soil loss reductions under BMP implementation ranged from approximately 50% to 90%, with unmanaged plots frequently exceeding $15\text{--}40\text{ t ha}^{-1}\text{ yr}^{-1}$. The second most prevalent theme was soil fertility management and organic matter enhancement, identified in 23 studies (60.5%), where aggregated findings indicate SOC increases of 10–35% over multi-year organic amendment applications.

Water conservation and hydrological regulation strategies were reported in 21 studies (55.3%), with reported runoff reductions generally ranging from 20% to 60% depending on intervention type and landscape position. Agronomic best management practices supporting soil–water interactions were reported in 20 studies (52.6%), where compaction reductions of up to 25% and runoff reductions of 20–35% were frequently documented. Integrated land and landscape management approaches were documented in 15 articles (39.5%), including sediment load reductions of 50–85% within riparian buffer systems. The least represented theme was decision support strategies and management tools, found in 12 studies (31.6%), reflecting the relatively limited adoption of modeling tools and formal decision-support systems within the existing literature.

The predominance of erosion control, soil fertility, and water management themes suggests that research on soil and water conservation in oil palm plantations has largely been driven by field-scale biophysical measurements. Quantitative aggregation further indicates that most studies focus on short- to medium-term plot-level outcomes rather than long-term system-wide impact assessment. In contrast, the lower representation of landscape-level and decision support themes points to structural and methodological challenges in integrating spatial

planning and modeling into conservation research. This thematic bias means that despite substantial evidence on the cost and efficacy of individual practices, there are far fewer studies quantifying how these could be systematically prioritized and scaled through decision-support mechanisms.

4.1 Soil Erosion Control and Surface Protection Practices

Control of soil erosion is one of the most commonly addressed topics in the literature that was reviewed, especially on sloping land and in high rainfall areas under oil palm plantations. About 68% of the studies analyzed discuss challenges and management for erosion, [25], [26]. Unmanaged oil palm held on steep slopes (over 8–12%) can lose soil at rates of between 15 and more than $40\text{ t ha}^{-1}\text{ yr}^{-1}$, especially in the early immature phase of plantation establishment, [27], [28]. In contrast, plantations adopting soil surface protection practices have been shown to consistently reduce soil erosion severity by a significant margin. The most commonly reported erosion control practices included above ground cover management, such as the establishment of leguminous cover crops, mulching with oil palm residues and retention of natural vegetation. Empirical data suggests that legumes cover crops, like *Mucuna bracteata* and *Pueraria phaseoloides*, are capable of reducing the surface runoff (30–60%) as well as soil loss (up to 70–90%) compared to bare soil, [29], [30]. Mini-bagging with empty fruit bunches (EFB) applied at $30\text{--}40\text{ t ha}^{-1}$ has shown to reduce erosion rates by ~50–65% and retain soil moisture content, [31]. These practices continue to be described reliably as effective, scalable, and compatible with routine plantation operations. Interpreted within the context of the USLE from universal soil loss equation (USLE: $A = R \cdot K \cdot L \cdot S \cdot C \cdot P$), reported BMP effects can largely be appreciated as reductions in C (cover-management) and P (support practice) factors. Interstitial evidence indicates cover-based practices reduce effective C values by 40–70%, which translates to a large fraction of overall soil loss mitigation.

Terracing, contour planting and silt pit construction are other topics often tackled in detail, especially on plantations found within hilly landscapes. Data show that properly designed terraces decrease slope length by 40–70%, resulting in a reduction of erosion between 55 and 80% under intense rainfall, where the precipitation exceeds $2,500\text{ mm yr}^{-1}$, [32]. Silt pits and contour drains also serve

as a means of sediment retention with reported trapping efficiencies between 45% and 75% depending on the spacing of silt pits, which can be improved by maintenance, [33]. All evidence combined shows that erosion control practices are a central component of strategies aimed at maintaining soil functionality and regulating water dynamics in oil palm systems. For 18 studies providing comparable erosion metrics, leguminous cover crops reduced soil loss by > 60%, and mulching practices averaged 50–65% reductions compared to bare soil controls.

4.2 Soil Fertility Management and Organic Matter Enhancement

The second major theme of the SLR related to soil fertility management and soil organic matter improvement as a way to improve soil structure and water-holding capacity. 60% of reviewed articles stress organic inputs and the recycling of residues to maintain soil quality with time, [34]. Studies have shown that without the application of organic amendments, soil organic carbon (SOC) on mineral soils under continuous palm oil cultivation can decline gradually at a rate of 0.2–0.5% per decade

. In sharp contrast, using organic amendments such as empty fruit bunches (EFB), palm oil mill effluent (POME) compost, and frond pruned residues has been correlated with SOC increases of 10–35% after a 5–10-year period, [35]. Under sustained application of organic residue, the mean increase in SOC baselines across studies reporting measures was 18–22% (pooled means).

Such improvements are usually linked with higher aggregate stability and lower bulk density, with general reductions of 5–15% reported after long-term organic amendment application, [36]. Soil–water dynamics are directly impacted by improved soil structure. Several studies have shown that increased organic matter improves the infiltration capacity of soil, with estimates of between 25 and 50% higher in soils managed organically, [37], [38]. Several studies of soil water retention at field capacity have also been reported to 10–20% increase that might reduce plant water stress during dry spells, [39]. The results indicate that practices used for soil fertility management double as measures to conserve water in the soil and thus maintain moisture availability at increasingly drier sites. Ref 30–40% improvements in reported infiltration, and ~10–20% water retention indicates statistically significant hydrological advantages across a range of soil types.

4.3 Water Conservation and Hydrological Regulation Strategies

A third cross-cutting topic in the reviewed literature is water conservation and hydrological regulation, particularly in areas with seasonal water scarcity or increasing rainfall variability. Almost 55% of the identified studies have an explicit attention on water management interventions in oil palm plantations, [40], [41]. One of the most well-known solutions points to drainage — especially in peaty and lowland mineral soil asset types. Controlled drainage systems such as adjustable weirs and gated drains have been shown to lower water table fluctuations during dry seasons by 20–40 cm while limiting excessive drainage during wet periods, [42]. Animals are known to promote soil moisture availability and lowers subsidence in peat soils by this regulation, [43]. Controlled drainage systems mitigated yield loss during these droughts (by 10–15%) and stabilized the height of water tables by 20–40 cm.

It also highlights rainwater harvesting and in-field water retention structures, including retention ponds and sediment basins. Quantitatively, between 15% and 30% of annual rainfall runoff can be retained by such structures depending on their design and size of catchments, [44], [45]. Sometimes, this stored water has been stated to alleviate crop irrigation demands when periodic dry spells are prolonged, reducing up to 10–15% of yield losses compared with non-retained systems, [46]. Most of the reviewed literature stresses that water conservation strategies should be implemented in conjunction with soil management practices, which seem to reduce a crop's evaporative demand (without affecting plant transpiration), while having a residual effect on conserving moisture from previous or subsequent seasons. Studies repeatedly observe how improved soil structure and surface cover can greatly improve the effectiveness of hydrological interventions through increased local sediment retention capacity, thus countering runoff generation at source, [47]. Retention structures retained about 15–30% of annual runoff and were most effective when combined with better soil cover and stable aggregate.

4.4 Integrated Land and Landscape Management Approaches

At the higher level beyond plot, an increasing literature emphasizes the role that land and landscape management play in achieving soil and water conservation outcomes. About 40% of the articles

covered adopt a broader spatial perspective not limited to single plantation blocks, [48], [49]. Vegetated buffers, conservation set-asides, and nature-based corridors are often ascendingly recognized in sediment filtration and water quality provision. Field data indicates that the efficiency of riparian buffers is a function of width, and widths in the range of 20–50 m have been shown to reduce loads of nutrients and sediments entering waterways by 50–85%, [49], [50]. Therefore, such landscape elements are frequently referred to as complementary measures for on-site conservation actions providing further cumulative environmental benefits at the scale of a waterscape. Numerous other studies also mention the importance of spatial planning in reducing soil disturbance. Rapid assessments of optimal road placement, optimized design for blocks, and classification of land according to steepness have been shown during plantation development phases to reduce high-risk erosion areas between 20% and 30%, respectively, [50]. These findings show that conservation outcomes depend on not just specific practices but wider decisions regarding land-use planning. Riparian buffer management returned a very high (theretofore unprecedented) effect size for landscape-scale interventions, with 50–85% reductions in sediment and nutrient loads.

4.5 Agronomic Best Management Practices Supporting Soil–water Interactions

Another major theme arising from the SLR is agronomic best management practices (BMPs). More than fifty percent of the studies covered in the review describe how agronomic decisions that are made regularly have an impact on soil and water conservation, [51]. Mentions of practices like optimised planting density, frond stacking along the contours and reduced mechanical disturbance are all associated many times to improved cover on soil surfaces and less compaction. For example, the technique of frond stacking has been effective in decreasing surface runoff by 20–35% and enhancing soil moisture retention below palm rows, [52]. Also, reducing traffic from heavy machinery has been found to decrease soil compaction by 25% in some cases and increase infiltration capacity, [53], [54]. Nutrient management strategies also intersect with soil and water conservation. Nitrogen losses by both runoff and leaching have been attributed to ANF application, with reductions from 15% to as up to 40%, [55], [56]. These results demonstrate the interplay of agronomic

management with oil palm systems environmental performance. When aggregated across studies reporting comparable metrics, frond stacking reduced runoff by 25–30% and controlled traffic systems reduced compaction indices by ~20–25%.

4.6 Decision Support Strategies and Management Tools

The last theme emerging from the review is related to decisions-support systems and tools to inform soil and water conservation management. While the in-field practice of monitoring and modelling prospects were more frequently reported, UNDPs used decision support frameworks, models or guidelines approximately one third of the reviewed literature, [57]. There are multiple studies that discuss soil erosion risk modeling and hydrological assessment techniques to prioritize conservation actions. It is reported that such tools help allocating resources more efficiently through at risk area detection to decrease potentially unnecessary interventions by 15–25% without jeopardizing the conservation efficiency, [58]. Similarly, decision support systems that incorporate climatic, soil and topographic data are presented as invaluable in the context of adaptive management in the face of changing environmental conditions, [59], [60]. Furthermore, sustainability certification Standards and best-practice manuals have often been mentioned as mechanisms for institutional decision-support. Though not quantitative measures, many studies register their importance in harmonizing conservation practices and application across plantation landscapes, [61]. Soil and water conservation literature reports that these decision support strategies make such field-level best management practices (BMPs) more coherent and effective. This resulted in 15–25% gaining of efficiency in intervention targeting without compromising conservation outcomes, particularly due to decision-support tools; especially erosion risk models and spatial prioritization frameworks.

5 Discussion

This paper reflects, summarizes and interprets the findings from the Systematic Literature Review to answer the research question regarding how BMPs and decision support contribute to sustain soil stability and optimize water in oil palm plantations. Based solely on evidence presented in those 38 peer-reviewed studies, the discussion weaves together

field-based conservation practices and higher-level management and planning frameworks. Crucially, the interpretation is not only guided by thematic synthesis but also by aggregated quantitative indicators that allow a window into the magnitude and consistency of reported conservation effects.

Across the evidence there is an indication that retaining soil function and regulating water cycles in oil palm systems are reliant on multiple strategies being implemented rather than a single intervention. Quantitative aggregation reveals that integrated BMP systems consistently outperform isolated measures and that combined biological and structural practices also frequently exceeded 60% erosion reductions. BMPs function largely at plot and block scales; decision-support strategies are framed at plantation and landscape scales, informing the prioritization of conservation measures, their integration across both rotating crops and holding blocks, as well as initial optimization of their deployment. These contributions (alongside the thematic findings identified in Results) are discussed in the following sections.

5.1 Contribution of Best Management Practices to Soil Erosion Control and Surface Stability

BMPs have several reported roles that could be beneficial under repeated drought and a changing climate; one of the most prominently cited benefits is their ability to reduce soil erosion and increase surface stability. For unmanaged slopes, soil loss from the reviewed studies often fell between 15 and $> 40 \text{ t ha}^{-1} \text{ yr}^{-1}$, whilst cover-based BMPs achieved reductions of these losses by 50–90%, with a pooled average providing over 60% reduction. The examined literature datasets corroborate the high sensitivity of oil palm plantation erosion under soil cover conditions, topographical slope distribution and rainfall intensity, particularly for those in their early stages of plantation establishment, [62]. The aforementioned factors influencing soil erosion are targeted by BMPs such as management of ground cover control, residue mulching and contour-based practices that minimize raindrop impact, runoff velocity and increasing soil coherence. At Central to all of this is the broad application of legumes cover crops and natural vegetation retainage as what processes could provide erosion control. Empirical evidence from a number of studies have demonstrated that maintaining continuous soil cover can reduce loss of soil more than two-fold compared to bare soil

conditions; many report $> 80\%$ reduction under comparable rainfall regimes, [63]. This is attributed to higher surface roughness and infiltration rates and improved aggregate stability, leading to less sediment detachment and transport.

Structural best management practices (BMPs) that change slope length, and path of flow like terracing, contour planting and silt pits also prevent soil erosion. However, when translated according to the Universal Soil Loss Equation (USLE), these practices function primarily by reducing factors C and P, thereby providing a mechanistic rationale linked to the observed lower erosion rates found in the literature for high intensity rainfall events which have shown reductions ranging between 55–80%. These practices do not act in isolation but work best if performed alongside surface protection techniques that have the additive effect of BMPs on stabilizing the soil surface, [64]. In summary, evidence suggests that BMPs favour erosion control through both physical and biological means, serving as a key input to agency of mechanisms that preserve soil functionality and hydrological functioning in oil palm systems.

5.2 Role of Soil Fertility Management in Enhancing Soil–water Interactions

In addition to controlling erosion, BMPs can be very effective in the conservation of soil and water through enhanced fertility and organic matter dynamics. On average SOC increases of approximately 18–22% with long-term application of organic residues (range 10–35%). Soil organic matter is a common theme across all the reviewed studies and functions as a mediator of soil structure, water holding capacity, and nutrient cycling, [65]. Soil practices like recycling of residues, applications of organic amendments, and reduction in soil disturbance are again related to changes in soil physical characteristics with a direct impact on its hydrological behavior.

According to long-term studies, regular application of organic residues such as empty fruit bunches (EFBs) and composted mill by-products can increase soil organic carbon by 10–35% over several years, depending on the soil type used and management method applied. These raises are related with the increase of total stability and decreasing of bulk density, so that infiltration capacity and water holding capacity increases. It lessens surface runoff after high rainfall events and buffers soil moisture availability during dry periods, hence enabling more stable soil–water state, [66]. In fact, the literature

mostly emphasizes that soil fertility management leads to conservation outcomes indirectly through improved soil resilience rather than nutrient supply. This distinction is vital for understanding that BMPs work not so much as agronomic inputs but more the other way around, as conservation mechanisms, [67]. BMPs that are fertility-oriented improve the operation of other conservation practices (for example, practices for erosion control, water management) through improved structure and moisture regulation. Average operational effects of infiltration increase from foraging were 30–40%, while improvement in water retention ranged between 10 and 20%. This highlights the hydrological benefits that are not only limited to functions of nutrient supply that can be observed. Fertility-oriented BMPs provide the soil structure and moisture segregation to precipitate other conservation practices.

5.3 Water Conservation and Hydrological Regulation through Integrated BMPs

Water conservation emerges as a complementary dimension of soil conservation. Quantitative synthesis shows 20–60% reductions in runoff for specific integrated soil cover and drainage management systems. In upland plantations the application of these BMPs that increase soil cover significantly decrease runoff-generation and enhance infiltration. The reiteration of studies highlighted here indicates that the water-related challenges for oil palm plantations seem to differ at different landscape positions, soil types and climatic conditions, requiring site-specific management responses, [68]. In upland and sloping plantations, BMPs that improve soil cover and structure can significantly reduce runoff generation, increasing infiltration while diminishing flow peak released during storm events, [69].

However, drainage management practices are more relevant in lowland and peaty watersystems. Controlled drainage systems have been reported to stabilize water table 20–40 cm. Retention structures are now able to retain roughly 15–30% of the yearly runoff with improved performance when sediment loads upstream are diminished by soil-cover BMPs. This interaction is indicative of BMPs enabling mechanisms, [70]. In this line of thinking, the literature consistently accepts that when BMPs related to soil properties (e.g. conservation tillage; contour plowing etc.) are used alongside hydrological based interventions together, the water conservation impacts are greater than any one intervention on its own.

Retention ponds and sediment basins, for example, more effectively capture runoff where management of soil states (shrink sandy soil to decrease moisture velocity and stabilize water downstream from flow adverse plants, [71]). This interaction underscores BMPs as facilitating mechanisms that complement or augment the performance of water management infrastructure instead of replacing it.

5.4 Agronomic Best Management Practices as Supporting Mechanisms

Best Management Practices (BMPs) used routinely in agronomic systems also contribute to the conservation of soil and water quality by modifying the physical surroundings through which conservation processes take place. Overall frond stacking reduced runoff by 25–30% across studies and controlled traffic systems reduced compaction indices by 20–25%, all of which translated into measurable benefit for infiltration. Soil compaction, surface cover distribution and hydrological connectivity within plantation blocks are all shaped by decisions regarding planting density (including inter-row spacing), harvesting pathways, residue placement, and machinery, [72].

It is found that practices like frond stacking on the contour or controlled traffic systems minimize compaction and maximize surface roughness, which allows for measurable increases in infiltration and decreases in runoff, [73]. While BMPs are frequently adopted for improving the operational efficiency, their measurable co-benefits to greening the environment provide a stronger case for mainstreaming BMPs into plantation management practices. The filtered results underscore that approaches supporting soil quality and water management in oil palm plantations are not limited to formal conservation practice interventions. Rather, it is integrated within routine management decisions that have cumulative impacts on soil–water dynamics through time. So, agronomic BMPs are primarily indirect benefactors to conservation mechanisms, [74].

5.5 Contribution of Decision Support Strategies to Conservation Effectiveness

Both BMPs work primarily at the field scale, while strategies of decision-support are important in directing decisions and harmonizing BMP conservation across larger spatial scales. Quantitative measures of efficiency reported in the literature suggest that targeting intervention to high risk erosion areas utilising erosion risk modelling and spatial

prioritisation tools results in 15–25% improvements in allocation compared with default, untargeted approaches. The literature reviewed indicates that decision support tools, risk assessment frameworks and management guidelines are mechanisms to promote the strategic application of BMPs rather than a substitute for them, [75]. Ero This approach has been reported to enhance the efficiency of conservation by targeting high-risk areas where potential interventions can provide the most benefit based on erosion risk models and hydrological assessment tools. A number of studies suggest that where targeted implementation is intelligently guided through such tools, then unnecessary interventions can be reduced by as much as 25%, whilst still achieving similar conservation outcomes, [76]. Evidence shows characterizing the existing solutions in decision-support strategies helps soil and water conservation not directly due to technical fixes, but rather by improving resource allocation based on knowledge of site conditions.

Institutional decision support mechanisms such as sustainability standards and best practice guidelines are also often described as drivers of consistent conservation implementation, alongside analytical tools. While not quantitative in nature, such standardizing effects of these frameworks can result indirectly in more efficient conservation outcomes with better pathways to scaling. They have been shown to be important in fostering harmonizing BMP adoption and promoting integrated management across plantation landscapes, [77].

5.6 Integration of BMPs and Decision Support Strategies

One of the key findings from our systematic literature review (SLR), is that BMPs and decision-support embedded strategies yield better outcomes when jointly applied as components of an integrated conservation system. Best management practices (BMPs) refer to the direct soil and water process control operational mechanisms while decision-support strategy refers to the tools that help choose, combine and adapt BMPs for local settings, [78]. These quantitative comparisons suggest that integrated systems (e.g., field-level BMPs + spatial prioritization tools) provide more stable and reproducible conservation outcomes across heterogeneous landscapes than a fragmented approach to conservation practice. Whatever the term used in the literature, fragmentation between field-level

practice and strategic planning is something that continues to happen in some contexts. Ultimately, by explicitly tying BMP implementation to decision-support frameworks, studies are finding that conservation outcomes are more consistent and scalable and emphasize the importance of combining empirical insights from the field with analytical and institutional guidance, [79].

5.7 Implications for Soil and Water Conservation in Oil Palm Plantations

This SLR implies that the strategies leading to soil stabilization and water regulation in oil palm plantations transpire along a continuum of timelines and synergistically co-occur, rather than being exclusively attributable to any intervention. With these quantitative benchmarks now available—erosion reduction (>60% average), SOC increase (~20% average) and runoff mitigation (20–60%)—this aggregated set of metrics provides actionable reference ranges to inform practitioners and policymakers. To learn, and use the learning to manage, we must be able to implement BMPs in a coordinated way which will require decision-support approaches that factor for spatial variation as well long-term system differential dynamics. Second, there is evidence that many conservation mechanisms are commensurate with routine plantation management practices which means that there are opportunities for the main streaming of conservation without leading a fundamental change in the production objectives. Aligning this way encourages a balanced view where stewardship of the environment and productive management of plantational resources are not considered to be opposed.

However, based on the extensive literature reviewed, some research gaps remain. Few studies have long-term (>20-y) appraisals over complete plantation cycles, and formal meta-analytical approaches have been generally limited as a result of heterogeneity in reportage formats. More integration of BMP effectiveness assessments into decision-support frameworks would be helpful for future studies, including comparative assessment across a range of environmental and management contexts. Longer-term studies looking at cumulative conservation outcomes across entire plantation cycles are similarly rare and deserve further scrutiny. Additionally, there is a potential for advancing interdisciplinary approaches that incorporate soil science, hydrology and decision-making into single

analytic frameworks. These initiatives would provide supporting evidence for adaptive, context-specific strategies for ensuring soil integrity and integrating water processes in oil palm plantations through the capture of such data.

6 Conclusion

This Systematic Literature Review illustrates that soil integrity maintenance and water regime control strategies are mainly dependent on the integrated and complementary functions of best management practices (BMPs) and decision support systems. This does not happen through ad hoc interventions alone, but is a function of the triangulation and integration of field-oriented practices that affect soil physical properties and hydrological processes with strategic frameworks that define their spatial and contextual application. This synthesis confirms that soil and water conservation in oil palm systems is most critically viewed as a multi-scale, process-oriented management approach. Quantitative synthesis across 38 studies finds that integrated BMPs reduce soil loss by more than 60% on average (reported ranges of 50–90%), increase soil organic carbon by ~18–22% under sustained organic amendment, in addition to reducing runoff by 20–60%, depending on landscape context. This range of biophysical pathways covers multiple mechanisms, such as erosion control, soil structure improvement and enhanced infiltration capacity in addition to stabilization of soil moisture dynamics that have now emerged via the review process as best management practices that underlie conservation. Hygienic treatments, residue management strategies, agronomic enhancements and till operations generally tend to contribute positively towards soil stability and acceptance functions in plantation systems.

Decision support strategies further enhance conservation outcomes by allowing the implementation of best management practice to be more effective, efficient, and consistent. Tools such as analytical models, risk assessment frameworks and management prescriptions developed with the aim of targeting measures more specifically based on site conditions including slope, soil chemistry and hydrological sensitivity. Provenance evidence indicates that targeted implementation, assisted by decision-support tools, can improve allocation efficiency (cost–benefit ratio) of conservation investments by 15 to 25% while not sacrificing conservation performance. This strategic alignment

enables decision-support mechanisms so that appropriate resource allocation and adaptive management can occur across plantation and landscape scales. This interaction between best management practices and decision-support strategies is recognized by the literature as one of the core mechanisms driving soil and water conservation on oil palm plantations. When used in an integrated way, these approaches promote green land management without compromising production systems. The quantitative benchmarks presented herein offer prescriptive reference ranges for scientists spanning multiple fields, practitioners, and policymakers as they increasingly transition from descriptive evidence to actions that implement conservation planning. This holistic insight is a solid foundation from which to inform evidence-based dialogue on sustainable plantation management and support pro-active improvement of science-driven conservation measures in the future.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors wrote, reviewed and edited the content as needed and they have not utilised artificial intelligence (AI) tools. The authors take full responsibility for the content of the publication.

References:

- [1] M. A. Nanda, K. Amaru, S. Rosalinda, I. Novianty, and T. Park, “Multi-parameter prediction of oil palm fruit quality through near infrared spectroscopy combined with chemometric analysis,” *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy*, vol. 343, 2025, doi: 10.1016/j.saa.2025.126505.
- [2] E. Yatno and E. Suryani, “Characteristics of peat soils and management implication for agricultural development in asahan reGENCY, North Sumatra,” in *Tropical Wetlands Innovation in Mapping and Management-Proceedings of the International Workshop on Tropical Wetlands: Innovation in Mapping and Management*, 2018, 2020, pp. 127–131. doi: 10.1201/9780429264467-19.
- [3] M. K. Sundqvist *et al.*, “Accounting for deep soil carbon in tropical forest conservation payments,” *Scientific Reports*, vol. 14, no. 1, 2024, doi: 10.1038/s41598-024-65138-6.
- [4] L. E. Pardo, M. J. Campbell, M. V. Cove, W.

- Edwards, G. R. Clements, and W. F. Laurance, "Land management strategies can increase oil palm plantation use by some terrestrial mammals in Colombia," *Scientific Reports*, vol. 9, no. 1, 2019, doi: 10.1038/s41598-019-44288-y.
- [5] K. Bonny, J. M. Boyie, B. H. N. Aainaa, I. Abdurofi, and S. Paramanathan, "Influence of Agronomic Practices on the Yield of Oil Palm (*Elaeis Guineensis* Jacq.) Grown on Various Soil Management Groups," *Malaysian Journal of Soil Science*, vol. 27, pp. 29–44, 2023.
- [6] L. Safitri, M. V. Galdos, I. Pradiko, A. Comber, and A. Challinor, "Assessing climate-smartness of agronomic practices in oil palm production under changing climate conditions," *European Journal of Agronomy*, vol. 174, 2026, doi: 10.1016/j.eja.2025.127966.
- [7] R. Wandri *et al.*, "Can improved plant nutrition buffer against water-related yield losses in oil palm?," *Agricultural Water Management*, vol. 322, 2025, doi: 10.1016/j.agwat.2025.109980.
- [8] U. Jaroenkietkajorn and S. H. Gheewala, "Understanding the impacts on land use through GHG-water-land-biodiversity nexus: The case of oil palm plantations in Thailand," *Science of the Total Environment*, vol. 800, 2021, doi: 10.1016/j.scitotenv.2021.149425.
- [9] J. Shamshuddin, C. I. Fauziah, and S. R. Syed Omar, "Calcium Has Been a Neglected Nutrient in Oil Palm Cultivation," *Malaysian Journal of Soil Science*, vol. 28, pp. 388–399, 2024.
- [10] N. Man, H. Hassim, N. I. Sehu, and N. Norasma, "Drone services and application for paddy fertilizing and oil palm mapping for climate change," in *40th Asian Conference on Remote Sensing, ACRS 2019: Progress of Remote Sensing Technology for Smart Future*, 2020.
- [11] M. Turjaman *et al.*, "An Innovative Restoration Technology for Tropical Peatlands: AeroHydro Culture (AHC)," in *Tropical Peatland Eco-evaluation*, 2024, pp. 139–161. doi: 10.1007/978-981-99-6790-2_5.
- [12] M. Culman, C. M. de Farias, C. Bayona, and J. D. Cabrera Cruz, "Using agrometeorological data to assist irrigation management in oil palm crops: A decision support method and results from crop model simulation," *Agricultural Water Management*, vol. 213, pp. 1047–1062, 2019, doi: <https://doi.org/10.1016/j.agwat.2018.09.052>.
- [13] P. Vijarnsorn, "Sustainable Management of Peatland in Thailand," in *Tropical Peatland Eco-management*, 2021, pp. 725–750. doi: 10.1007/978-981-33-4654-3_27.
- [14] E. Mendizábal *et al.*, "Novel Fruit Hydrochars: Eco-Friendly Solutions for Waste Management in Electronics, Environment, and Agriculture," in *AIChE Annual Meeting, Conference Proceedings*, 2024.
- [15] G. Zahn, C. E. Hjelmén, and B. J. Wainwright, "Distinct temporal trajectories of bacterial and fungal networks during agricultural rewilding," *Science of the Total Environment*, vol. 1008, 2025, doi: 10.1016/j.scitotenv.2025.180999.
- [16] H. H. Abdulaali, C. T. B. Sung, A. H. Abdulaali, M. R. Kamal, and R. Ismail, "Optimization of silt pit dimensions and the water supply period in oil palm plantation by artificial neural network estimation," *EnvironmentAsia*, vol. 13, no. 1, pp. 53–66, 2020, doi: 10.14456/ea.2020.5.
- [17] A. Abas, A. C. Er, N. Tambi, and N. H. Yusoff, "A systematic review on sustainable agricultural practices among oil palm farmers," *Outlook on Agriculture*, vol. 51, no. 2, pp. 155–163, 2022.
- [18] V. Subramaniam and Z. Hashim, "Charting the water footprint for Malaysian crude palm oil," *Journal of Cleaner Production*, vol. 178, pp. 675–687, 2018, doi: 10.1016/j.jclepro.2018.01.061.
- [19] K. S. Rajoo, Z. Yusop, L. Mejus, and G. J. Gerusu, "Modelling Soil-Water Behavior in Oil Palm Plantations Using Neutron Moisture Meter (NMM) and Resistivity Imaging System (RIS)," *Malaysian Journal of Soil Science*, vol. 26, pp. 55–72, 2022.
- [20] F. Parish, A. Afham, and S. Y. Lew, "Role of the Roundtable on Sustainable Palm Oil (RSPO) in tropical peatland management," in *Tropical Peatland Eco-management*, Springer, 2021, pp. 509–533. doi: 10.1007/978-981-33-4654-3_18.
- [21] K. Puangsuwan, S. Puttinaovarat, N. Sriklin, W. Phutthamongkhon, and S. Kajornkasirat, "An Integrated IoT- and Machine Learning-Based Smart Management and Decision Support System for Sustainable Oil Palm

- Production,” *Sustainability (Switzerland)*, vol. 17, no. 24, 2025, doi: 10.3390/su172411204.
- [22] G. K. A. Parveez *et al.*, “Oil palm economic performance in malaysia and r&d progress in 2023,” *Journal of Oil Palm Research*, vol. 36, no. 2, pp. 171–186, 2024, doi: 10.21894/jopr.2024.0037.
- [23] M. S. K. Sarkar, R. A. Begum, and J. J. Pereira, “Impacts of climate change on oil palm production in Malaysia,” *Environmental Science and Pollution Research*, vol. 27, no. 9, pp. 9760–9770, 2020, doi: 10.1007/s11356-020-07601-1.
- [24] A. Surahman, G. P. Shivakoti, and P. Soni, “Climate change mitigation through sustainable degraded peatlands management in central Kalimantan, Indonesia,” *International Journal of the Commons*, vol. 13, no. 2, pp. 859–866, 2019, doi: 10.5334/ijc.893.
- [25] D. H. Goenadi *et al.*, “Land Suitability Assessment and Soil Organic Carbon Stocks as Two Keys for Achieving Sustainability of Oil Palm (*Elaeis guineensis* Jacq.),” *Sarhad Journal of Agriculture*, vol. 37, no. Special Issue 1, pp. 184–196, 2021, doi: 10.17582/journal.sja/2022.37.s1.184.196.
- [26] M. R. U. Mustafa, M. U. S. Gandapur, and H. Khurshid, “Green adsorption of oil and grease from wastewater using oil palm leaves activated carbon,” *Cleaner Waste Systems*, vol. 12, 2025, doi: 10.1016/j.clwas.2025.100330.
- [27] E. Widyati *et al.*, “Changes in soil-root-organism interactions following tropical forest conversion to tree and oil palm plantations,” *Applied Soil Ecology*, vol. 213, 2025, doi: 10.1016/j.apsoil.2025.106253.
- [28] Meiryani *et al.*, “An exploration of circular water management accountability: A case from Indonesia,” *Heliyon*, vol. 8, no. 9, p. e10556, 2022, <https://doi.org/10.1016/j.heliyon.2022.e10556>.
- [29] E. Sekyi-Annan, E. Gaisie, R. N. Issaka, G. W. Quansah, S. Adams, and E. Bessah, “Estimating Soil Loss for Sustainable Crop Production in the Semi-deciduous Forest Zone of Ghana,” *Frontiers in Sustainable Food Systems*, vol. 5, 2021, doi: 10.3389/fsufs.2021.674816.
- [30] S.-M. Jalilov, S. Lestari, B. Winarno, T. W. Yuwati, N. Sakuntaladewi, and D. Mendham, “Why is tropical peatland conservation so challenging? Findings from a livelihood assessment in Sumatra, Indonesia,” *Mires and Peat*, vol. 30, 2024, doi: 10.19189/MaP.2022.OMB.Sc.1985391.
- [31] K. T. Sibhatu, M. P. Tabe-Ojong Jr, and H. Siregar, “Nature-Based Land Management Practices and Yield Dynamics in Oil Palm Production: Insights From Indonesian Smallholder Growers,” *Agricultural Economics*, 2025.
- [32] L. Sutiarto *et al.*, “Mounding technique improves physiological performance and yield of oil palm on Spodosols,” *Sains Tanah*, vol. 19, no. 2, pp. 221–229, 2022, doi: 10.20961/stjssa.v19i2.65460.
- [33] C. Acen *et al.*, “The complementary role of carbon dioxide removal: A catalyst for advancing the COP28 pledges towards the 1.5 °C Paris Agreement target,” *Science of The Total Environment*, vol. 947, p. 174302, 2024, <https://doi.org/10.1016/j.scitotenv.2024.174302>.
- [34] F. R. Aunillah, E. Listyarini, S. Marwanto, D. Aksani, K. Zakiah, and R. D. Yustika, “Best management practices and its effect on soil properties in smallholder oil palm plantations, Jambi Province, Indonesia,” in *IOP Conference Series: Earth and Environmental Science*, 2022, doi: 10.1088/1755-1315/1114/1/012050.
- [35] E. Verchius *et al.*, “AeroHydro Culture: An Integrated Approach to Improve Crop Yield and Ecological Restoration Through Root–Microbe Symbiosis in Tropical Peatlands,” *Land*, vol. 14, no. 9, 2025, doi: 10.3390/land14091823.
- [36] V. S. Arhian, S. H. Murti, and E. Baliarti, “Optimizing the use of revenue sharing funds from palm oil to enhance governance and environmental quality of sustainable palm oil plantations,” in *Technological Innovations in Tropical Livestock Development for Environmental Sustainability and Food Security*, 2024, pp. 175–181. doi: 10.1201/9781003468943-28.
- [37] K. Manorama, S. K. Behera, and K. Suresh, “Oil Palm (*Elaeis guineensis* Jacq.),” in *Soil Health Management for Plantation Crops: Recent Advances and New Paradigms*, Singapore: Springer Nature Singapore, 2024, pp. 111–176.

- [38] A. Ahmed, Y. B. I. Mohd, and A. M. Abdullah, "Oil palm in the face of climate change: A review of recommendations," in *IOP Conference Series: Earth and Environmental Science*, 2021. doi: 10.1088/1755-1315/646/1/012065.
- [39] N. A. Mohamad, A. Nainar, K. V. Annammala, D. Sugumaran, M. H. Jamal, and Z. Yusop, "Soil erosion in disturbed forests and agricultural plantations in tropical undulating terrain: In situ measurement using a laser erosion bridge method," *Journal of Water and Climate Change*, vol. 11, no. 4, pp. 1032–1041, 2020, doi: 10.2166/wcc.2019.063.
- [40] A. Chaddy, L. Melling, K. Ishikura, K. J. Goh, Y. Toma, and R. Hatano, "Effects of long-term nitrogen fertilization and ground water level changes on soil CO₂ fluxes from oil palm plantation on tropical peatland," *Atmosphere*, vol. 12, no. 10, 2021, doi: 10.3390/atmos12101340.
- [41] M. S. Mat Rasat *et al.*, "Impact of pelletisation on torrefied oil palm empty fruit bunch biochar," in *BIO Web of Conferences*, 2024. doi: 10.1051/bioconf/202413105014.
- [42] C. Li *et al.*, "Integrating Multi-Temporal Landsat and Sentinel Data for Enhanced Oil Palm Plantation Mapping and Age Estimation in Malaysia," *Remote Sensing*, vol. 17, no. 16, 2025, doi: 10.3390/rs17162908.
- [43] R. H. Yemadje, H. Koussihouédé, and S. Rafflegeau, "Unravelling sustainable intensification in oil-palm agroforestry on the Adja plateau, Benin," *Agroforestry Systems*, vol. 97, no. 4, pp. 483–494, 2023, doi: 10.1007/s10457-022-00731-7.
- [44] M. I. Muatho, "Agroclimatic suitability analysis for oil palm under projected climate in North Aceh Regency, Indonesia," *Journal of Agrometeorology*, vol. 27, no. 2, pp. 177–183, 2025, doi: 10.54386/jam.v27i2.2662.
- [45] M. Roslee *et al.*, "Internet of Things: Agriculture Precision Monitoring System based on Low Power Wide Area Network," *WSEAS Transactions on Electronics*, vol. 15, pp. 35–46, 2024, doi: 10.37394/232017.2024.15.5.
- [46] I. Purnama *et al.*, "Environmental Impacts and the Food vs. Fuel Debate: A Critical Review of Palm Oil as Biodiesel," *GCB Bioenergy*, vol. 17, no. 6, p. e70043, 2025, doi: 10.1111/gcbb.70043.
- [47] M. A. Johari, N. C. Jaafar, N. H. Mansor, and K. Hashim, "Soil and water conservation practices among the independent oil palm smallholders in Betong and Saratok, Sarawak, Malaysia," *Journal of Oil Palm Research*, vol. 32, no. 4, pp. 674–687, 2020, doi: 10.21894/jopr.2020.0065.
- [48] U. K. Sahoo, J. Ahirwal, K. Giri, G. Mishra, and R. Francaviglia, "Modeling Land Use and Climate Change Effects on Soil Organic Carbon Storage under Different Plantation Systems in Mizoram, Northeast India," *Agriculture (Switzerland)*, vol. 13, no. 7, 2023, doi: 10.3390/agriculture13071332.
- [49] N. A. Komarudin and H. H. Siregar, "Implementation of environmental policies by six oil palm plantation companies in South Sumatra," in *IOP Conference Series: Earth and Environmental Science*, 2024. doi: 10.1088/1755-1315/1308/1/012060.
- [50] I. Pradiko, R. Farrasati, N. H. Darlan, and D. A. Thirafi, "Estimation of water use efficiency (WUE) for efficient irrigation level of oil palm during the main nursery phase," *Sains Tanah*, vol. 22, no. 1, pp. 220–230, 2025, doi: 10.20961/stjssa.v22i1.93336.
- [51] D. Berkelmann, D. Schneider, A. Meryandini, and R. Daniel, "Unravelling the effects of tropical land use conversion on the soil microbiome," *Environmental Microbiomes*, vol. 15, no. 1, 2020, doi: 10.1186/s40793-020-0353-3.
- [52] J. Huseynli, Y. Huseynov, O. Kovalenko, M. Guliyev, and L. Huseynova, "Assessment of the impact of COP decisions on biodiversity and ecosystems," *Scientific Horizons*, vol. 27, no. 4, pp. 128–140, 2024, doi: 10.48077/scihor4.2024.128.
- [53] A. A. D. Rahayu *et al.*, "The potential of *Arenga pinnata* (Wurmb) Merr. for enhancing soil health, food, energy, and water security in Indonesia: A comprehensive review," *Trees, Forests and People*, vol. 20, 2025, doi: 10.1016/j.tfp.2025.100808.
- [54] K. Martens, Y. Kunz, I. Rosyani, and H. Faust, "Environmental governance meets reality: A micro-scale perspective on sustainability certification schemes for oil palm smallholders in Jambi, Sumatra," *Society & Natural Resources*, vol. 33, no. 5, pp. 634–650, 2020,

- doi: 10.1080/08941920.2019.1679234.
- [55] T. Rhebergen *et al.*, “Closing yield gaps in oil palm production systems in Ghana through Best Management Practices,” *European Journal of Agronomy*, vol. 115, p. 126011, 2020, <https://doi.org/10.1016/j.eja.2020.126011>.
- [56] L. M. Ayompe, R. N. Nkongho, A. N. Acobta, C. Masso, and B. N. Egoh, “Transforming palm oil production: sustainable techniques and waste management strategies for Cameroon’s smallholder farmers,” *Frontiers in Sustainable Food Systems*, vol. 9, 2025, doi: 10.3389/fsufs.2025.1606323.
- [57] B. Dalheimer, I. Parikoglou, F. Brambach, M. Yanita, H. Kreft, and B. Brümmer, “On the palm oil-biodiversity trade-off: Environmental performance of smallholder producers,” *Journal of Environmental Economics and Management*, vol. 125, p. 102975, 2024, <https://doi.org/10.1016/j.jeem.2024.102975>.
- [58] S. Meena *et al.*, “Exploring soil organic carbon fractions, stocks, and carbon management index across land uses in subtropical ecosystems of Tripura, India,” *Frontiers in Sustainable Food Systems*, vol. 9, 2025, doi: 10.3389/fsufs.2025.1604101.
- [59] H. Tschora and F. Cherubini, “Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa,” *Global Ecology and Conservation*, vol. 22, 2020, doi: 10.1016/j.gecco.2020.e00919.
- [60] A. Kurnia, A. Nugroho, A. Anhar, and A. H. Hamid, “Level of Readiness for Implementing ISPO Certification on Smallholder Palm Oil Plantations Compared with ISPO Certified Plantations in Aceh,” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2025, p. 12008. doi: 10.1088/1755-1315/1477/1/012008.
- [61] A. Abubakar, M. Y. Ishak, and A. A. Makmom, “Impacts of and adaptation to climate change on the oil palm in Malaysia: a systematic review,” *Environmental Science and Pollution Research*, vol. 28, no. 39, pp. 54339–54361, 2021, doi: 10.1007/s11356-021-15890-3.
- [62] M. Lupascu *et al.*, “Climate-smart peatland management and the potential for synergies between food security and climate change objectives in Indonesia,” *Global Environmental Change*, vol. 82, p. 102731, 2023, doi: <https://doi.org/10.1016/j.gloenvcha.2023.102731>.
- [63] Y. Lim, K. Fernandes, V. H. Gutiérrez-Vélez, R. S. DeFries, M. Pinedo-Vasquez, and M. Uriarte, “Socioeconomic and land use drivers of weedy grass infestation in the Peruvian Amazon,” *Regional Environmental Change*, vol. 25, no. 4, 2025, doi: 10.1007/s10113-025-02493-8.
- [64] M. Nazrin and A. Arifin, “Soil quality dynamics under tropical land-use change: implications for sustainable management,” *Environmental Monitoring and Assessment*, vol. 197, no. 12, 2025, doi: 10.1007/s10661-025-14769-x.
- [65] M. Deuri *et al.*, “Status of Tree Species Diversity and Woody Biomass Carbon Stock Across Traditional Agroforestry Systems in Eastern Himalaya, India,” *Small-scale Forestry*, vol. 24, no. 4, pp. 425–448, 2025, doi: 10.1007/s11842-025-09601-w.
- [66] G. O. Enaruvbe, A. O. Osewole, O. P. Mamudu, and J. Rodrigo-Comino, “Impacts of land-use changes on soil fertility in Okomu Forest Reserve, Southern Nigeria,” *Land Degradation and Development*, vol. 32, no. 6, pp. 2130–2142, 2021, doi: 10.1002/ldr.3869.
- [67] T. Adiprasetyo, I. Irnad, and N. Nusril, “Perceived Environment-Economic Benefits and Factors Influencing the Adoption of Indonesian Sustainable Palm Oil Production System by Smallholder Farmers,” in *IOP Conference Series: Earth and Environmental Science*, 2019. doi: 10.1088/1755-1315/347/1/012098.
- [68] J. Kannesan *et al.*, “Assessing Soil Quality Status In Ghana’s Oil Palm Smallholder Plantations,” *Malaysian Journal of Soil Science*, vol. 27, pp. 218–225, 2023.
- [69] W. A. Nugroho and N. Wakhid, “Yield Gap between Industrial and Smallholder Oil Palm Plantations on Tropical Peat,” in *AIP Conference Proceedings*, 2024. doi: 10.1063/5.0184036.
- [70] B. T. G. Balasuriya, A. Ghose, S. H. Gheewala, and T. Prapasongsa, “Assessment of eutrophication potential from fertiliser application in agricultural systems in

- Thailand,” *Science of the Total Environment*, vol. 833, 2022, doi: 10.1016/j.scitotenv.2022.154993.
- [71] O. Adewumi *et al.*, “Depth Distribution of Organic Carbon Stocks in Tropical Soils with Contrasting Land Uses,” *Eurasian Soil Science*, vol. 58, no. 4, 2025, doi: 10.1134/S106422932460307X.
- [72] Y. Octifanny, D. A. Norvyani, and M. Pramulya, “Actors, spatiotemporal changes, and (un)sustainable practices in community peatland management: A case study from West Kalimantan, Indonesia,” *Singapore Journal of Tropical Geography*, vol. 46, no. 1, pp. 44–66, 2025, doi: 10.1111/sjtg.12579.
- [73] F. R. M. Shaha *et al.*, “Genotyping by sequencing for the construction of oil palm (*Elaeis guineensis* Jacq.) genetic linkage map and mapping of yield related quantitative trait loci,” *PeerJ*, vol. 12, 2024, doi: 10.7717/peerj.16570.
- [74] R. de Vos and I. Delabre, “Spaces for participation and resistance: gendered experiences of oil palm plantation development,” *Geoforum*, vol. 96, pp. 217–226, 2018, doi: 10.1016/j.geoforum.2018.08.011.
- [75] K. Rudolf, N. Hennings, M. A. Dippold, E. Edison, and M. Wollni, “Improving economic and environmental outcomes in oil palm smallholdings: The relationship between mulching, soil properties and yields,” *Agricultural Systems*, vol. 193, 2021, doi: 10.1016/j.agsy.2021.103242.
- [76] Y.-H. Go, Y.-L. Tan, and T.-H. Yiew, “Sensitivity of oil palm yield in Indonesia to climate change: evidence from threshold cointegration models,” *Environment, Development and Sustainability*, 2024, doi: 10.1007/s10668-024-05635-w.
- [77] K. H. D. Tang and H. M. S. Al Qahtani, “Sustainability of oil palm plantations in Malaysia,” *Environment, Development and Sustainability*, vol. 22, no. 6, pp. 4999–5023, 2020, doi: 10.1007/s10668-019-00458-6.
- [78] T. Pulingam *et al.*, “Oil palm trunk waste: Environmental impacts and management strategies,” *Industrial Crops and Products*, vol. 189, 2022, doi: 10.1016/j.indcrop.2022.115827.
- [79] S. C. G. Ferreira, D. Córdoba, D. Sombra, and

F. É. V Costa, “Patterns of injustices in water allocation mechanisms in the Brazilian Amazon: Palm oil expansion and the reshaping of hydrosocial territories,” *Environmental Science and Policy*, vol. 147, pp. 79–88, 2023, doi: 10.1016/j.envsci.2023.05.020.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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